Finding the best path to Tier 4i (interim) nonroad emissions compliance: The answer depends on the application

A comparison of SCR and EGR/DPF emissions control strategies for diesel applications

For more than 100 years, diesel engines have been a popular prime mover in a variety of nonroad applications, such as marine and railway propulsion, and as special drives for mobile cranes, mine haul trucks and military vehicles. Although modern diesel engines are efficient and clean energy converters, increasingly stringent emissions regulations require further improvements in controlling constituents in diesel exhaust – primarily nitrogen oxides (NOx) and particulates.

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In recent years, a variety of technologies have been employed to reduce harmful emissions in diesel exhaust. The most effective efforts involve various methods of improving combustion efficiency, such as common rail fuel injection, electronic engine management and changes in turbo charging, valve timing, injection timing and combustion chamber geometry. These internal engine design changes accomplish remarkable reductions in all of the emissions products in diesel exhaust. For most diesel engine sizes and platforms, these internal engine improvements have allowed manufacturers to meet EPA Tier 1, Tier 2 and even Tier 3 emissions standards in engines less than 750 hp without exhaust aftertreatment.

However, in order to meet the new Tier 4i (interim) nonroad emissions standards that will take effect in January 2011, engine manufacturers will need to apply both internal engine technology and the exhaust aftertreatment technology that is most appropriate for the engine application. There are currently two approaches being used by manufacturers: one strategy involves SCR (selective catalytic reduction) exhaust aftertreatment, and the other involves the use of EGR (exhaust gas recirculation) and a DPF (diesel particulate filter). While the EGR/DPF strategy works well in some applications, SCR appears to be an ideal strategy for controlling emissions on engines of less than 750 hp, especially those used in low-duty-cycle applications. This paper examines and compares SCR and EGR/DPF strategies for meeting Tier 4i emissions standards for nonroad diesel engines.

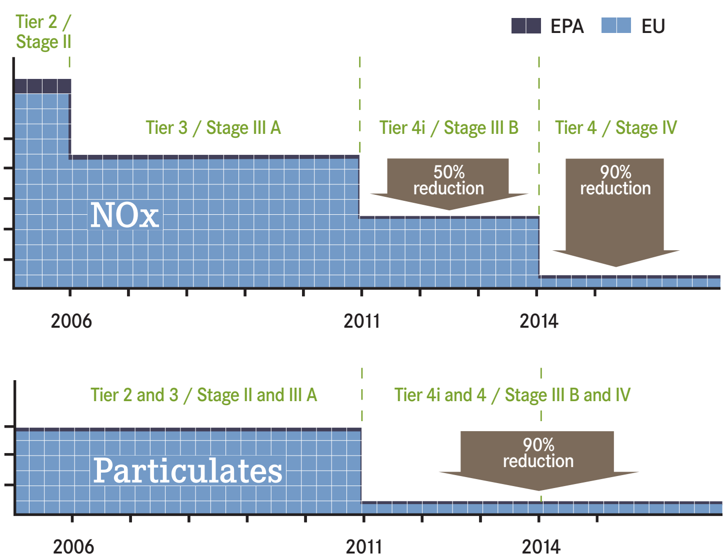
THE EMISSIONS REGULATORY LANDSCAPE

The current emissions limits for nonroad diesel engines are almost harmonized between Europe and North America. This benefits both manufacturers and customers by creating an even playing field where the emissions goals and manufacturing solutions are consistent.

In the United States, the EPA's Tier 4i standards go into effect beginning in 2011 for engines between 175 hp and 750 hp. This corresponds to the Stage III B standards that go into effect at the same time in Europe. The even more stringent Tier 4 final and Stage IV regulations go into effect beginning in 2014. The major change for the EPA's Tier 4 final is a further reduction in NOx, which may require all manufacturers of engines below 750 hp to use both SCR and cooled EGR with DPFs. See Figure 1.

The two deciding factors in selecting the most appropriate emissions control method for meeting Tier 4i are engine application and duty cycle.

Emission regulations for mobile machinery, 175 hp to 750 hp
(Fig. 1)



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WHAT IS SCR?

