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NON-ROAD DIESEL ENGINE EMISSIONS AND TECHNOLOGY OPTIONS FOR MEETING THEM

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Non-Road Diesel Engine Emissions and Technology Options for Meeting Them

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Abstract. *This lecture focuses on emissions reduction for non-road diesel engines, although we refer to on-road diesel engines often. We first highlight global emissions criteria and test procedures for non-road engines and compare them with on-road requirements. We then describe critical components and system integration technologies as building blocks for meeting emissions criteria, followed by engine development through emissions tiers. We provide an outlook for what comes after criteria pollutant reduction. We conclude with a summary and perspectives. With this focus on emissions, we will limit our discussion of other product attributes, such as reliability, not because they are not important (in fact, they are critical) but because thorough discussion of those attributes requires lengthy papers on their own.*

Keywords. *Aftertreatment, Cooled EGR, Emissions, Nonroad, Tier 4, Turbocharger.*

We begin this lecture with our personal stories. When we started our college education, we had the vague idea that we would pursue engineering, hoping to contribute to a better world through what we would learn and do. We were not planning to minor in environmental quality. But we have each dedicated most of our careers to cleaner air, and we are proud of it.

Moving on to the subject of engine emissions, the U.S. government enacted Clean Air legislation for the automotive industry in the 1970s, followed by the truck engine industry in the late 1980s, and non-road engine industry in the 1990s. Criteria for vehicle or engine exhaust gas emissions were established for nitric oxide (NOx), hydrocarbon (HC), carbon monoxide (CO), and particulate matter (PM). These emissions have been referred to as criteria pollutants. Following the U.S. lead, emissions regulations have been enacted across the globe. Billions of dollars have been invested to reduce criteria pollutants by the auto and engine industry in research, engineering development, and manufacturing. As a result, we breathe cleaner air and we live in a healthier environment.

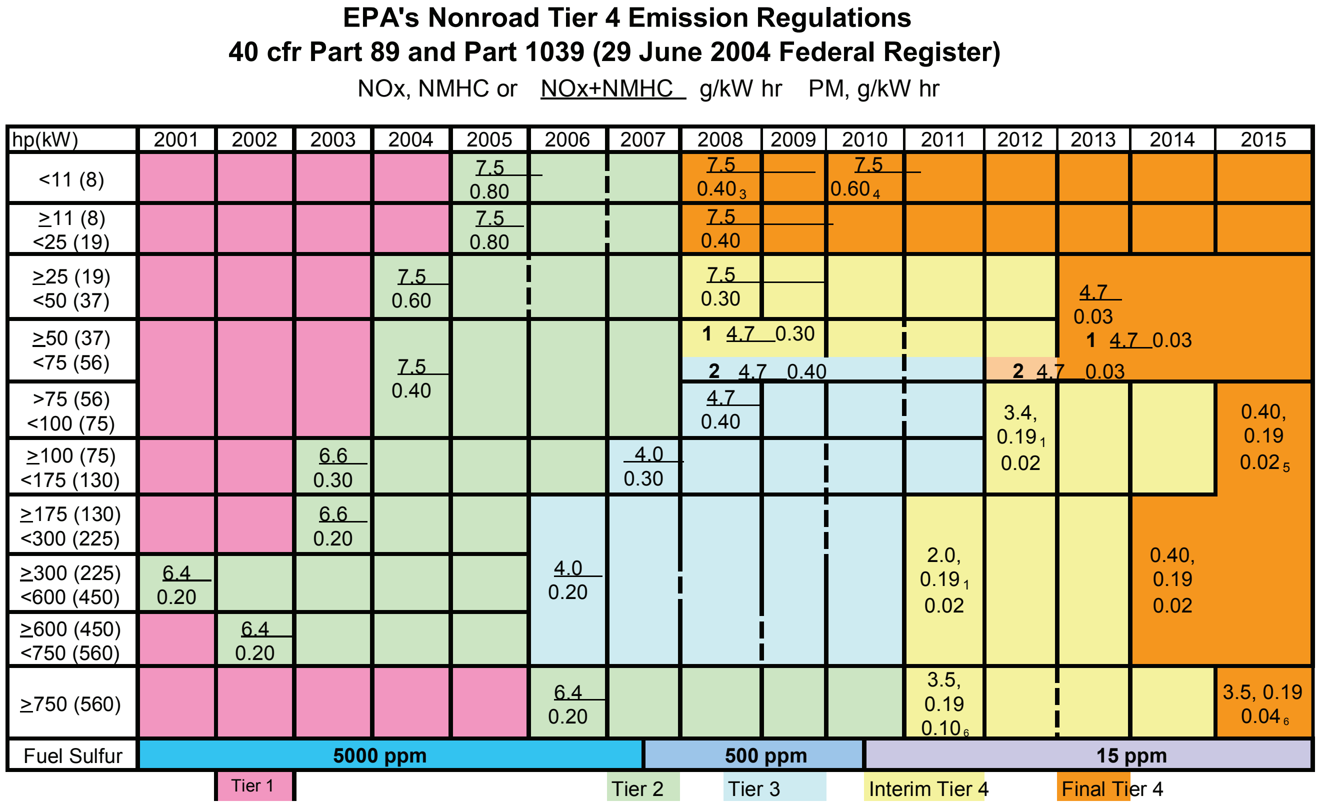
This lecture focuses on emissions reduction for non-road diesel engines, although we refer to on-road diesel engines often. In section 1, we highlight global emissions criteria and test procedures for non-road engines and compare them with on-road requirements. In sections 2 and 3, we describe critical components and system integration technologies as building blocks for meeting emissions criteria. In section 4, we describe engine development through emissions tiers. We provide an outlook for what comes after criteria pollutant reduction in section 5, and we conclude with a summary and perspectives. With this focus on emissions, we will limit our discussion of other product attributes, such as reliability, not because they are not important (in fact, they are critical) but because thorough discussion of those attributes requires lengthy papers on their own.

1. Global Non-Road Emissions Regulations

Non-road diesel engine emissions are defined by power category and by tiers that were implemented over time. Tier 1 requirements were first implemented for engines between 130 kW (175 hp) and 560 kW in 1996, with NOx limit of 9.2 g kWh^{-1} and particulate matter (PM) limit of 0.54 g kWh^{-1}. Tier 1 requirements for other power ranges were implemented between 1997 and 2000, with appropriate limits at different power levels. Figure 1 shows a summary of criteria emissions requirements since Tier 1 by power category and by tiers over the time frame from 2001 through 2015 by the U.S. EPA. Over this period, NOx is reduced from 9.2 to 0.4 g kWh^{-1} and particulate matter is reduced from 0.54 to 0.02 g kWh^{-1} for most power categories. In addition to NOx and PM, hydrocarbon (HC), particularly non-methane hydrocarbon (NMHC) and carbon monoxide (CO), are also regulated. Figure 2 shows the same information in graphical form for a visual perspective. When Tier 4 implementation is complete by 2015, non-road diesel engines will produce near-zero criteria pollutants.

The tiers of regulations have provisions for averaging, banking, and trading emission credits in the U.S., commonly referred to as ABT credits, which can result in complex strategies unique to each manufacturer.

In addition to the 8-mode test of previous tiers, the Tier 4 standard has two added requirements: one is the not-to-exceed (NTE) zone, and the other is the non-road transient test cycle NRTC). The NTE zone is defined by the torque curve, the 100% engine speed, the 15% speed, the 30% power line, and the 30% torque line. Figure 3 shows an example NTE zone. Within the NTE zone, the peak exhaust emissions cannot exceed the cycle emissions times a multiplier, which is 1.5 if the exhaust NOx emission is below 2.5 g kWh^{-1} and 1.25 if the exhaust NOx is above 2.5 g kWh^{-1} over the NRTC.



EPA's Nonroad Tier 4 Emission Regulations
40 cfr Part 89 and Part 1039 (29 June 2004 Federal Register)
NOx, NMHC or NOx+NMHC g/kW hr PM, g/kW hr

hp(kW)	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
<11 (8)					7.5 0.80			7.5 0.40[3]		7.5 0.60[4]					
≥11 (8) <25 (19)					7.5 0.80			7.5 0.40							
≥25 (19) <50 (37)				7.5 0.60				7.5 0.30					4.7 0.03		
≥50 (37) <75 (56)				7.5 0.40				1 4.7 0.30 2 4.7 0.40				2 4.7 0.03	1 4.7 0.03		
>75 (56) <100 (75)								4.7 0.40				3.4, 0.19[1] 0.02			0.40, 0.19 0.02[5]
≥100 (75) <175 (130)			6.6 0.30				4.0 0.30								
≥175 (130) <300 (225)			6.6 0.20			4.0 0.20					2.0, 0.19[1] 0.02			0.40, 0.19 0.02	
≥300 (225) <600 (450)	6.4 0.20														
≥600 (450) <750 (560)		6.4 0.20													
≥750 (560)						6.4 0.20					3.5, 0.19 0.10[6]				3.5, 0.19 0.04[6]
Fuel Sulfur	**5000 ppm**						**500 ppm**			**15 ppm**					

1. Phase-out of Tier 3 NOx+NMHC engines and phase-in of NOx A/T engines. All engines must meet 0.02 Pm.
2. The dashed lines separating the years show when the 7 year life of the Tier 2/3 equipment flexibility program ends.
3. Air-cooled, direct injection, hand start applications are exempt from these standards.
4. Applies to only air-cooled, direct injection, hand start applications. Credit generation is prohibited.
5. 1/1/2014 is compliance date for using and 12/30/2014 is 'optional' effective date for not using Tier 2 ABT credits.
6. Different standards apply to gen set engines: 0.67 NOx for >900 kW in 2011, 0.67 NOx and 0.03 PM for > 560 kW in 2015.

Figure 1. U.S. EPA emissions requirement for non-road diesel engines by power category, assuming no Tier 2 credit is claimed by the engine manufacturer.

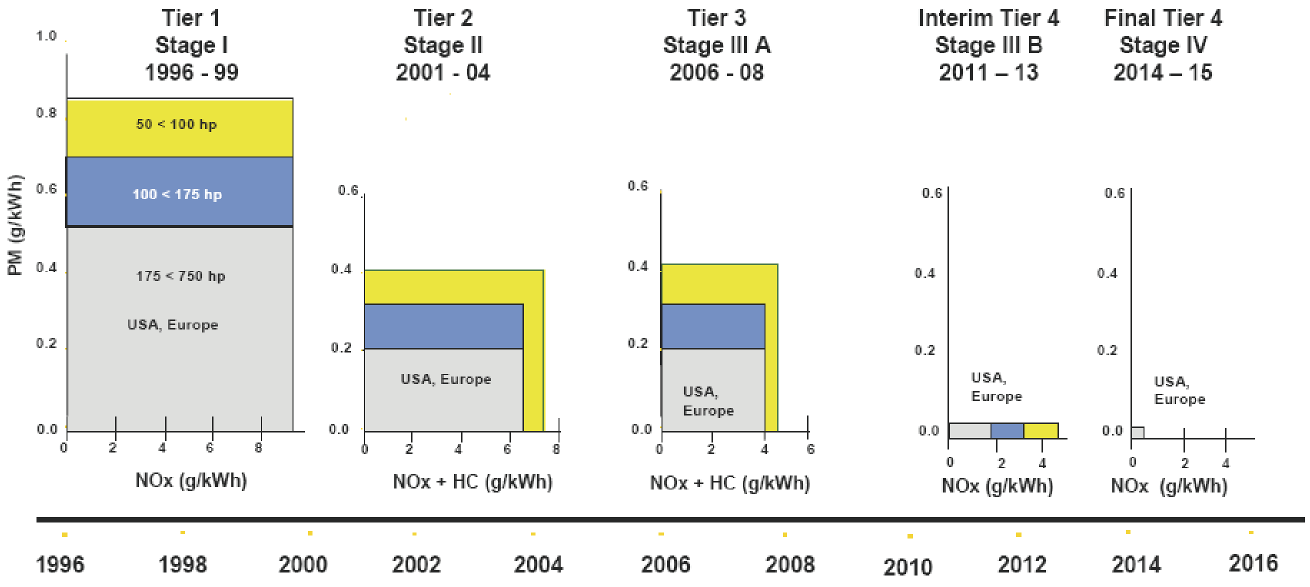


Figure 2. Non-road emissions requirements for diesel engines by tiers.

