EPA Tier 4 Locomotive Development Status Update

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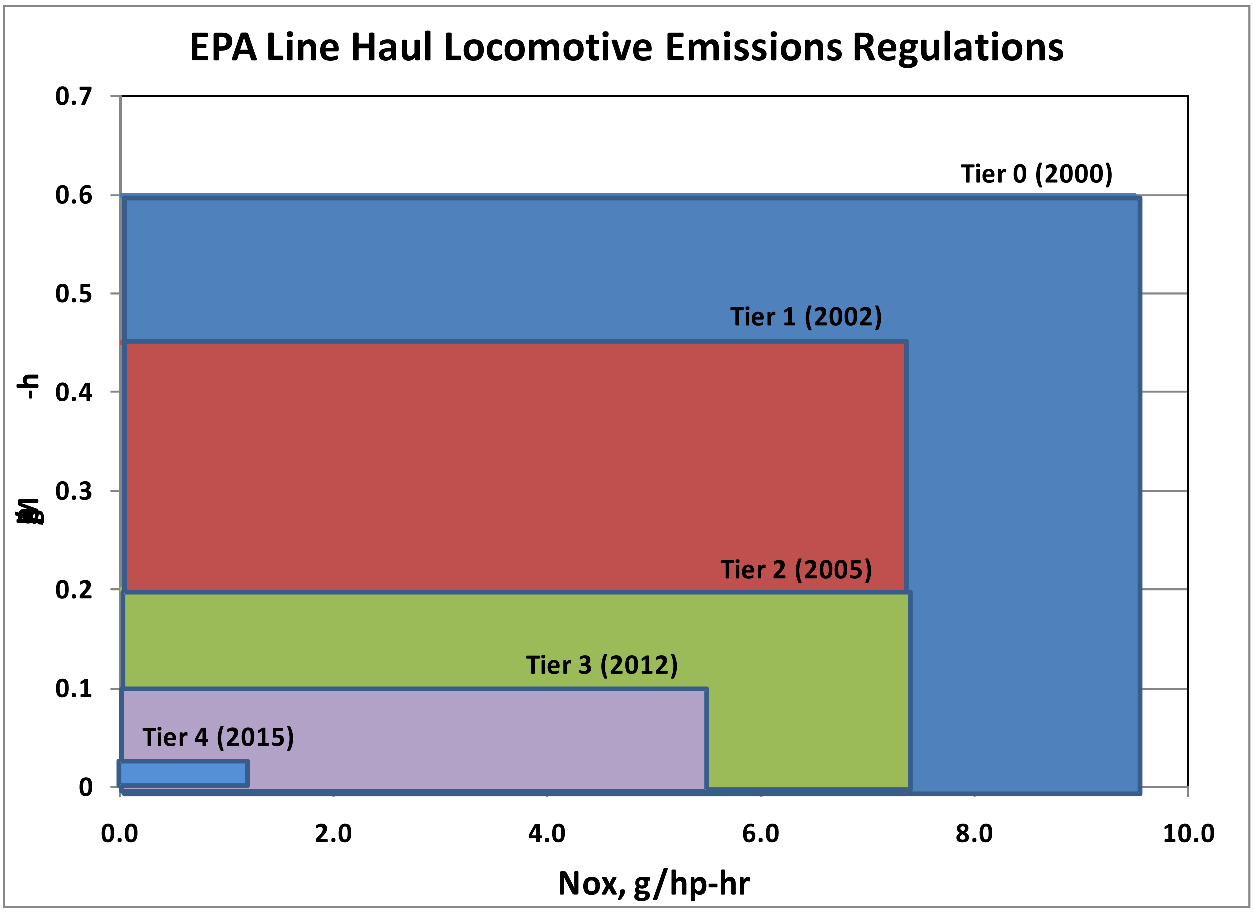
In January 2012 Tier 3 locomotive emissions standards take effect. This will be the fourth regulatory change since 2000 resulting in NOx and PM emissions reductions by more than 75% since the late 1970s. Base engine technical improvements such as turbo charging, charge air cooling, and higher cylinder pressure capability, coupled with significant advances in fuel systems and piston bowl design have seemingly made reaching these lower levels somewhat uneventful. Development engineers have optimized virtually every engine component for thermal efficiency gains which for the most part have been able to offset the inefficiencies resulting from methods that were required to lower emissions. This is critical considering a locomotive will burn well over a million dollars of fuel per year in typical line haul service.