SCR is a technology that injects aqueous ammonia in the form of diesel exhaust fluid (DEF, also known as urea) into the exhaust stream, where a catalyst then helps convert NOx into harmless diatomic nitrogen (N_2), CO_2 and water vapor. (N_2 is inert and constitutes 78 percent of the air we breathe.) See Figure 2.

The technology has been in use for decades to control NOx emissions from industrial boilers and power plants. In recent years, it has been employed to control NOx from on-highway engines in Europe and North America and some nonroad diesel and gaseous engines used for power generation in California and other nonattainment areas. SCR is very effective at controlling NOx, with typical reduction rates of 70 percent to 95 percent.

WHAT IS EGR/DPF?

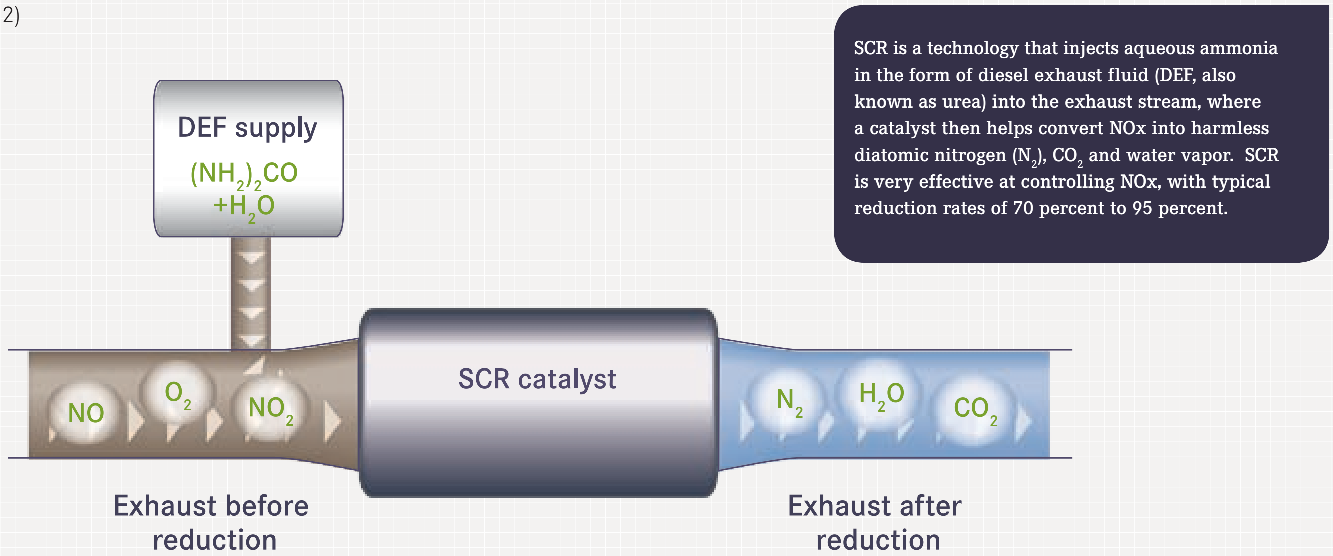
EGR uses a valve and a control system to recirculate cooled, inert gases from the exhaust manifold back into the intake manifold, resulting in lower combustion temperatures and reduced NOx. See Figure 3. In use on both gasoline and diesel engines for quite some time, EGR is very effective at controlling NOx. However, when used in diesel engines to comply with Tier 4i limits, it requires a DPF in the exhaust system to capture the particulates that increase due to the lower combustion temperatures. The DPF contains a catalyst that helps burn the soot particles when there is sufficient heat in the exhaust for the catalyst to be activated. The DPF traps particulates, which are then "burned off" at intervals in a manner similar to that of a self-cleaning oven.