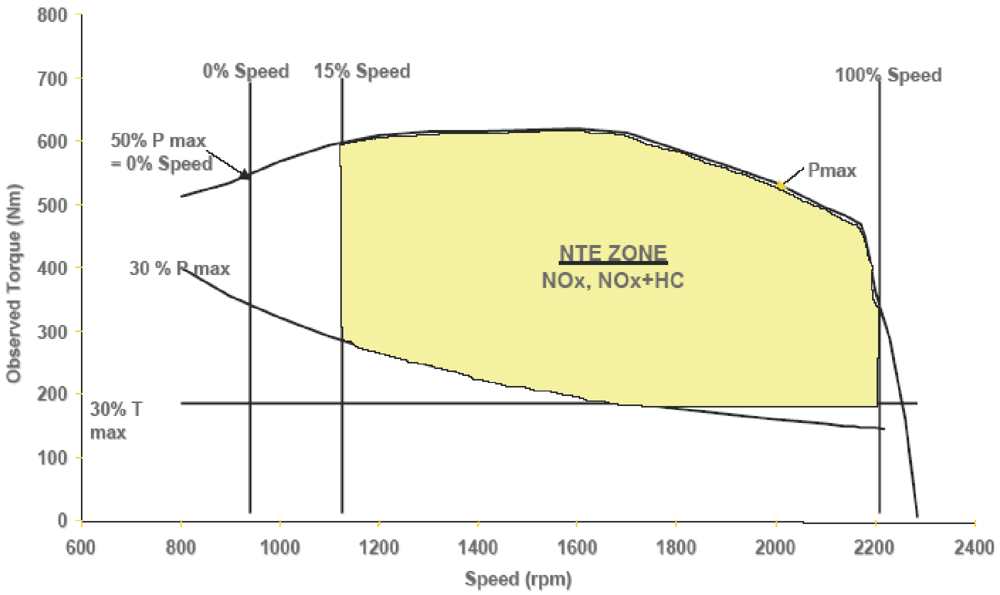


Figure 3. Not-to-exceed (NTE) area definition.

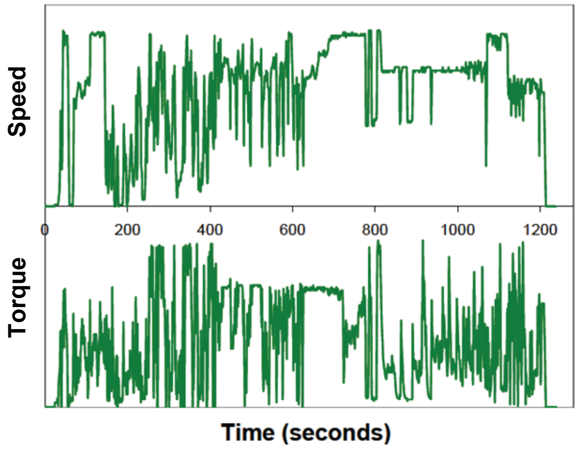


Figure 4. Tier 4 non-road transient test cycle per U.S. Code of Federal Regulations, Title 40.

The non-road transient test cycle (NRTC) is defined by a time sequence of engine speed and torque, as shown in figure 4. The engine must be run in accordance with this time sequence for certification testing. The NRTC must be executed twice: the first run is when engine is at 19.5°C (67°F), which is referred to as the cold cycle, and the second run is 20 minutes after the completion of the cold cycle. This second run is referred to as the hot cycle. The reported emission is the sum of 5% from the cold cycle and 95% from the hot cycle for the U.S. and 10% and 90% for Europe.

The change from steady-state 8-mode testing to non-road transient testing is quite significant in itself. A fully functional transient test cell that meets EPA certification requirement costs multiple million U.S. dollars to build, requires several months if not longer to commission, and needs skilled staff to operate and maintain. Details of test procedure and facility guidelines are available in the U.S. Code of Federal Regulations (CFR, 2005).

Figure 5 shows the NRTC points overlaid on an engine torque-speed map in comparison with the 8-mode test of the previous tiers. When viewed on the torque-speed map, several clusters of test points can be seen. These clusters represent typical operating duty cycles of non-road machine types, such as row crop tractors, combines, loaders, excavators, backhoes, and crawlers. Therefore, NRTC can be viewed as the sum of non-road machine operating profiles. Note that the 8-mode test is still required, and not replaced by NRTC, for Tier 4 engine emissions certification.

The emission standards discussed above must be met over the entire useful life of the engine. The U.S. EPA requires application of deterioration factors (DFs) to all engines under regulation. The DF is a factor applied to the emission certification test data to represent emissions at the end of the useful life of the engine. The engine useful life and the in-use testing period, as defined by the EPA for emission testing purposes, are listed in table 1 for different engine categories. These requirements remain the same for Tier 4 engines.

Criteria emissions reductions are accompanied by fuel sulfur reduction. There are two motivating factors to require sulfur reduction in parallel with criteria emissions reduction. One is that sulfur becomes sulfate coming out of the engine exhaust and is counted as particulate emission. The second is that removal of sulfur enables some emissions reduction technologies to be adopted. These technologies include exhaust gas recirculation, NOx sensors, and aftertreatment systems. For Tiers 1 through 3, the sulfur content in non-road diesel fuels was not limited by environmental regulations. The oil industry specification was 0.5% (wt., max), with an average in-use sulfur level of about 0.3% or 3,000 ppm. To enable sulfur-sensitive control technologies in Tier 4 engines, the EPA requires that sulfur content in non-road diesel fuels be 500 ppm effective June 2007 for non-road, and 15 ppm (ultra-low sulfur diesel) effective June 2010 for non-road mobile equipment and June 2012 for locomotive and marine fuels.

Engine emissions regulations started in the U.S., and many nations now regulate engine emissions. For the non-road equipment sector, the EU refers to non-road emission regulation by stages and is largely harmonized with the U.S. emission tiers, including NRTC. The exception is the NTE, which is yet to be fully defined at this time. Brazil is discussing Tier 3. Russia has adopted ECE stage I. India adopted Bharat Stage II (Tier 1) in 2005 and will implement Bharat Stage IIIA (Tier 3) between 2010 and 2011. China implemented Stage I (Tier 1) in 2007, with Stage II (Tier 2) in 2010 and Stage III in draft mode for 2013. For a single-source overview of worldwide diesel emissions requirements including non-road engines, refer to www.dieselnet.com.

On-road diesel emissions regulation typically leads the non-road regulation by three to four years in the U.S. It is often natural to compare non-road emissions with the on-road requirement, but they are not directly comparable. For example, fuel sulfur levels are different, although they are converging, useful life requirements are defined by operating hours for non-road and by driving distance for highway vehicles, and most notably, the test cycles are different. Table 2 summarizes key differences in representative test cycles. NRTC has substantially higher cycle engine speed and torque than both the Federal Transient Procedure (FTP) and the European Transient Cycle (ETC). These differences result in differences in engine combustion signature, exhaust gas temperature, and flow. Engine components such as turbochargers and aftertreatment devices behave differently. Electronic engine controls must adapt to these differences and behaviors. Therefore, any attempt to compare non-road and on-road diesel engine emissions can only be an approximation.

With these qualifications, figure 6 gives comparison between non-road and on-road diesel emissions requirements. In this comparison, non-road interim Tier 4 is between EPA 2007 and the European on-highway requirement of Euro 5, and non-road final Tier 4 is similar to EPA 2010 and the European on-highway requirement of Euro 6. As will be discussed later, engine technology choices are similar between non-road interim Tier 4 and EPA 2007 or Euro 5, and between non-road final Tier 4 and EPA 2010 or Euro 6.

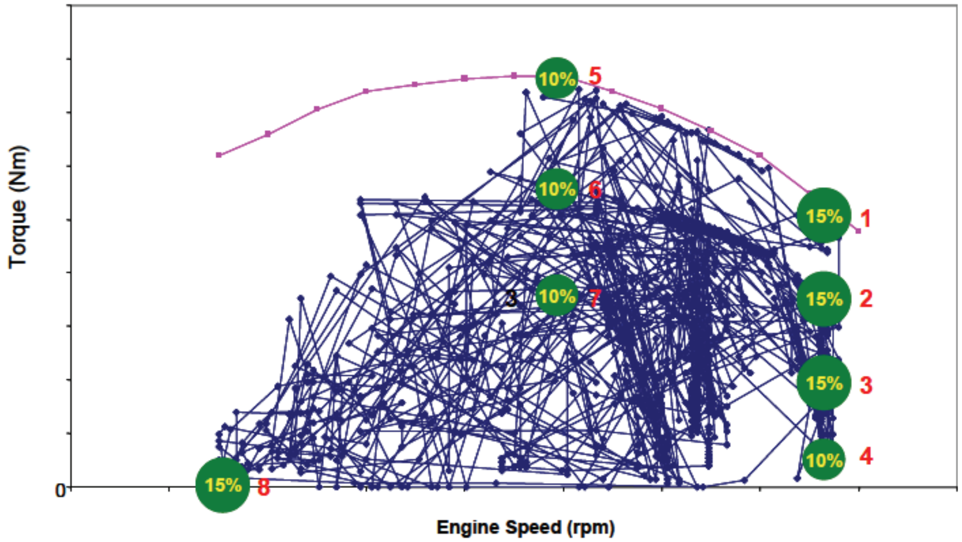


Figure 5. Non-road transient test cycle (NRTC) comparison with 8-mode test.

Table 1. Engine useful life requirements.

Power Rating	Rated Engine Speed	Useful Life		In-Use Testing Period	
		Hours	Years	Hours	Years
< 19 kW	All	3000	5	2250	4
19-37 kW	Constant speed ≥ 3000 rpm	3000	5	2250	4
	All others	5000	7	3750	5
> 37 kW	All	8000	10	6000	7

Figure 7 provides a conceptual framework towards technology and product planning. In this chart, the bottom third is the foundation of engine technology. The critical components consist of fuel injection system, air systems, aftertreatment, and sensors and actuators. Critical components serve as essential elements for the combustion system, exhaust system, and controls and diagnostics, which together with the basic engine architecture and thermal management form the basic building blocks for advanced, low-emission engines.

Table 2. Comparison of representative test cycles worldwide.

	Non-Road Transient Cycle (NRTC)	Heavy-Duty Federal Transient Procedure (FTP, U.S. on-road)	European Transient Cycle (ETC, European on-road)
Average torque	39.3%	24%	36.7%
Average speed	67.7%	41.5%	50.9%
Test repeat	2	3	One test only
Cold cycle weighting	5% U.S., 10% Europe	1/6	None

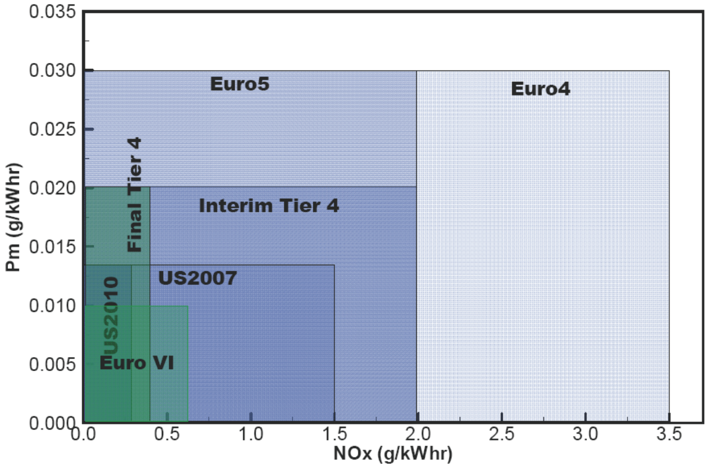


Figure 6. Comparison of on-road and non-road emissions requirements.