Through Tier 3, levels have been achieved primarily via "in-cylinder" technologies however, in most cases the practical limits of those technologies appear to have been reached. Quality improvements in design, materials, machining, and assembly have laid the foundation for increased durability and life to overhaul, but this has been countered by complex control systems that facilitate pushing engines to extremes with somewhat compromised reliability.

Upcoming Tier 4 emissions levels will require additional reductions of 75% in NOx and 70% in particulate matter which on a percentage basis is equivalent to all previous emissions reductions combined. The goal of the engine developers is to achieve these extremely low emissions while maintaining acceptable reliability and total operating costs. 2015 is only three years away so there is keen interest in knowing what new technologies are being employed, the impact to operations and scheduled maintenance, where manufacturers are in their development cycles, and how the new engines are performing.

The LMOA New Technologies Committee assembled the following OEM Tier 4 status updates.

GE Transportation

GE launched the Evolution Series in 2005 which met Tier 2 requirements while delivering improved fuel efficiency. Since then they have been conducting a vast array of research around progressive emissions control ranging from advanced catalyst chemistries, hydrocarbon reductants and innovative combustion technologies. After the Tier 4 regulations were confirmed in 2008 GE was able to focus on evaluating the various technology options developed against regulatory & customer requirements. GE has selected a series of technologies that, in concert, will meet the stringent Tier 4 emissions standards without the use of urea and without requiring a significant infrastructure investment by the railroads.

- 2008 - technology validation began on a single-cylinder engine.
- 2009 - full engine testing at the development lab in Erie, Pennsylvania.
- 2012 - a prototype Tier 4 Evolution Series locomotive will be completed and will undergo exhaustive testing on a test track and local short line routes.
- 2013 - pre-production locomotives will be will be put in extended field tests.
- Jan. 1, 2015 - GE will be ready with Tier 4 compliant Evolution Series locomotives.

The GE team is optimistic that they will once again be able to break the emissions – fuel paradigm and deliver a new Tier 4 compliant Evolution Series locomotive that reduces NOx & particulate matter and does not degrade fuel efficiency.

Electro-Motive Diesel

EMD did not respond to Tier 4 information requests. Research of public sources suggests that they are aggressively pursuing a Tier 4 solution for the 710 series engine. They express that inherent advantages of the 2-stroke design will promote lower NOx and lessen the need for SCR aftertreatment. EMD is committed to delivering a non-urea system to avoid the increased costs associated with operations and infrastructure. Further enhancements to the fuel system and power-cylinder have achieved substantial reductions in oil consumption and exhaust particulate which will greatly ease the requirements of an exhaust PM reduction system.

There is no publicly documented development schedule, but EMD confirms that they have demonstrated Tier 4 levels in test facilities and are committed to a full engine development and validation program to release a reliable product on time.

Progress Rail

The Progress Rail PR30C is the first locomotive greater than 3000 hp to be packaged with urea-SCR after-treatment. The PR30Cs are built off of SD40-2 chassis fit with a Tier 2 3,005 hp Caterpillar 3516C-HD V16 engine. A Caterpillar Clean Emissions Module (CCEM) is fit directly over the engine, a Diesel Emissions Fluid (DEF) tank is mounted cross wise behind the fuel tanks, and a dosing cabinet housing a pump and a control module is installed in the front of the rear compartment. The 250 gallon DEF tank is sized to allow one fill for every three fuel refills. The Dosing system, tank, and supply lines are heated to prevent freezing. This conversion alters the external appearance of the locomotive. In addition to the addition of the large exhaust treatment box, the radiator section is replaced with one similar in appearance to that of an EMD SD70ACe.