EMISSIONS SOLUTION LINKED TO DUTY CYCLE

The two deciding factors in selecting the most appropriate emissions control method for meeting Tier 4i are application and duty cycle. For example, an engine powering an airport push-back tractor is used only intermittently during any given day. The engine spends a good deal of time idling and is under heavy load only when it is accelerating the aircraft. Once the aircraft is moving, the load on the engine is minimal and of short duration. Under these operating conditions, the tractor's engine may never get to a stable operating temperature. If equipped with EGR/DPF, this engine would not be able to provide enough exhaust heat to regenerate the DPF. As a result, the filter would soon plug unless soot removal was performed with manual regeneration, which would lead to increased

Nonroad applications where lightly loaded engines idle for long periods or have intermittent duty cycles are best suited to SCR as an emissions control solution.

Selective Catalytic Reduction (SCR)
(Fig. 2)



downtime and greater fuel consumption. Examples of similar nonroad applications include equipment such as single-engine mobile cranes, quarry trucks, rock crushers and yard spotters, to name but a few. These types of nonroad applications, where lightly loaded engines idle for long periods or have intermittent duty cycles, are best suited to SCR as an emissions control solution. Unlike an EGR/DPF engine that requires a consistently high exhaust temperature to burn off its higher volume of particulate matter, the SCR engine has inherently low particulate levels, so maintaining a consistent exhaust temperature is not an issue. Instead, the main emissions consideration in the SCR engine is controlling NOx, which is not produced in substantial volume under light load conditions, as in the examples described above. In fact, the SCR system injects DEF only during operating conditions that result in a rise in NOx emissions. Applications best suited to EGR/DPF are those where the engine is heavily loaded for extended periods. Under these conditions, exhaust temperatures stay consistently high enough to passively regenerate the DPF.

TWO DESIGN PATHS

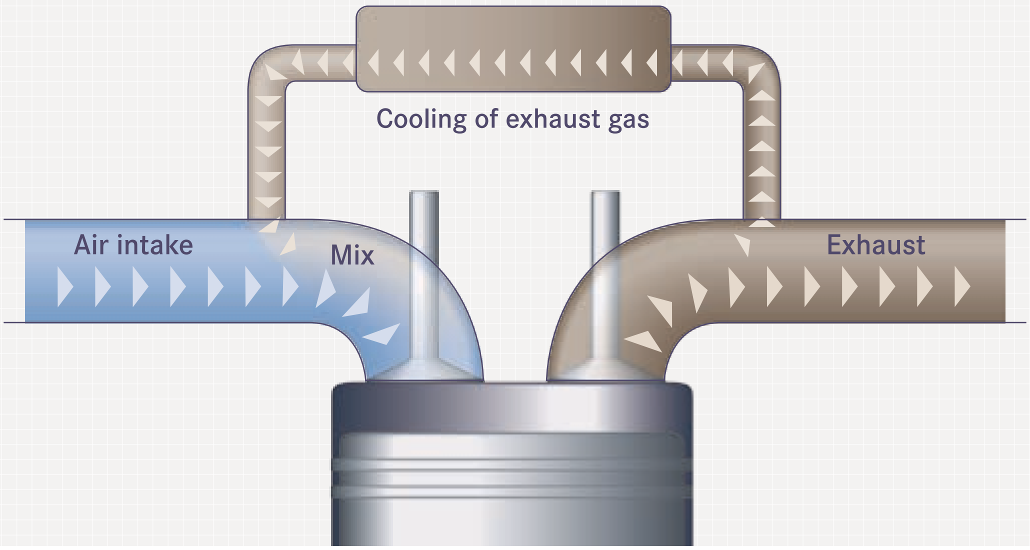
No matter which emissions control strategy a manufacturer selects — SCR or EGR/DPF — each requires significant alterations to the operating parameters of the engine. The majority of the internal engine design changes center around optimizing the combustion process for the emissions control method selected, because what happens during combustion affects the relative amounts of both NOx and particulates in the exhaust.
In diesel engines, when combustion is optimized for low NOx by lowering combustion temperatures, particulates and fuel consumption go up. Conversely, when combustion is optimized for low particulates by raising combustion temperatures, NOx goes up and fuel consumption goes down. The question then becomes, is it better to optimize combustion for low NOx production and then capture particulates with a DPF, or is it better to optimize combustion for low particulates and control NOx with SCR? The answer to this question depends heavily on the application, and for many nonroad diesel engines, SCR appears to have many advantages.