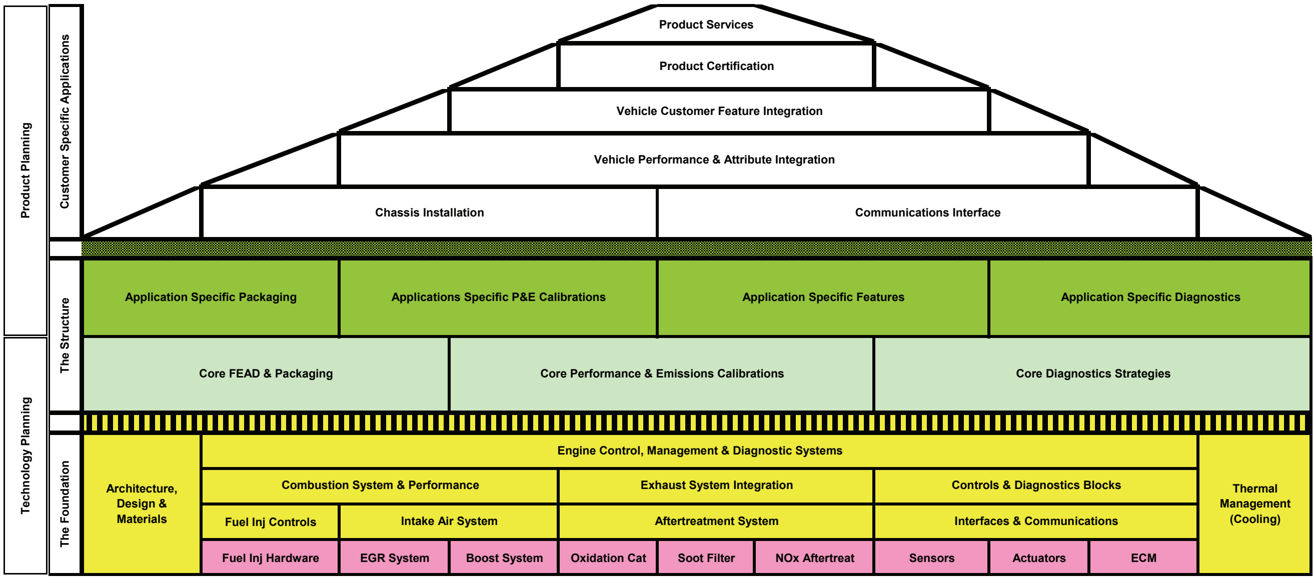


Figure 7. Conceptual framework that establishes building blocks of advanced engines.

2. Building Blocks of Diesel Engines

Fuel Injection System

The fuel injection system is the heart of the engine. It must consistently deliver precise quantities of fuel at high pressure to the combustion chamber. The flow rate is similar to that of a garden hose, but this flow passes through holes the size of a human hair for a period on the order of a millisecond. Premium diesel engines previously had, and many still have, unit injectors, which are individual piston pumps combined with a nozzle (fig. 8). These can be mechanically driven by a camshaft, either directly or through rocker arms and pushrods, or they can be hydraulically driven. Less expensive engines tended to have pump-line-nozzle injection systems in which one pumping element for each cylinder was contained in a block and actuated by a camshaft gear driven from the engine's crankshaft, with individual lines from each pumping element to each injection nozzle. Unit pumps were also used in which the individual pumping elements were on the engine's camshaft, thereby avoiding a separate box with a camshaft, with fuel lines connecting each pumping element to an injection nozzle. The least expensive diesel engines used rotary injection pumps. This system shared the pumping elements, and a distributor head connected each injection line to the pumping elements at the appropriate time.

Figure 8. Electronic unit injector (top) and common-rail injection system (bottom).

Modern off-highway diesel engines have electronic injection systems, including electronically controlled rotary pumps and electronic unit injectors (fig. 8) and unit pumps. The injection system that is gaining the most popularity is the common-rail injection system (fig. 8). In this system, a high-pressure fuel pump is driven from the engine's crankshaft in a controlled manner to maintain the desired fuel pressure in a pressure vessel, which is called a "rail." The electronically controlled injection nozzles are connected to this rail with high-pressure lines and inject fuel on command. This provides great flexibility, since the rail pressure can be controlled to the desired value and multiple injections can be commanded to occur at desired times. As electronic common-rail injection systems have been developed, the rail pressure and number of injections have been increased and the minimum separation between injections has been decreased. Consequently, new diesel engines are now typically designed with common-rail injection systems. Rail pressures greater than 200 MPa are now available, and 300 MPa is being pursued by fuel injection equipment manufacturers.

Turbocharging

In addition to providing fuel to the combustion chamber, it is important to provide the necessary air for combustion. Increased air flow is provided by a turbocharger, which consists of a turbine wheel in the exhaust stream that drives a compressor wheel in the intake air stream. The compressor pressurizes the air, allowing the engine to induct more air and thereby burn more fuel and make more power. Consequently, turbocharging is almost a requirement for modern low-emission engines, and cooling of the air compressed by the turbocharger is common. With turbocharging, a turbine wastegate (a valve that opens to allow exhaust to bypass the turbine wheel) can be used to limit the boost at high speeds. An increasingly popular alternative is to use a variable-geometry turbocharger (VGT) to control the boost across the operating range. There are two common types of VGT: the swing vane (fig. 9) and the sliding vane. The moving mechanical parts change the velocity and direction of the flow entering the turbine wheel in order to change the work extracted from the exhaust.

Figure 10 shows a double layer passage VGT. There are two passages in the turbine housing. Exhaust gas enters the turbine through the inner passage at low engine speed and load, as shown by the red arrow, and through both inner and outer passages at high engine speed and load, as shown by the red and blue arrows. The opening of the outer passage is controlled by a simple actuator, typical of a wastegate actuator.

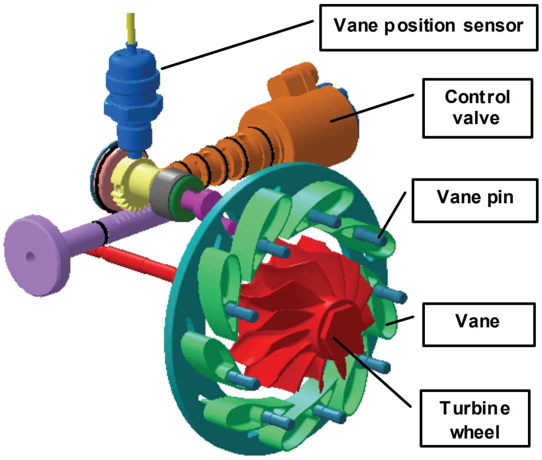


Figure 9. Swing vane type variable geometry turbocharger (courtesy of Honeywell).

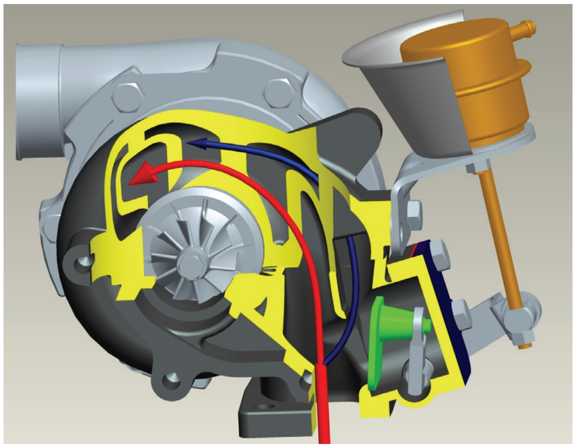


Figure 10. Double layer passage VGT (courtesy of Kangyue Turbocharger, Ltd).

Turbocharging increases air flow and allows more fuel flow to increase engine power density. In addition, fuel efficiency is improved because the engine can be smaller and have less friction and because the power needed to compress the cool inlet air is obtained by the expanding hot exhaust, which is an efficient process. The extra air provided by turbocharging reduces smoke emissions and allows diluent, i.e., EGR (discussed below), to be added to the cylinder while maintaining adequate air in the cylinder. Despite all the benefits of turbocharging, there can be a concern that the air is provided as quickly as needed during transients to avoid compromise in transient torque response. Careful system design must be conducted with the aid of computer simulation.

In recent years, staged turbocharging, using both a low-pressure and a high-pressure turbocharger, is being used to increase engine output and altitude capability. Future concepts are power augmentation of the turbocharger using electrical, mechanical, or hydraulic connections to the turbocharger shaft. Supercharging using a belt- or gear-driven blower remains a remote possibility because of the high power required by the supercharger.

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) has become an important addition to low-emission diesel engines. This concept involves taking a portion of the exhaust gas and using it as part of the fresh intake air in order to provide inert mass in the cylinder to reduce peak flame temperatures and thereby reduce NOx emissions. There are many ways of adding EGR. The simplest is internal EGR whereby some of the exhaust is retained in the cylinder or leaked into the fresh air charge while it is being inducted. However, internal EGR is not cooled and therefore the NOx reduction is relatively small. External EGR allows the recirculated exhaust gas to be cooled as it flows through a pipe, or more aggressively by a heat exchanger using engine coolant or cooling air. Cooled EGR is much more effective at reducing NOx, and larger amounts of EGR can be used without displacing as much air. Therefore, cooled EGR has become a popular method of NOx control. Figure 11 shows an example of EGR cooler and an EGR control valve.

On a turbocharged engine, the EGR can flow from the turbine inlet to the intake manifold, which is commonly referred to as high-pressure EGR or short-route EGR (fig. 12). Alternatively, the EGR can flow from the turbine outlet to the compressor inlet, which is called low-pressure EGR or long-route EGR. Both systems require enough pressure difference to drive the EGR through the piping and the EGR cooler. However, in a low-pressure system, the EGR needs to be cleaned of particulate matter to avoid fouling the compressor and charge air cooler. Therefore, high-pressure EGR is currently far more common.

Figure 11. EGR cooler (left) and EGR control valve (right).

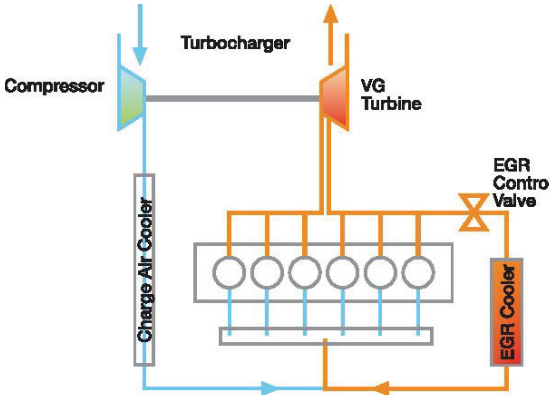


Figure 12. Schematic of high-pressure, cooled EGR system (source: Cummins brochure).

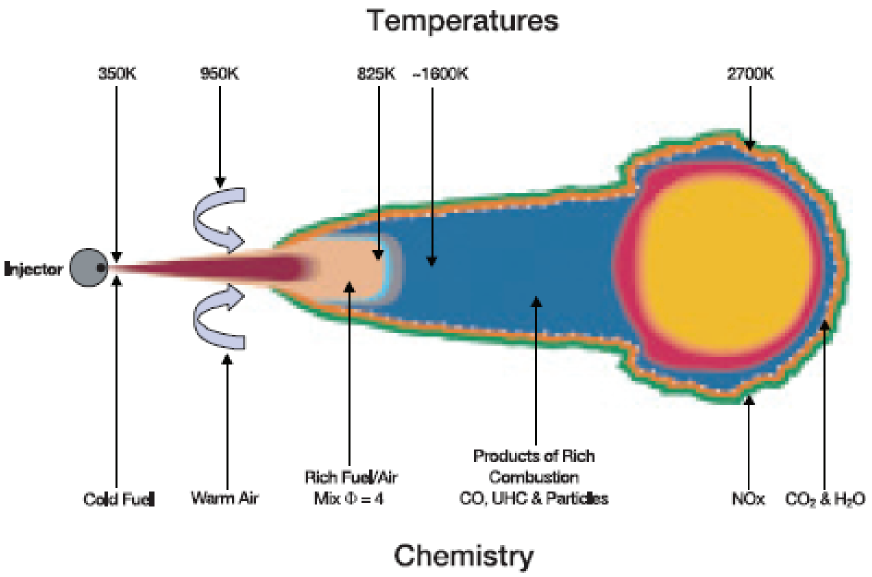


Figure 13. Characteristics of diesel combustion (source: John Dec).

Careful design of the EGR system is necessary to properly cool, measure, and control the EGR over the life of the engine. This can be a challenge because the EGR gas contains particulate matter, which can be sticky, so the components must accommodate some accumulation of material without malfunction. The design must also recognize that water condensation can occur in the EGR system and that this water will be corrosive because of dissolved sulfuric and nitric acids. Of course, condensed water will freeze at low ambient temperatures.

Combustion System

The combustion system must rapidly and completely burn the small quantity of fuel injected into the hot air and EGR. At the same time, the combustion system must avoid formation of excessive particulate emissions (formed from poorly mixed rich regions) and avoid formation of excessive amounts of NOx emissions (formed from high-temperature reaction of nitrogen and oxygen). The characteristics of the diesel combustion process are shown in figure 13, which was a result of collaborative study by the diesel engine industry and Sandia National Laboratory during the 1990s. The conflicting requirements of rapid combustion and low NOx and PM emissions are a difficult challenge for diesel combustion systems, and there have been many different approaches to meet this challenge.