Five PR30C locomotives revenue freight service in California and Arizona in July 2010 and have accumulated well over 15,000 hours. The engine after-treatment system has demonstrated 0.90 g/bhp-hr NOx and 0.03 g/bhp-hr PM and achieved a 5% fuel economy benefit over a standard Tier 2 3516.

MTU

The Series 4000 will remain as MTU's future engine for line haul and heavy switcher locomotives. At InnoTrans 2010 in Berlin, MTU introduced the latest-generation Series 4000 R84, the first locomotive engine to comply with the upcoming Stage IIIB emission regulations in Europe.

The Series 4000 R84 incorporates both new technologies and concepts that have proven themselves in earlier Series 4000 engines. It maintains the Miller cycle valve timing that was introduced on the Series 4000 R43, as well as continuing the evolution of the high-pressure common rail fuel injection system that has been a hallmark of the Series 4000 since its introduction almost fifteen years ago.

Chief among the new technologies introduced on the Series 4000 R84 are controlled two-stage turbocharging, charge air cooling after each turbocharger stage, and cooled exhaust gas recirculation (EGR). A diesel particulate filter (DPF) completes the emission reduction strategy. MTU engineers are further investigating the development of these technologies to achieve Tier 4 certification in time for the 2015 effective date of these regulations.

For smaller industrial switcher locomotives, in 2012 MTU is releasing its Tier 4i certified 12V2000 and 16V2000. As with the Series 4000 R84, the Tier 4i Series 2000 adds controlled two-stage turbocharging, charge air cooling after each turbocharger stage, and cooled EGR. In contrast with the Series 4000, the Tier 4i Series 2000 uses high-pressure common rail fuel injection for the first time in Series 2000 engines for industrial and rail applications.

Two key achievements with the Tier 4i Series 2000 are that it meets the Tier 4i limits without any aftertreatment, and that its fuel consumption has been reduced by 10% compared with the existing Tier 2 Series 2000. The same basic engine will be used for Tier 4 Final, with the addition of only a diesel oxidation catalyst (DOC) as aftertreatment. The Tier 4 Final Series 2000 is scheduled for commercial production in 2014.

Cummins

In early 2011 Cummins released its QSK Tier 3 locomotive engines which span from 750–2700 hp. The Tier 3 QSK engines feature a field proven electronic common rail fuel system, charge air after-cooling, and piston bowl designed to meet Tier 3 switcher and line haul emissions without sacrificing fuel economy and reliability. The 700 hp QSK19 has been employed in gen-set switcher applications and Cummins feels that the updated 750 hp Tier 3 model with improved fuel consumption will continue to perform well and greatly reduce operation costs over standard switchers.

Cummins will release the 600 hp Tier 4 QSX15 in early 2012. The new QSX15 will be certified for use in single, double, and triple gen-set switcher configurations up to 1,800 hp. To meet Tier 4, the QSX15 base engine has been re-engineered and up fit with a variable geometry turbo-charger, cooled EGR, a common rail fuel system, and coupled with a particulate filter. The QSX15 will meet Tier 4 emissions without the need for urea infrastructure.

Cummins will release Tier 4 compliant QSK engines in 2015, maintaining all current Tier 3 ratings. These engines will optimize in-cylinder combustion to reduce PM and add urea-SCR technology to the exhaust reduce NOx emissions. The Tier 4 base engine coupled with exhaust after-treatment will perform as a fully integrated system. SCR technology combined with higher fuel system pressure and optimized injectors and pitons allows balance of the engine to remain unchanged from Tier 3. This approach will retain Tier 3 performance and durability, and deliver a 5-10% decrease in fuel consumption.

The following are excerpts from Tier 4 Diesel Emission Reduction Strategies which was presented by Bruce Wolf at the North American Rail Summit in Montreal Quebec, October 2010.

Engine-Based Emission Reduction

Up to and including the current Tier 3 standards, engine manufacturers have met emission limits by implementing changes within the engine itself. The following sections describe a sample of such engine-based technologies.