1. SCR design path – In this design strategy, the combustion process is optimized for minimum particulates and maximum fuel efficiency without limiting combustion temperatures. The high combustion temperature results in decreased particulates as opposed to EGR, but increased NOx production. The NOx is effectively controlled in the SCR by injecting DEF into the exhaust stream, where the NOx is converted to harmless nitrogen, CO_2 and water vapor as it passes through a catalyst. This design path results in very effective control of NOx and particulates, although it, too, has some advantages and disadvantages.

Advantages:
- The cost of DEF to operate the SCR is more than offset by the improved fuel economy over EGR/DPF.
- Better fuel economy results in lower heat rejection and a more compact radiator and charge-air cooler. Because of this, SCR-equipped engines require a smaller overall envelope than EGR engines.

EGR is currently used for on-highway applications and will probably be used in conjunction with SCR to meet even more stringent Tier 4 final emissions standards after 2014.

Exhaust Gas Recirculation (EGR)
(Fig.3)



EGR uses a valve and a control system to recirculate cooled, inert gases from the exhaust manifold back into the intake manifold, resulting in lower combustion temperatures and reduced NOx. EGR is very effective at controlling NOx. However, when used in diesel engines to comply with Tier 4i limits, it requires a DPF in the exhaust system to capture the particulates that increase due to the lower combustion temperatures.

- The SCR-equipped engine's smaller overall envelope results in a lower installed cost than an EGR/DPF engine.
- An SCR-equipped engine does not require ultra-low-sulfur diesel fuel because the NOx reduction catalysts are less sensitive to sulfur content. This makes SCR-equipped engines suitable for applications in any part of the world.
- Because particulates are well controlled during combustion, no DPF is required on the exhaust to meet Tier 4i regulations.
- Since only about one gallon of DEF is consumed for every 25 gallons of diesel fuel, operating costs are low.
- SCR-equipped engines contribute less greenhouse gas (CO_2) to the atmosphere due to their lower fuel consumption per unit of work.

Disadvantages:

- SCR systems require the purchase of DEF in a 1:25 proportion to the amount of diesel fuel consumed. Currently, a gallon of DEF is about the same cost as a gallon of diesel fuel.
- Additional space is required in any SCR-equipped engine installation to accommodate the DEF tank.

2. EGR/DPF design path – EGR reduces NOx production during combustion by recirculating a portion of cooled exhaust gas back into the combustion chamber. This reduces combustion temperatures and also NOx production. With lower combustion temperatures, particulates increase and have to be captured in a DPF fitted to the exhaust. EGR/DPF is a very effective strategy for controlling NOx and particulates. It is currently used for on-highway applications and will probably be used in conjunction with SCR to meet even more stringent Tier 4 final emissions standards after 2014. Nonetheless, employing EGR/DPF to meet Tier 4i standards has advantages and disadvantages for nonroad applications.

Advantages:

- A major advantage of EGR/DPF is that it is a very effective emissions control strategy in high-duty-cycle nonroad applications.
- While periodic maintenance of the DPF is required with EGR/DPF, there is no cost or inconvenience involved in having to purchase DEF.

Disadvantages:

- Since EGR introduces inert gas into the combustion chamber, less power is produced on each engine stroke, reducing efficiency.
- Injection timing is often retarded to help reduce temperatures, resulting in an increase in fuel consumption by about 5 percent.
- Higher fuel consumption for a given power output results in up to a 20 percent increase in heat rejection and some increase in greenhouse gas emissions (CO_2). Higher heat rejection requires a larger cooling system and thus a larger total envelope, which can create problems when trying to design the EGR/DPF engine into an existing nonroad equipment chassis.
- EGR/DPF requires the use of ultra-low-sulfur diesel fuel (<15 ppm) to prevent contamination of the oxidation catalysts in the DPF. Because ultra-low-sulfur diesel fuel is not readily available in all areas of the world, this requirement could limit the global use of EGR/DPF engines.