When injection pressures were lower, high-swirl combustion systems were popular, but the increased mixing energy of higher injection pressures has allowed lower-swirl systems with greater fuel economy. As emission standards have become more stringent, EGR has been added to off-road engines and in many cases swirl has been increased to further improve mixing, although injection pressures have continued to increase.

With the advent of injection systems that can inject multiple times in a cycle, a number of new combustion modes have become available. Partially premixed compression ignition (PCI) is the term used for an early pilot injection that ignites near the time that the main injection starts. It is used to reduce NOx emissions by allowing late main injection. Close pilot injections are sometimes used to reduce noise and hydrocarbon emissions, and post injections can be added to reduce particulate emissions. At various engine speeds and loads, the effects of these additional injections change, so they are not necessarily always used, but it is possible in some cases to have four or more injections for a single combustion process.

A new combustion concept is homogeneous charge compression ignition (HCCI), which involves mixing the fuel and air outside of the cylinder, or early in the cycle, to obtain a fairly uniform mixture, often with EGR added. When this mixture is heated by piston compression, it spontaneously combusts and typically produces low emissions. That is the good news; the bad news is that the mixture may ignite too early, too late, or not at all. In addition, the combustion can be violent and noisy. It is also difficult to control the timing of combustion over the engine's operating range and achieve good fuel efficiency. Consequently, it appears that HCCI will be primarily used at light loads for applications such as light-duty vehicles. Attempts to use HCCI combustion at high loads have resulted in unattractive engine systems with high fuel consumption, high noise, high cost, and/or high heat rejection.

HCCI combustion is one form of low-temperature combustion (LTC) in which the peak local temperatures remain low enough to avoid significant formation of NOx by reaction of nitrogen and oxygen. Another method to obtain LTC is to use very large quantities of EGR (or some other diluent, such as water) to avoid high local temperatures. Researchers have observed that combustion with sufficient diluent will also suppress smoke emissions because the temperature necessary to make the precursors to smoke is not reached. While this combustion process sounds ideal, achieving LTC combustion requires cooling and recirculating more than half the engine exhaust flow, and there is a narrow range of acceptable diluent fraction. Too little diluent will result in excessive NOx emissions, while too much diluent will cause excessive carbon monoxide emissions, and engine fuel efficiency tends to be low with LTC.

Another new concept, in which John Deere has been a leader, is the stoichiometric diesel engine. In this concept, a fairly conventional diesel engine is operated at the chemically correct air/fuel ratio at all times in order to allow use of a three-way catalyst, as is routinely used with stoichiometric gasoline engines. A particulate filter is used to remove PM emissions. The primary virtues of this engine concept are its low emissions at relatively low cost, although fuel consumption may be comparable to that of conventional gasoline engines. Therefore, it is thought that stoichiometric diesel engines may be used in applications where diesel fuel is required for safety or convenience and where fuel consumption is less important.

As diesel engines have developed over the years, there have been some clearly discernible design trends, although the recent emphasis on very low emission levels has affected some of these trends. One clear trend has been increased power output and increased cylinder pressure. Technology in materials and design has allowed these increases. Especially notable has been the change from aluminum to steel pistons on larger engines. Another important change has been increased boost from turbochargers and staged turbocharging to provide more air and thereby allow power density to increase. As a consequence of this technology, diesel engines have been becoming lighter and smaller for the same power output.

Another important development has been the increased use of computers for simulation of engine air systems and cycles, computational fluid dynamics of flows and combustion, computer-aided design, and finite element analysis of structures. These tools have greatly aided engine development and are now critical in the design of new engines and an integral part of any significant design change.

Electronic control of diesel engines is now common, since it is necessary to control injection systems, EGR systems, and air systems. Additional sensors and controls continue to be developed to improve engine operation. At one time, it was sufficient that an engine produced the desired power without making excessive emissions. Now the engine must also work with the aftertreatment system to provide exhaust gas temperatures and constituents that can be accommodated.

3. Aftertreatment Technologies

Particulate Matter and NOx

Before we discuss aftertreatment component technologies, we will first define particulate matter and NOx:

Particulate Matter (PM): PM is formed by diesel engine combustion. PM is composed of carboneous soot particles, soluble organic fraction (SOF), and sulfates. The volatile content is highly dependent on engine combustion conditions. Sulfates are formed by combustion of sulfur present in diesel fuel and lube oil. A representative PM composition and particle size distribution are shown in figure 14.

NOx: Nitrogen oxide (NO) and nitrogen dioxide (NO_2) are formed during high-temperature diesel combustion from reactions of N_2 and O_2. Typically when exhaust gas recirculation (EGR) is increased, peak flame temperature and engine out NOx are reduced. At the same time, engine out PM quantity is increased. This behavior is known as the NOx-PM trade-off.

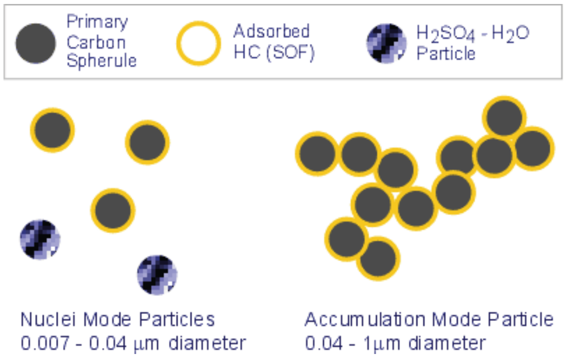


Figure 14. Representative PM composition and particle size distribution.

Exhaust Filtration

Exhaust PM filters are divided into two categories: full-flow filters(or wall-flow filters) in which all exhaust gas flows through the filtration media and filtration efficiencies are above 80%, and partial-flow filters in which only part of the exhaust gas flows through the filtration media and filtration efficiencies are typically less than 50%. If a soot layer is established on a full-flow filter, the filtration efficiency stays above 95% because the soot layer is also a filtration media. Inorganic material formed from combustion of lube oil also accumulates on filters as ash. An ex-

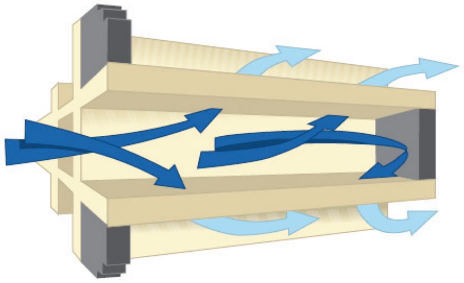


Figure 15. Full-flow filter example: alternatively plugged cordierite diesel particulate filter.

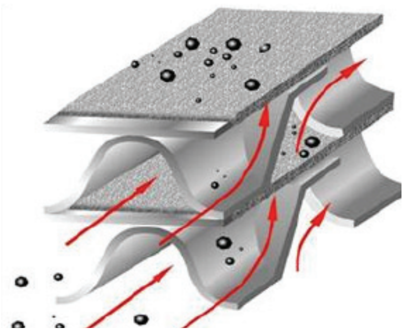


Figure 16. Partial-flow filter example: Emitec's PM-Metalite (Emitec GmbH, Lohmar, Germany).

ample of a full-flow filter is shown in figure 15, and an example of a partial-flow filter (Emitec's PM-Metalite) is shown in figure 16.

Regeneration Types

PM trapped on filters can be oxidized (cleaned) by NO_2 and O_2. This process is called regeneration. Passive regeneration refers to PM oxidation by nitrogen dioxide (NO_2), and active regeneration refers to PM oxidation by O_2, as shown in figure 17. Passive regeneration occurs at normal engine operation above 300°C without any special engine control intervention. Engine out NOx is predominately NO, so most of the NO_2 is formed by the diesel oxidation catalyst. Active regeneration requires inlet gas temperature to be above 550°C. Oxygen levels in diesel exhaust are typically above 5%. Therefore, the O_2-based active soot burn rate is primarily limited by exhaust temperatures.

Passive soot oxidation reaction:

$$C + 2\,NO_2 = CO_2 + 2\,NO$$

Active soot oxidation reaction:

$$C + O_2 = CO_2$$

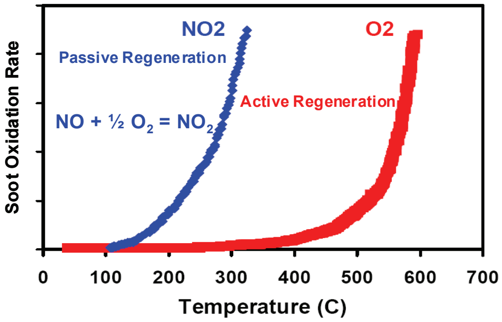


Figure 17. Passive and active DPF regeneration temperature window.

Active Regeneration Technologies

Due to the high PM reduction efficiency (> 85%) required to meet new off-road regulations, full-flow diesel particular filters (DPF) with active regeneration are preferred. Active regeneration requires a means of raising the exhaust temperatures above 550°C. Two primary heating technologies for active regeneration are exhaust diesel fuel burners and diesel oxidation catalysts (DOC). The diesel burner can be integrated either with the engine or with the diesel particulate filter. A major advantage of a burner is its ability to regenerate the DPF at idle even with cold ambient temperatures (table 3). Disadvantages are design, control, and installation complexity due to the combustion air supply, flame stability, and temperature uniformity. Regeneration with a DOC requires a controlled amount of hydrocarbon (HC) to be injected upstream. In order to reduce heat loss, the DOC is preferably integrated with the DPF. Advantages of a DOC system are enhanced passive regeneration and robustness with exhaust flow and O_2 levels (A/F ratio).

Table 3. Trade-offs of burner vs. DOC for active regeneration.

Active Regeneration	Burner	DOC
Fuel supply	Yes	Yes
Fuel injection	Yes	Yes
Ignition	Yes	No
Combustion/injector air supply	Yes	No
Flame management	Yes	No
Engine exhaust temperature management	No	Yes
NO_2 passive regeneration	Worse	Better
Idle and cold ambient regeneration	Better	Worse
Precious group metal usage	No	Yes

PM Aftertreatment System Design Considerations

To meet above 130 kW interim Tier 4 non-road emission standards, John Deere engines will be equipped with a cooled EGR, an advanced combustion system, flexible air and fuel systems, and an electronic engine control unit (ECU). The engine out NOx is reduced with a cooled EGR and combustion optimization to meet the interim T4 regulations. PM is reduced by a DPF. An integrated DOC|DPF with three temperature sensors and a differential pressure sensor, as shown in figure 18, is installed on the engine.

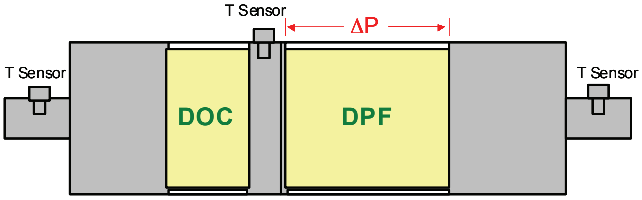


Figure 18. Integrated DOC|DPF with associated sensors.

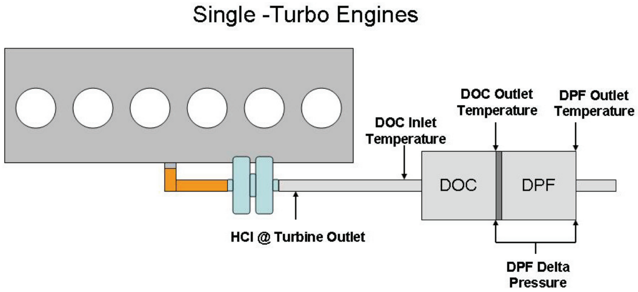


Figure 19. John Deere engine and aftertreatment system schematic (HCI stands for HC injector).

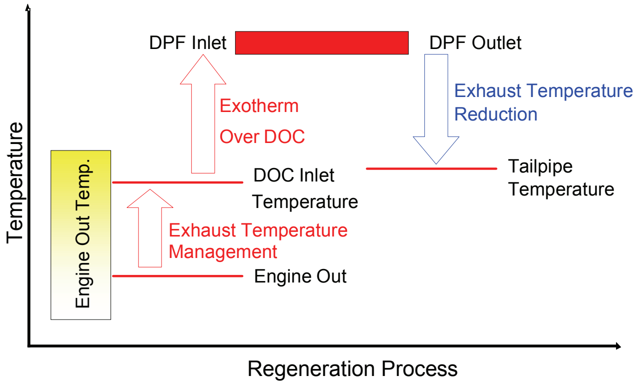


Figure 20. Overall exhaust temperature control schematic.