High-Pressure Common Rail Fuel Injection

Combustion in a diesel engine takes place when fuel is injected at high pressure into the hot, dense air that has been compressed by the piston in the cylinder. Traditionally, the fuel has been pressurized for injection by individual cam-driven pumps for each cylinder. This results in the injection pressure gradually building up and falling off during the injection event. Lower fuel pressures at the beginning and end of injection can cause incomplete atomization of the fuel spray, forming large droplets that lead to oxygen-poor regions in combustion. This increases PM, CO and HC emissions.

A technology that has been successfully implemented in several engines is high-pressure common rail injection. In this system, a single high pressure pump pressurizes fuel to maintain the optimum injection pressure for all cylinders. This fuel is then delivered to the cylinders by a common pipe, or “common rail”, that connects all the injector nozzles to the high pressure fuel pump. This system ensures that full fuel pressure is available from the beginning of injection right through to the end, resulting in improved atomization and more complete combustion. In addition, electronic control of the injector nozzles allows the possibility of injecting a small amount of fuel before the main injection, to reduce noise, as well as post-injection of fuel to help further reduce emissions. The latter can be used in conjunction with possible aftertreatment devices (to be discussed later).

In-Cylinder Combustion Development

As well as increased fuel injection pressure, engine manufacturers have made great improvements in the combustion process inside the cylinder to reduce emissions, increase power and reduce fuel consumption. These improvements have included:

- Optimizing the piston crown / bowl design to achieve a more complete combustion event by controlling the interaction between combustion plume and the cooler piston surface,
- Injector tip design to produce better fuel atomization and targeted dispersion with reference to the piston
- Electronic fuel injection control to optimize injection timing and pressure based on engine speed and load, and
- Valve and head design to minimize restriction to intake air (on a four-cycle engine) and exhaust flow.

Unfortunately, some of these changes can lead to reduction of NOx emissions at the cost of increasing PM, or vice versa.

Turbocharging and Aftercooling

Turbocharging increases the amount of air entering the cylinder. This leads to increased power by increasing the amount of fuel that can be burned in each combustion cycle. However, the air heats up as it is compressed by the turbocharger, leading to increased NOx emissions.

The increased air temperature can be mitigated by cooling the intake air after it leaves the turbocharger, and before it enters the cylinder. Charge air coolers have been incorporated which use the engine coolant, a separate low-temperature coolant circuit, or air-to-air cooling using ambient air drawn from outside the locomotive, to cool the compressed air. Cooling the intake air combines the benefits of high-pressure air for increased power, with lower intake air temperature for reduced NOx emissions.

Another development is multiple-stage turbocharging, with charge air cooling after each stage of turbocharging. Used in, for example, MTU's next generation of engines for surface mining, this system could also be applied to locomotive engines.

Miller Cycle

The Miller Cycle is a modification of valve timing on a four-cycle engine to reduce peak cylinder temperatures. This leads in turn to a reduction of NO_x emissions.

In the Miller Cycle, the intake valve is left open until partway through the intake stroke, expelling some of the intake air and reducing the temperature rise during compression. Effective supercharging is required to maintain the ability to produce torque at low engine speeds.

Examples of locomotive engines using variations on the Miller Cycle include EMD's two-cycle engines, including the current 710ECO, and MTU's Series 4000 R43. In the two-cycle engine, the intake ports in the cylinder wall remain uncovered until partway through the compression stroke. In MTU's Series 4000 R43, the intake valve is closed early, rather than being left open partway through the compression stroke.

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is another technique used to reduce NOx emissions by reducing peak cylinder temperatures. With EGR, a controlled amount of exhaust gas from one or more "donor" cylinders are diverted from the exhaust stream, cooled in an EGR cooler, and mixed with the intake air before entering the cylinders. The higher specific heat capacity of the water and carbon dioxide in the exhaust gas limits the temperature rise during combustion.

There are a few drawbacks to EGR. Presence of exhaust gas in the cylinder leads to increased PM emissions, often requiring a diesel particulate filter (see below). An EGR-equipped engine can have less power and lower fuel efficiency than an equivalent non-EGR engine. And finally, the presence of sulfur in diesel fuel causes sulfuric acid to form when the exhaust is cooled, leading to corrosion and premature failure of the EGR cooler. This last problem has largely been prevented through the requirement for only ULSD (Ultra-Low Sulfur Diesel, with no more than

15 parts per million sulfur content) to be used for locomotives by the time the Tier 4 standards come into effect in 2015.