The major change for the EPA's Tier 4 final standards is a further reduction in NOx, which may require all manufacturers of engines below 750 hp to use both SCR and cooled EGR with DPFs.

— The DPF requires sufficiently high exhaust temperatures to regenerate — that is, to incinerate the carbon soot particles that are collected. Engines that idle a lot or are used in low-duty-cycle applications may not get the catalyst hot enough to properly regenerate the DPF — resulting in the need for manual regeneration, which increases downtime and fuel consumption.

DISPELLING MYTHS CONCERNING SCR

While SCR proves to be a very effective solution for controlling NOx from diesel engines, there are often questions about the technology's operation, maintenance and cost. As with any evolving technology, there is always the likelihood of misinformation. Some of the common myths and concerns about SCR are dispelled below.

Myth: SCR equipment is bulky – The major components in an SCR system include a DEF tank, control system, SCR catalyst and associated exhaust ductwork. Current SCR catalysts and ductwork are significantly smaller than they were just a few years ago. To save space, however, DEF tanks can even be designed into the fuel tank. In addition, SCR-equipped engines have up to 20 percent less heat rejection than EGR/DPF-equipped engines, which allows for smaller cooling packages. The overall engine footprint on SCR engines is smaller than on EGR/DPF engines, because the SCR engines do not have the additional internal and external engine components of the EGR/DPF system.

Myth: DEF is not readily available and is expensive – DEF availability is rapidly expanding in Europe and North America as more and more on-highway vehicles are equipped with SCR systems. Beginning in 2010, virtually all highway truck stops, including TA Travel Centers, Pilot and Petro, will have DEF to accommodate the on-highway demand. The cost of a gallon of DEF is expected to be about the same as a gallon of diesel fuel (i.e., topping off the DEF tank will add about 4 – 5 percent to the cost of a fuel fill-up). It is expected to be readily available in various containers and also in bulk quantities beginning in 2010.

Myth: DEF will freeze in colder climates – Just as diesel fuel tends to gel in sub-zero environments, DEF can potentially freeze. Cold-weather operation of SCR-equipped engines has already been addressed and solved. Engine coolant, which has been heated by the engine, is circulated through the DEF tank to thaw DEF for vehicle operation.

Nonroad applications where lightly loaded engines idle for long periods or have intermittent duty cycles are best suited to SCR as an emission control strategy. Examples of these applications include airport ground support equipment, quarry trucks, mobile cranes and many military vehicles. In these applications, the engine may never get to the stable operating temperature required to provide adequate exhaust heat to regenerate a DPF.

For many engines under 750 hp, SCR appears to offer the best combination of emissions control, fuel efficiency and ease of integration to meet Tier 4i.

Myth: The engine will be damaged if the DEF tank runs dry – If an SCR-equipped engine runs out of DEF while it is operating, a warning light will come on to alert the operator. NOx emissions will naturally go up, but the engine will continue to produce power normally until it is shut down. On the next start-up, the engine's computer will derate the power to minimize NOx emissions until the DEF supply is replenished.

Myth: Integrating an SCR-equipped engine will be difficult – Manufacturers will certify SCR-equipped engines at the factory and will ship them with most of the SCR equipment already installed. Customers may choose to source their own DEF tanks to facilitate installation in a custom chassis, but the engine manufacturer can supply DEF tanks if desired.

CONCLUSION

Internal engine design changes have accomplished remarkable reductions in all of the emissions products in diesel exhaust; however, these design optimizations have gone as far as they can go. Beginning in 2011, Tier 4i and Stage III B regulations will require nonroad diesel engines to be equipped with either EGR/DPF or SCR to further reduce NOx and particulate emissions.

For many engines under 750 hp, SCR appears to offer the best combination of emissions control, fuel efficiency and ease of integration to meet Tier 4i.

The advantages of SCR include optimum fuel economy, lower heat rejection, smaller engine footprint and lower greenhouse gas emissions with no requirement for ultra-low-sulfur fuel. While EGR/DPF is an effective emissions reduction strategy, it is best suited to regions of the world with ample supplies of ultra-low-sulfur diesel fuel and to applications where the engine operates at high loads for extended periods.

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