The engine aftertreatment system with an exhaust HC dosing system is shown in figure 19. The engine is capable of achieving DOC light-off temperatures at low speed and light load by combustion modification for exhaust heating. HC is introduced in front of the DOC and oxidized over the DOC to raise exhaust temperature above 550°C. The hot exhaust leaving the DPF is diluted with ambient air by an exhaust diffuser, so the exit gas temperature is reduced to acceptable levels. The overall exhaust gas temperature control schematic is shown in figure 20.

Critical PM Aftertreatment Components

Diesel Oxidation Catalyst (DOC)

The primary function of the DOC is to oxidize HC delivered by the hydrocarbon injector (HCI) to raise the exhaust temperature during DPF regeneration. DOC substrates are typically flow-through monoliths, as shown in figure 21, made from cordierite material. Cordierite has a very low coefficient of thermal expansion (CTE of 6×10^{-7} °C^{-1}) and great thermal stability (>1200°C). A catalytic coating (washcoat) containing precious metals such as platinum (Pt) and palladium (Pd) is deposited on the substrate internal walls to maximize exhaust gas contact. HC is injected upstream of the DOC and is oxidized into CO_2 and water by the DOC. The fuel energy released heats the DOC and raises the exhaust gas temperature. The DOC requires a minimal exhaust temperature to light-off and be active, as shown in figure 22. Above the DOC light-off temperature, the DOC stays hot and HC is oxidized at greater than 90% efficiencies, which ensures very little HC slippage. High efficiency and robustness with varying O_2 levels and flow rates enable precise DOC outlet temperature control.

Under normal operating conditions, the DOC cleans up CO, HC, and SOF of PM emitted from the engine. The DOC also oxidizes NO to NO_2 to promote passive soot oxidation. Optimal NO_2 conversion efficiency occurs around 300°C, as shown in figure 22, where the kinetic reaction rate is fast and NO_2 yield is not limited by thermodynamics.

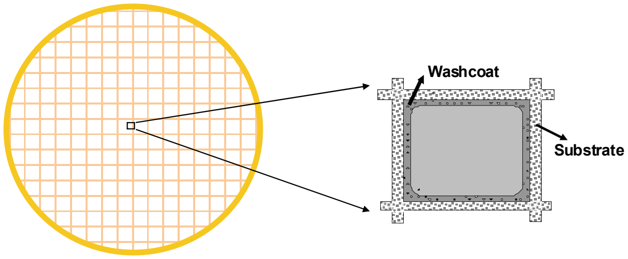


Figure 21. DOC with catalytic coating deposited on a monolithic cordierite substrate.

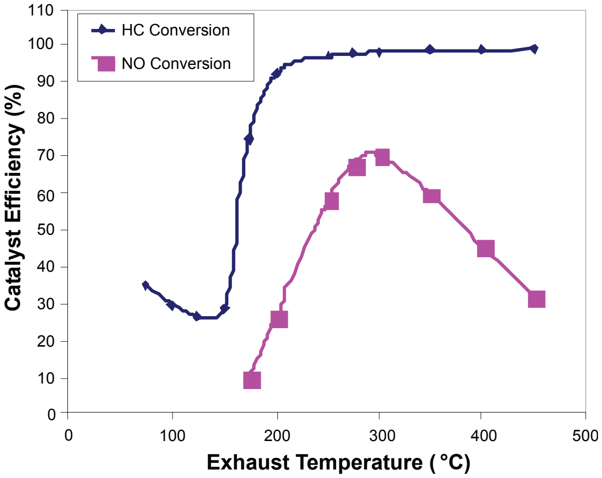


Figure 22. Typical DOC HC conversion light off curve and NO to NO_2 conversion efficiencies.

Diesel Particulate Filter

The primary purpose of a DPF is to trap particulate matters (PM). The two most popular material choices are silicon carbide (SiC) and cordierite, as shown in figure 23. Key DPF material properties are summarized in table 4. SiC filters allow a higher soot loading limit of ~5 g L^{-1} than the 3 g L^{-1} for cordierite filters. However, due to high thermal expansion, SiC filters must be segmented and assembled with cement boundaries, while this design provision is not required for cordierite DPF. Both cordierite and SiC filters can be further catalyzed to enhance passive regeneration and reduce HC and CO emission during active soot burn.

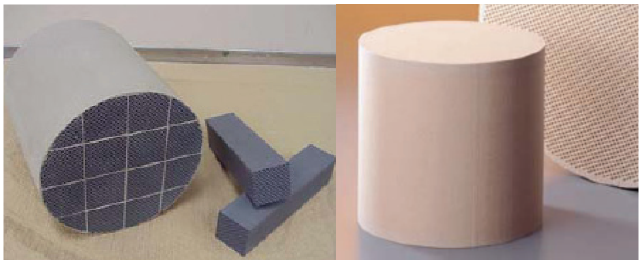


Figure 23. Segmented SiC DPF (left) and cordierite DPF (right).

Table 4. Key material properties of different diesel particulate filters.

Porous Material	Melting Temperature (°C)	CTE ($\times 10^{-7}$ °C^{-1})	Intrinsic Density	Specific Heat at 500°C (J g^{-1} °C^{-1})	Thermal Conductivity at 500°C (W mK^{-1})
Cordierite	1460	6	2.51	1.11	1
Aluminum titantate ($TiAl_2O_5$)	1600	10	3.4	1.06	1
Alpha-SiC	2400	45	3.23	1.12	20
Si-bonded alpha-SiC	1400	43	3.19	1.12	10

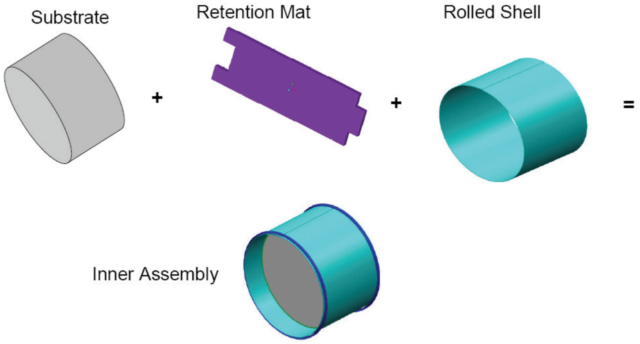


Figure 24. DOC and DPF canning.

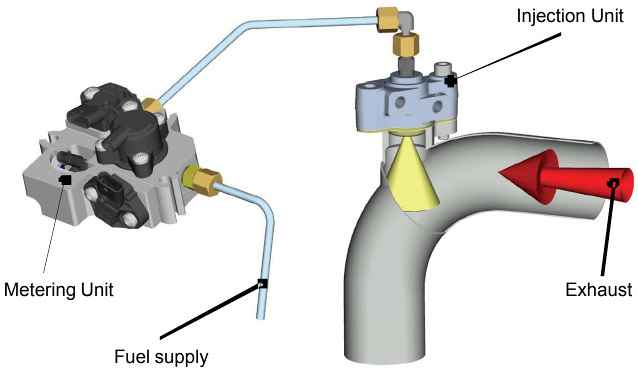


Figure 25. Exhaust fuel metering and dosing system for DPF active regenerations (courtesy of Bosch).

Catalyst Canning

The ceramic DOC and DPF are canned into an integrated converter, as shown in figure 18, and packaged onto a vehicle with connecting pipes, brackets, isolators, flex elements, etc. An integrated DOC|DPF converter is preferred over separated DOC and DPF elements due to its better space utilization and reduced heat loss. In a typical design, the DOC or DPF is wrapped with a ceramic mat and secured into a stainless steel casing under pressure, as shown in figure 24. Friction force immobilizes the DOC and DPF. In general, the retention force through friction must exceed the combined *g* force from vibrations and the pushing force from the exhaust gas. The ceramic mat further serves as an exhaust gas seal and thermal insulation, so the converter skin temperature and heat loss remain low during regenerations. The inlet cone geometry is critical to guarantee uniform exhaust flow entering the DOC and DPF. Additional design provisions include sensor installation and flanges and clamps so that the DPF can be removed for ash cleaning.

Exhaust Fuel Dosing System

Fuel required for DPF active regeneration can either be introduced by a late post injection during the power stroke or by an exhaust fuel doser. If fuel is introduced by an engine late post injection, then the HC is fully evaporated and is well mixed with exhaust gas. The DOC|DPF can therefore be close-coupled with the turbocharger to further reduce heat loss. Since fuel is injected late in the combustion cycle, frequent post injections increase the oil dilution with fuel, which can lead to shorter oil change intervals. An example of a fuel dosing system is shown in figure 25. Sufficient mixing distance is required to ensure fuel evaporation and uniform HC distribution before the exhaust gas enters the DOC.

Aftertreatment System Integration and Controls

Active DPF regenerations require sophisticated controls to manage exhaust temperature and the soot burn rate. The soot oxidation reaction with oxygen is highly exothermic. Heat released from soot combustion will increase the DPF temperature and further accelerate the reaction rate and increase thermal stress (Boger et al., 2008).

To prevent device-damaging runaway regenerations, the soot loading on the DPF must be limited. These “safe” soot levels are highly dependant on DPF material, geometry, exhaust flow rate, DPF temperatures, etc. Key DPF control features such as DOC outlet temperature control, soot loading prediction, and active regeneration control are discussed in more detail below.

DOC Outlet Temperature Control

A controlled amount of fuel is introduced to achieve a desired DOC outlet temperature based on the DOC inlet temperature and desired DPF regeneration temperature. Fuel energy is released to heat exhaust gas and DOC before entering the DPF, which follows the energy balance equation shown in equation 1. Uniform HC distribution ensures a uniform DOC outlet and DPF inlet temperature radial distribution. Computational fluid dynamics (CFD) simulation is commonly used to study the fuel evaporation rate

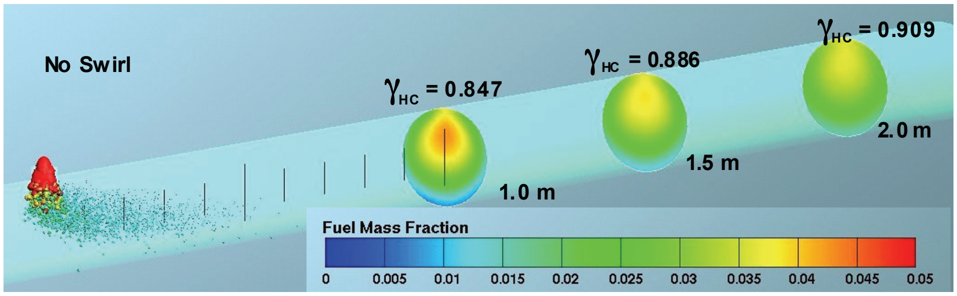


Figure 26. CFD analysis of diesel fuel evaporation and HC distribution uniformity.

and HC uniformity. One such example at 330°C exhaust gas temperature for a straight pipe is shown in figure 26.

$$d(\Delta T)/dt = (M_{fuel} * LHV * DOC_{eff} - M_{fuel} * Cp_{exhaust} * \Delta T - M_{exhaust} * Cp_{exhaust} * \Delta T - \Delta H_{loss}) \div (M_{DOC} * Cp_{DOC}) \quad (1)$$

where ΔT is the temperature rise, M_{fuel} is the amount of fuel injected, LHV is the fuel low heating value, DOC_{eff} is the DOC energy conversion efficiency, $Cp_{exhaust}$ is the specific heat capacity of the exhaust gas, ΔH_{loss} is the heat loss to ambient, M_{DOC} is the diesel oxidation catalyst mass, and Cp_{DOC} is the specific heat capacity of the diesel oxidation catalyst.

Soot Loading Prediction

As soot accumulates, the pressure drop (ΔP) across the DPF will increase. Soot prediction models typically use a flow-adjusted pressure drop as the primary signal to estimate soot loading. Redundant soot prediction models based on soot mass and operational hours are typically used to complement the ΔP model. As an example, at a steady-state engine operation condition, ΔP increases linearly with DPF soot loading after a soot layer is established on the filter, as shown in figure 27. The ΔP over a DPF has three components, as shown in equation 2, and a detailed physical model has been well described by Konstandopoulos et al. (2002) (Boger et al., 2002):

$$\Delta P = \Delta P_{filter} + \Delta P_{Forchiemer} + \Delta P_{expansion/contraction} \quad (2)$$

where ΔP_{filter} is the pressure drop of the filter wall/soot layer, $\Delta P_{Forchiemer}$ is the pressure drop from the Forchiemer effect, and $\Delta P_{expansion/contraction}$ is the pressure drop due to exhaust contraction and expansion as exhaust gas enters and exits the DPF.

As ash accumulates on the DPF, the ΔP model needs to be corrected for the ash contribution.

The soot mass model integrates engine out soot and subtracts the soot oxidized by passive regeneration to estimate the soot loading on the DPF, as shown in equation 3:

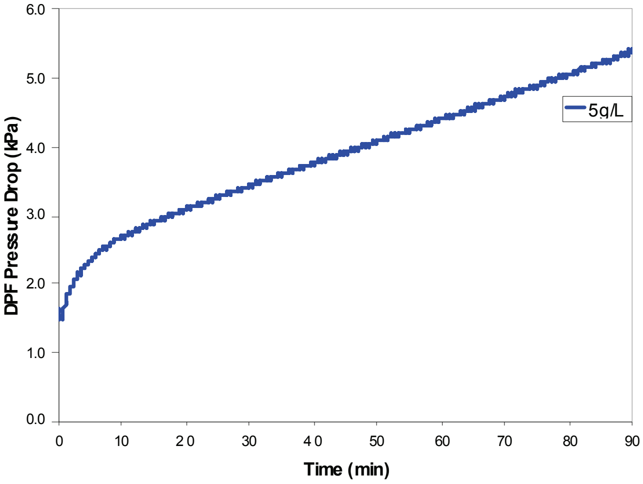


Figure 27. Steady-state soot loading vs. measured differential filter pressure drop.

Soot mass on DPF =

$$\int EO_{soot}(t) * \eta_{DPF\_trapping} * dt - \int Passive\_oxidation\_rate(t) * dt \quad (3)$$

where $EO_{soot}(t)$ is the engine out soot rate (g h^{-1}), $\eta_{DPF\_trapping}$ is the DEF soot trapping rate (%), and $Passive\_oxidation\_rate(t)$ is the soot passive oxidation rate (g h^{-1}).

Active Regeneration Control

The soot burn rate is a function of exhaust temperature, O_2 level, exhaust flow rate, soot loading, and other parameters. The energy balance equation is:

$$d(\Delta T)/dt = (\Delta H_{C+O2} + M_{exhaust} * Cp_{exhaust} * \Delta T - \Delta H_{loss}) \div (M_{DPF} * Cp_{DPF}) \quad (4)$$

where ΔH_{C+O2} is the heat release from soot burn, $M_{exhaust}$ is the exhaust mass flow, $Cp_{exhaust}$ is the exhaust gas specific heat capacity, ΔT is the exhaust temperature rise over DPF, ΔH_{loss} is the heat loss to ambient, M_{DPF} is the DPF mass, and Cp_{DPF} is the DPF specific heat capacity.

In most cases, heat loss to ambient is relatively small compared to the total energy introduced by fuel injection. An example of heat loss (combined from converter and pipe) at different exhaust inlet exhaust gas temperatures based on a free convection model is shown in figure 28. Heat loss to ambient increases with DOC inlet temperature and exhaust flow rate:

$$\Delta H_{loss} = \Delta H_{conduction} + \Delta H_{radiation} + \Delta H_{convection} \tag{5}$$

Ceramic DPFs are susceptible to thermal shock. A soot-loaded DPF has a high propensity to cracking if the engine suddenly transitions to idle operation after initiation of DPF regeneration. The soot burn will continue along the DPF flow axis with insufficient exhaust flow to dissipate the heat. During drop to idle, the soot burn becomes highly non-uniform, local high temperature is created toward the end of the DPF, and the large temperature gradient induces thermal stress. A thermocouple-instrumented DPF is commonly used to measure temperature gradient and soot limit during dropt to idle. The DPF temperature distribution (as in fig. 29) is fed into an FEA model to predict stress and compare the prediction with measured material properties. In this example, the high-stress area predicted by FEA (fig. 30) agrees well with the cracking detected in post-mortem analysis.

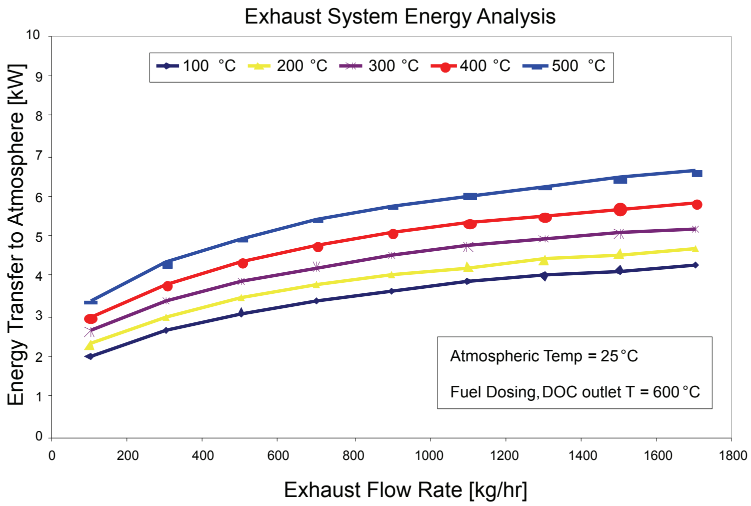


Figure 28. Simulation of heat loss from DOC|DPF during at different regeneration conditions.

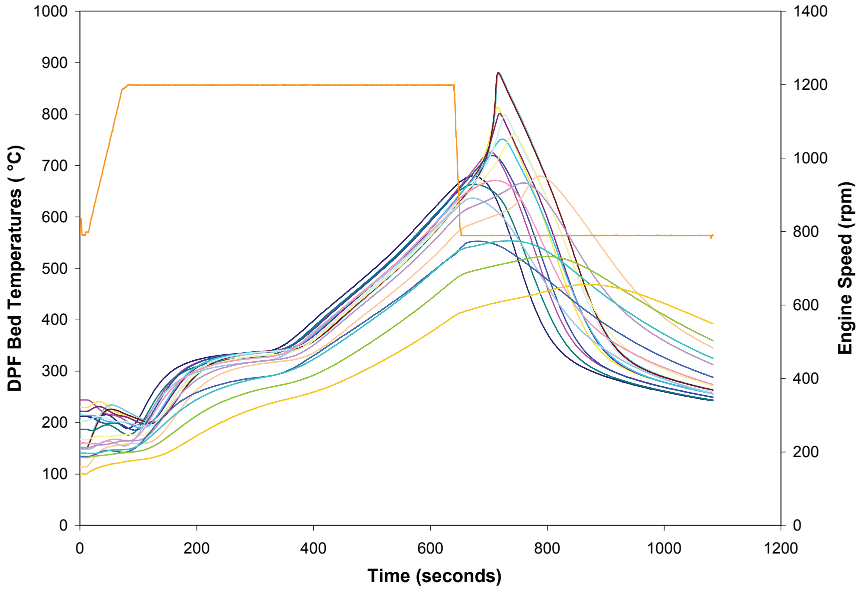


Figure 29. DPF temperature distribution during active regeneration with engine speed drops to low idle.

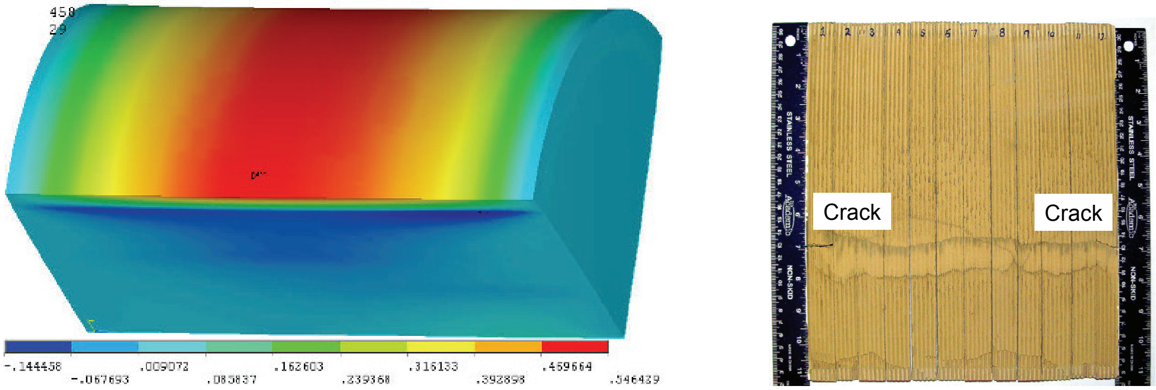


Figure 30. FEA analysis shows high stress area around DPF perimeter near midpoint (left) and picture of failed part (right).

Table 5. Trade-offs of different de-NOx technologies.

	Lean NOx Catalyst (LNC)	Lean NOx Trap (LNT)	Selective Catalytic Reduction (SCR)
NOx efficiency	~15%	~65%	~80%
Reductant	Diesel fuel	Diesel fuel	NH_3 (e.g., from urea)
Advantages	Simple	No extra fluid	Fuel efficiency
Disadvantage	Low efficiency, HC slip, and fuel penalty	Sulfur poisoning, durability risk, and fuel penalty	Complex fluid storage/delivery, and freeze and thaw

Diesel Engine NOx Aftertreatment Technologies

Depending on engine out NOx levels, several NOx aftertreatment technologies could be considered. Trade-offs of these technologies are summarized in table 5. LNT is viable for light-duty applications and SCR is preferred for heavy-duty applications due to its proven longevity and fuel efficiency advantages.

Lean NOx Catalysts (LNC)

Platinum LNC works at low temperatures of 150°C to 250°C (fig. 31) due to competing HC oxidation by O_2 at high temperatures. Additional HC can be introduced before the LNC to achieve 30% to 40% in a narrow temperature window around 200°C. Platinum LNC has a propensity to form N_2O. Base metal LNC operates around 350°C to 450°C. LNCs are sensitive to coking and sulfur poisoning. New LNC concepts such as Ag/Al_2O_3 continue to attract researchers (Johnson, 2008; Kharas, 1998; Kharas and Bailey, 1998).

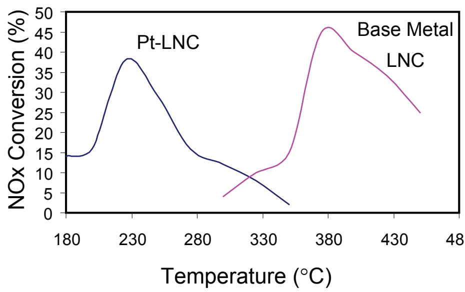


Figure 31. Operating temperature window of platinum (Pt) and base metal LNC.

Lean NOx Trap (LNT)

LNT is based on selective NO_2 storage on alkaline earth metals. Stored NOx is converted to N_2 when rich exhaust is introduced by the engine or by an HC exhaust doser, as shown in figure 25. An LNT with additional alkali metals offers better high-temperature NOx efficiencies (Dou et al., 2002), as shown in figure 32. LNT has been used in lean-burn gasoline and light-duty diesel applications. LNT requires high precious metal loadings, including the more expensive rhodium (Rh), for NOx conversions (fig. 33). LNT catalysts are highly sensitive to sulfur poisoning when active NOx storage sites are saturated by sulfates. Poisoned LNT requires rich exhaust and high temperature (above 650°C) to purge the sulfur and recover the NOx storage capacity. Repeated high-temperature sulfur purges thermally degrade the LNT and challenge its applicability for heavy-duty applications.

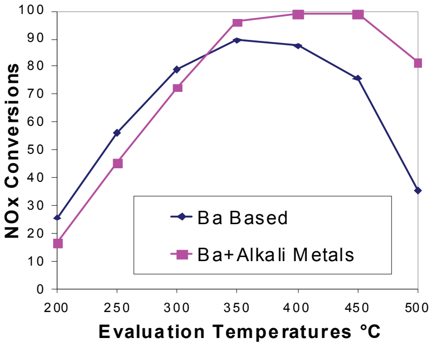


Figure 32. Comparison of low and high temperature LNT performance.

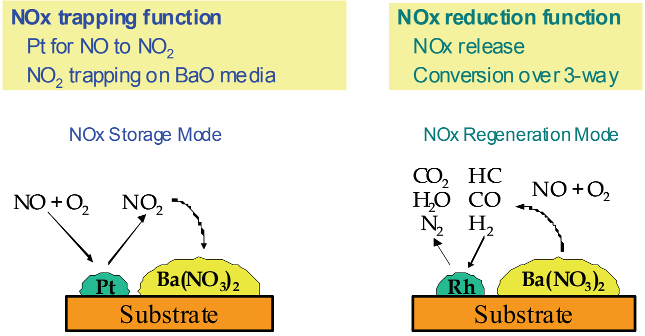


Figure 33. Working principles of LNT with lean NOx storage and rich NOx reduction.

Selective Catalytic Reduction (SCR)

SCR is based on the selectivity of NH_3 reaction with NOx in a temperature window of 150°C to 500°C, as shown in figure 34. Unlike HC LNC, NH_3 prefers to react with NO or NO_2 over O_2. NH_3 reaction with O_2 becomes profound only above 500°C. Standard and fast SCR reactions are shown below.

Standard SCR reaction:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

Fast SCR reaction:

$$4NH_3 + 2NO_2 + 2NO \rightarrow 4N_2 + 6H_2O$$

This technology has been proven for stationary applications when NH_3 gas is readily available. Generating onboard NH_3 is a major weakness of deploying SCR for mobile applications. Currently, on-highway OEMs have selected a high-purity 32.5% urea/water solution called diesel exhaust fluid (DEF) as the media to deliver NH_3. DEF thermally decomposes into NH_3 and isocyanic acid (HNCO), which further hydrolyzes into NH_3 and CO_2, as shown below.

Thermolysis:

$$(NH_2)_2CO \rightarrow NH_3 + HNCO$$

Hydrolysis:

$$HNCO + H_2O \rightarrow NH_3 + CO_2$$

Successful implementation of SCR to achieve high NOx efficiencies requires NH_3 to be uniformly distributed with exhaust. Non-uniform distribution results in NH_3 and NOx slip. Three types of SCR catalyst technologies exist in the market. V-SCR (V_2O_5-TiO_2-WO_3) is commonly extruded into monoliths, although it can be coated on a cordierite substrate. Fe-zeolite and Cu-zeolite SCR catalysts with much higher thermal stability than V-SCR are preferred in an aftertreatment system with an actively regenerating DPF. The NOx reduction temperature window of Fe-SCR and Cu-SCR with 500 ppm NO and 500 ppm NH_3 is shown in figure 35. In the absence of NO_2, Cu-SCR gives much greater NOx removal than Fe-SCR. If a DOC is used and a favorable NO_2/NOx ratio is established before the SCR, the performance difference of Fe-SCR and Cu-SCR diminishes.

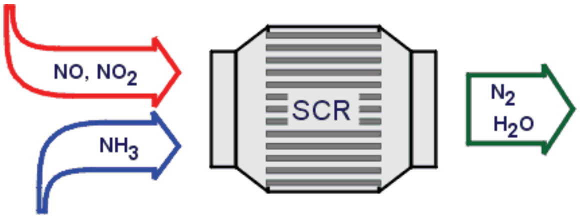


Figure 34. SCR converter and NOx and NH_3 reaction.

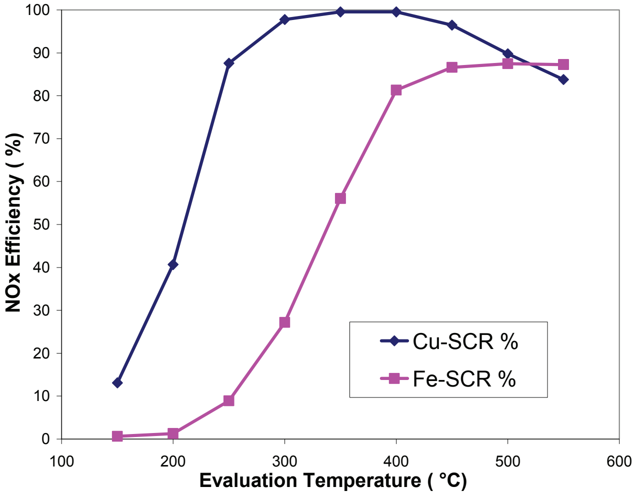


Figure 35. NOx conversion efficiency over temperature with 1:1 NH_3/NO ratio.

DEF solution freezes at -11°C. Therefore, the DEF tank must be designed with an active heating function. The DEF storage tank is typically thawed by engine coolant due to the high energy requirement, while DEF transfer lines and the DEF pump are commonly thawed by electrical power. Furthermore, the DEF solution decomposes above 65°C, which creates additional vehicle integration, storage, and transportation challenges. The DEF dosing system includes a supply pump and an injector. Pressurized DEF is metered and injected into the exhaust as a fine spray. Injection at low exhaust temperature is avoided since DEF cannot be fully decomposed into NH_3 and the catalyst is not active. The DEF infrastructure remains an open issue for off-road applications. The cost of DEF erodes part of the fuel economy benefit by the SCR technology.

A combination of LNT and SCR has also been studied in which NH_3 is produced during LNT regeneration and is temporarily stored on a downstream SCR. This combined system marginally improves the total NOx conversion efficiency of the LNT by the complementary NOx reduction on SCR (Hu et al., 2006; Johnson, 2007; Lambert et al., 2004; Bremm et al., 2008).

4. Meeting Diesel Emissions through Tiers

Tier 3 and Earlier Engines

Figure 36 shows engine technology menus through the emissions tiers. The first federal standards for new off-road engines were adopted in 1994. These were called Tier 1 standards and were phased-in from 1996 to 2000 for engines over 37 kW. Engines made before the Tier 1 standards are referred to as Tier 0 engines. Tier 2 standards were phased-in from 2001 to 2006, and Tier 3 standards were applied from 2006 to 2008. These first three phases of emission control required improved injection and air systems with internal and external EGR systems for Tier 3. Exhaust aftertreatment was avoided except for limited use of diesel oxidation catalysts.

Tier 3 engines on the market can be grouped into three categories: those that have low technology intensity, those that have medium technology intensity, and those that have high technology intensity. Table 6 summarizes key differences among these categories. The John Deere PowerTech M engine is an example of category 1, PowerTech E engine falls into category 2, and PowerTech Plus engine is the most sophisticated and represents an example of category 3.

Past	Present (Tier 3)	Interim Tier 4	Future
Basic engine sensors group Air-to-Air Inter-cooled Electronic Control, Logic Direct Injection 2 valves and 4 valves co-exist Fixed Geometry & WG turbo Naturally aspirated	Biofuel compatability Distributed vehcle cooling Cooled EGR Pilot Injection FIE, 1800 Bar Basic engine sensors group Air-to-Air Inter-cooled Electronic Control, Logic+models Direct Injection, Central, Vertical 2 valves and 4 valves co-exist FG & VGTTurbocharging co-exist	Partial on-board diagnostics Particulate filter regeneration Diesel particulate filter Torque based controls Distributed vehcle cooling Biofuel compatability Diesel oxidation catalyst Cooled EGR Enhanced Multiple injection FIE, 2100 Bar Basic engine sensors group Air-to-Air Inter-cooled Electronic Control, Logic+models Direct Injection, Central, Vertical 4 Valves Enhanced VGT and 2-stage	Hybrid technology Electric drives Waste heat recovery DeNOx catalyst active In situ SCR (w/o urea) NOx adsorber (LNT) system Amonia sensor Urea SCR & control Variable valve actuation (VVA) Stoichiometric compression ignition PCCI/Partial/Full HCCI Massive EGR NOx or Oxygen sensors Full on-board diagnostics Particulate filter regeneration Diesel particulate filter Torque based controls Distributed vehcle cooling Biofuel compatability Diesel oxidation catalyst Cooled EGR Enhanced Multiple injection, Ultra high pressure Basic engine sensors group Air-to-Air Inter-cooled Logic+enhanced model controls Direct Injection, Central, Vertical 4 Valves Enhanced VGT and 2-stage

Figure 36. Technology menu through the tiers.

Table 6. Tier 3 engine technologies.

	Category 1 **Low Tech Intensity**	**Category 2** **Medium Tech Intensity**	**Category 3** **High Tech Intensity**
Two-valve cylinder head	Yes	Maybe	--
Four-valve cylinder head	Maybe	Maybe	Yes
Mechanical fuel injection	Yes	--	--
Common-rail fuel injection	--	Yes	Yes
Standard turbocharger	Yes	--	--
Wastegate turbocharger	--	Yes	--
Variable-geometry turbocharger	--	--	Yes
Charge air cooling	Maybe	Yes	Yes
Cooled exhaust gas recirculation	--	--	Yes
Full electronic control	--	Yes	Yes, sophisticated

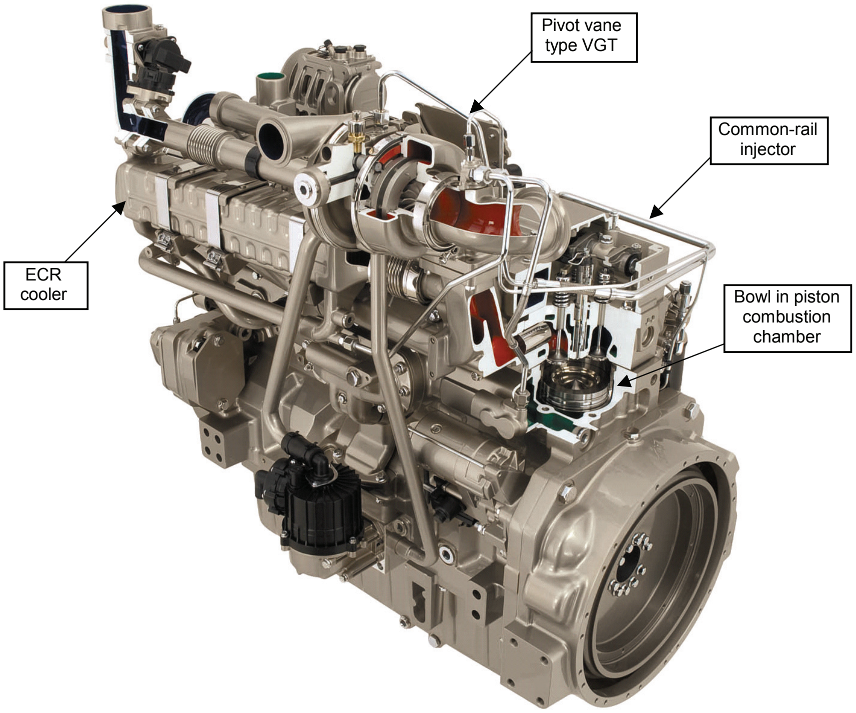


Figure 37. John Deere Tier 3 PowerTech Plus engine (courtesy of John Deere).

Engines with higher technology intensity typically cost more and are more fuel efficient. By way of an example, figure 37 shows a John Deere Tier 3 PowerTech Plus engine that features high-pressure loop-cooled exhaust gas recirculation (cEGR), a pivot vane type variable-geometry turbocharger, a high-pressure common-rail fuel injection system, and a swirl-assisted combustion system. The cEGR is taken from the exhaust manifold, cooled through a gas-to-water heat exchanger, and electronically controlled by a poppet-type valve. The heat exchanger (EGR cooler) is strapped to the engine. Needless to say, the EGR cooler works in a very harsh environment. It is subject to engine vibration that can cause mechanical cracking and fatigue. It is intended to cool the exhaust gas, which contains soot particles, hydrocarbon, and nitric oxide that can cause fouling inside the cooler. It is also subject to high temperatures that can induce thermal stress, and thermal cycles that can cause thermal fatigue. These are challenges for EGR cooler design and verification. Computational fluid dynamics (CFD) analysis can help understand flow and temperature distribution, and finite element analysis can help optimize the structure, vibration, and thermal design. Fundamental understanding and elimination of EGR cooler fouling is more of an art than a science.

Meeting Tier 4

Tier 4 standards include what are called interim and final Tier 4 standards, and they are being phased-in from 2008 to 2015. In comparison with the previous Tier 3 standards, it is easy to see the quantitative reduction in criteria pollutants. NTE and transient tests add additional dimensions to the Tier 4 standards. Either or both particulate matter and NOx exhaust aftertreatments are required for engines above 56 kW, although research is underway to avoid or reduce the increased cost and complexity, especially for smaller engines. This section describes alternatives for meeting interim Tier 4 (IT4) and final Tier 4 (FT4).

The common belief among engine technologists is that meeting final Tier 4 will require cooled EGR, advanced combustion and controls, diesel particulate filters (DPFs), and urea selective catalytic reduction (SCR). Assuming, for the moment, that meeting final Tier 4 requires all of these technologies, what is the path to get there, that is, what should the interim Tier 4 technology choice be? The answer lies in what building blocks are available and ready for each engine manufacturer. Figure 38 shows two pathways to reach the final destination. The first pathway follows the solid line, especially if a manufacturer has a Tier 3 product offering with cooled EGR. In this case, the manufacturer will use more EGR and add a DPF to satisfy the interim Tier 4, and continue on to final Tier 4 with the addition of SCR. The second pathway is to meet interim Tier 4 using combustion improvement and SCR without cooled EGR. However, cooled EGR and DPF will have to be added for final Tier 4, along with a redesigned SCR system.

It is perhaps natural to ask what are the advantages and disadvantages of each approach. While there are technical arguments for and against each approach, the ultimate judgment rests with the customer. Approximately 70% of global off-road engine makers have chosen to adopt path-

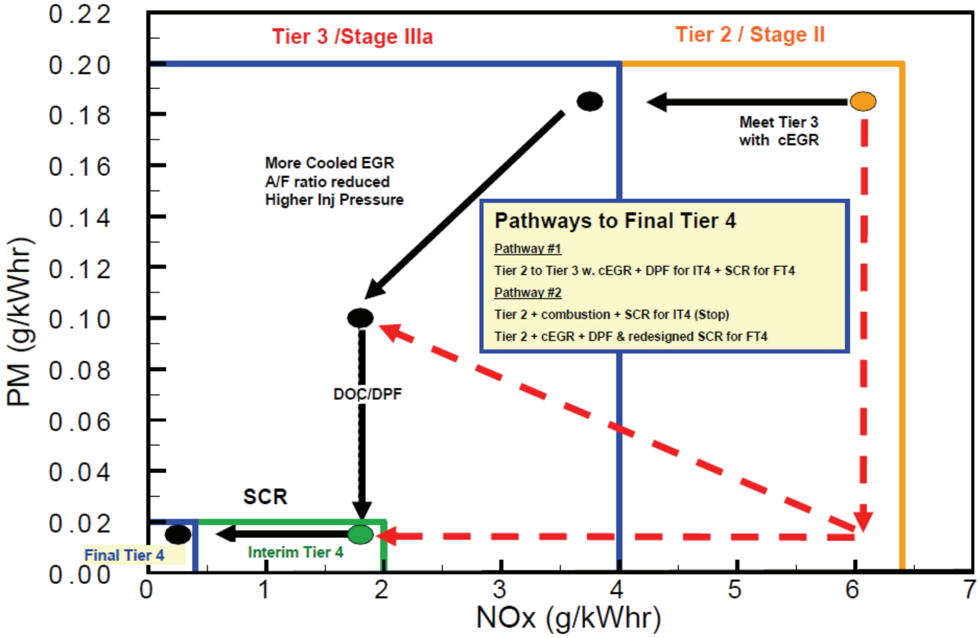


Figure 38. Pathways to meeting final Tier 4: pathway #1 is the solid line; pathway #2 follows the dotted line and then joins the solid line.

Table 7. European truck experience with EGR and SCR technology.

Brand[a]	Model	Power (hp)	Exhaust Gas Reduction Technology	Net List Price[b]	Consumption (L per 100 km)		Cost[c]	EGR/SCR Comparison		
					Diesel	AdBlue		Power (hp)	List Price	Cost[c]
M-B	Atego 1222 L Euro 4 platform	218	SCR	56,000	17.2	0.86	18.00			
MAN	TGL 12.210 Euro 4 platform	220	EGR	55,000	17.5	--	18.03	0.9%	-1.8%	0.1%
M-B	Actros 1832 L Euro 4 platform	320	SCR	71,500	25.0	1.25	26.17			
MAN	TGS 18.320 FLC Euro 4 platform	320	EGR	71,000	25.5	--	26.27	0.0%	-0.7%	0.4%
M-B	Actros 1844 L Euro 5 platform	435	SCR	88,000	33.0	1.65	34.54			
Scania	R 440 LB Euro 4 platform	440	EGR	88,000	33.5	--	34.51	1.1%	0.0%	-0.1%
M-B	Actros 2541 L Euro 5 change frame	408	SCR	93,000	33.0	1.65	34.54			
MAN	TGX 26.440 FNL Euro 5 change frame	440	EGR	94,500	33.0	--	33.99	7.8%	1.6%	-1.6%
M-B	Axor 1843 LS Euro 5 tractor	428	SCR	82,000	32.5	1.63	34.02			
MAN	TGX 18.440 Euro 5 tractor	440	EGR	83,000	32.5	--	33.48	2.8%	1.2%	-1.6%
M-B	Actros 1848 LS Megaspace Euro 5 tractor	476	SCR	92,000	33.0	1.65	34.54			
Scania	R 480 LA Highline Euro 5 tractor	480	EGR	92,000	33.5	--	34.51	0.8%	0.0%	-0.1%
M-B	Actros 1844 K Euro 4 dumper	435	SCR	101,000	27.0	1.35	28.26			
MAN	TGS 18.440 FK dumper	440	EGR	100,000	28.0	--	28.84	1.1%	-1.0%	2.1%
Iveco	Trakker AD 190 T 42 Euro 4 dumper	410	SCR	111,000	35.0	1.75	36.63			
MAN	TGS 18.400 FAK Euro 4 dumper	400	EGR	113,000	36.0	--	37.08	-2.4%	1.8%	1.2%

[a] M-B = Mercedes-Benz.

[b] Net list price is exclusive of VAT.

[c] Combined cost of diesel and AdBlue (in Euros per 100 km); gross diesel price = 1.03 Euros L^{-1}; gross AdBlue price = 0.3332 Euros L^{-1}.

way 1 and the balance pathway 2 as of this writing. On the basis of operating fluid cost, which is the cost of diesel fuel plus the cost of AdBlue or DEF (aqueous urea solution (32.5%) used in SCR to reduce oxides of nitrogen from diesel exhaust; called AdBlue in Europe and DEF in North America), table 7 shows that no statistically significant difference exists between SCR and cooled EGR technology for Euro 5 engines, which have very similar emissions requirements (NOx = 2 g kWh^{-1}, PM = 0.03 g kWh^{-1}) as interim Tier 4 (NOx = 2 g kWh^{-1}, PM = 0.02 g kWh^{-1}). Such a difference in total fluid consumption is a reflection of SCR system maturity at the Euro 5 level with a composite NOx conversion efficiency of approximately 70%. Note that the cost of AdBlue is about 1/3 that of diesel fuel in table 7. The operating fluid economy will vary depending on the diesel/DEF price ratio. Readers can use the data in table 7 to conduct sensitivity study if their local diesel and DEF price ratio differs.

Urea-based selective catalytic reduction offers effective NOx reduction for diesel engines. Figure 39 offers a method to set the SCR system design target. The x-axis represents the engine out NOx capability, and the y-axis is projected NOx conversion efficiency needed corresponding to engine out NOx capability. If the engine out NOx is nominally 2 g kWh^{-1}, then the required NOx reduction will need to be 80% to meet the 0.4 g kWh^{-1} NOx requirement of final Tier 4. The SCR converter design, urea mixing and decomposition, urea dosing strategy, and calibration must be optimized toward that performance target. Lower engine out will alleviate the need for high-efficiency SCR system performance, and vice versa. Figure 39 also provides a method to assess what alternative technologies may be viable for final Tier 4. For example, if engine out NOx approaches 1 g kWh^{-1}, then the lean NOx trap (LNT) technology will adequately meet final Tier 4 requirement at full useful life. Further engine out NOx reduction will enable even less-effective NOx reduction aftertreatment, such as LNC described in the previous section. When engine out NOx reaches below 0.4 g kWh^{-1}, there will be no need for an NOx reduction catalyst. Advanced EGR is the only known product-feasible technology to reach such low engine out NOx, as evidenced by the fact that truck and engine maker Navistar is pursuing advanced EGR for meeting on-road EPA 2010 emissions. HCCI, although a promising combustion technology, has not progressed enough to be production feasible. There are widely varying claims about the fuel efficiency benefits of various technologies. Our analyses indicate a likely range of 2% to 3% difference when each technology is optimized for final Tier 4 to its potential.

The above discussion focused on simplifying NOx reduction. Alternatively, one can consider simplifying particulate reduction. As described in the previous section, metal filters typically have filtration efficiency below 50%. If the engine out PM is below 0.03 g kWh^{-1}, for example, a metal filter can be adopted instead of a wall-flow filter, avoiding the need for active regeneration. On-road truck engine manufacturers MAN (MAN SE, Germany) and Scania (Scania Aktiebolg, Sodertalje, Sweden) have introduced Euro 5 EEV products with metal filters. Scania has stated publicly that it plans to meet Euro 6 emissions using cooled EGR and urea SCR, but without particulate filter aftertreatment. Meeting Euro 6 without diesel particulate filtering may be difficult if the particle number limit is below 8×10^{11} per kWh, as is currently the case in the Euro 6 requirement.

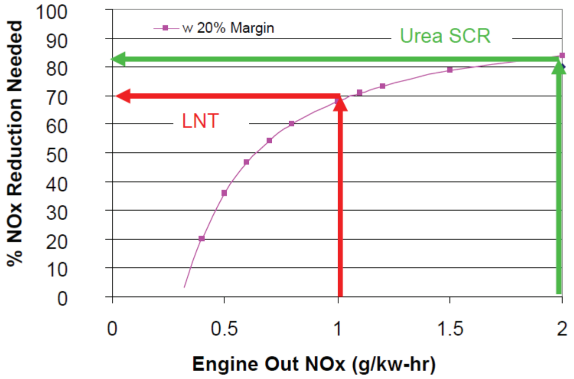


Figure 39. NOx aftertreatment efficiency requirement vs. engine out NOx.

5. Beyond Tier 4

When we will look back in 2015, we will find that non-road diesel engines are essentially free of criteria pollutants. We will find that we have solved one of the most challenging problems for our shared society. What will be our new challenges then? As engineers, we are destined to solve problems for humankind.

We will find that we will dive into many more challenging problems before we even finish final Tier 4. Energy security, energy efficiency, and greenhouse gas (GHG) reduction are facing us today. They will challenge us and future generations of engineers. Before we solve these energy and GHG issues, we will have improved on-board diagnostics that will significant enhance the robustness of emission controls and the customer-friendliness of our machines. Along the way, we will gain much more knowledge of how our products function in the real world. We may also have effectively controlled the particle number and size in diesel exhaust gas, in addition to reducing particulate mass.

As part of finding solutions for energy and GHG issues, we will have developed fuels that are alternatives to petroleum. Absent breakthrough technologies, biomass-based fuels such as biodiesel will play a small role in the quest for energy security and GHG reduction. Globally, biodiesel impact on energy availability is and will remain limited due to the limited availability of feedstock for making biodiesel. On the basis of economics, biomass-based fuels will likely compete with other fossil alternatives such as coal to liquid (CTL).

6. Summary and Perspectives

Criteria pollutant regulations have driven powertrain research and development over the last 20 years in the off-road engine industry. These regulations have resulted in low-emission engines with high fuel efficiency, contrary to some early expectations of a better environment only at the expense of energy efficiency. Nebraska Tractor Test records show that some production tractors, such as the John Deere

8000 series with Tier 3 engines, have the best fuel economy ever. We are not done with the race, but when Tier 4 is fully implemented by 2015, we will see near-zero emissions. We are optimistic that fuel economy will hold its place through engineering innovation and total vehicle system integration.

Non-road engines are becoming more complex throughout the emissions tiers. Tier 4 engines will have added hardware components, such as aftertreatment, and ever more sophisticated control software. Tier 4 powertrain engineering talents consist of design engineers and engineers with specialization in thermal and fluid science, materials science, chemistry and chemical engineering, electrical and electronics engineering, and embedded software engineering. World-class products depend on world-class talent in all of these areas.

Looking beyond Tier 4, greenhouse gas reduction and on-board diagnostics will likely continue the race for product improvement in the non-road equipment industry. Perhaps that will be another 20-year or longer journey. When we will look back at the end of the race, we shall be proud to see the achievements of multiple generations of engineers.

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Abbreviations

BSFC = brake specific fuel consumption
cEGR = cooled exhaust gas recirculation
DOC = diesel oxidation catalyst
DEF = diesel emissions fluid
DPF = diesel particulate filter
GHG = greenhouse gases
HC = hydrocarbon
LNC = lean NOx catalyst
LNT = lean NOx trap
NRTC = non-road transient test cycle
NTE = not to exceed area of the torque-speed map
OBD = on-board diagnostics
SCR = selective catalytic reduction, commonly refers to the urea-based system