Aftertreatment-Based Emission Reduction

The Tier 4 standards are intended to reduce locomotive engine emissions below what can be achieved strictly by engine-based emission reduction technologies. In order to meet these standards, some form of aftertreatment is likely to be required. The term aftertreatment describes any device in the exhaust stream after the engine, whose purpose is to remove or neutralize pollutants in the exhaust stream.

In general, the cleaner the exhaust leaving the engine, the less aftertreatment is required. This can reduce the volume needed to house the aftertreatment in the tight confines of a locomotive. However, effective aftertreatment can allow the engine to operate in a more fuel efficient - but more polluting - configuration. Choosing the right balance between on-engine exhaust reduction and exhaust aftertreatment is a challenge for engine and locomotive manufacturers.

Diesel Oxidation Catalyst

A diesel oxidation catalyst (DOC) is a passive catalyst chamber inserted into the exhaust stream. It can be used downstream of the turbocharger, or in some engines, in the exhaust manifold between the cylinder heads and the turbocharger. As exhaust passes over the catalyst, CO and HC react with remaining oxygen to form CO_2 and H_2O. DOC can be very effective at reducing CO and HC. It also has a small effect at reducing PM, but is generally not effective at reducing NO_x.

DOC can be used to condition the exhaust to enhance the function of further downstream aftertreatment. Because the oxidation reactions increase the exhaust temperature, controlled amounts of fuel can be injected into the exhaust upstream of the DOC (or added through post-injection in an electronically-controlled common-rail fuel system) for the specific purpose of raising the exhaust temperature to a level that maximizes the reaction rate in other aftertreatment devices further along the exhaust system.

Diesel Particulate Filter

As its name implies, a diesel particulate filter (DPF) acts as a filter to remove particulate matter from the exhaust stream. Based on its design, a DPF can remove anywhere from 50% to 85% or more of the PM from the exhaust. However, the higher PM removal comes with an increased backpressure, leading to increased fuel consumption in the engine.

As the PM builds up in the DPF the backpressure increases. If allowed to accumulate, the backpressure would soon reach a level where the engine could no longer operate. In order to keep the backpressure within limits, the DPF must be "regenerated" by burning off the PM and turning it into CO_2.

To regenerate, the DPF must reach a relatively high temperature and remain there for several minutes (depending on the amount of PM to be burned off). The use of a catalyst "washcoat" on the filter medium can reduce the temperature needed for regeneration. If the engine's load profile is high enough - for example, a locomotive in line-haul service - the engine's exhaust temperature is often high enough to cause DPF regeneration. On the other hand, an engine whose exhaust temperature is mostly too cold for regeneration - for example, a switcher - must use other means to raise the exhaust temperature. This could involve injecting diesel fuel upstream of a DOC. However, if the exhaust is too cold, even this will not be effective, as the liquid fuel would pass through the DOC without reacting. In this case, a fuel-fired burner upstream of the DPF, or an electric heating element within the DPF, may be required.

Generally, a DPF that can regenerate strictly from the high temperature of the exhaust is called a "passive DPF", while a DPF with a burner or electric heater is an "active DPF". The choice of the type and size of DPF depends not only on the emission characteristics of the engine, but also on a good understanding of how the engine will be used and what exhaust temperature can be expected.

A DPF can be plugged not only by PM, but also by ash coming from engine lubricating oil burned in the cylinder. Minimizing oil consumption and selecting a low-ash oil can help prolong the filter element life. Even so, periodic removal and cleaning of the filter element will be required. Depending on many factors, this cleaning interval may be semi-annual, annual or biennial.

Selective Catalytic Reduction

While HC, CO and ultimately PM are removed through an oxidation reaction, a reduction reaction is needed to convert NO_x back to harmless nitrogen (N_2) gas. In the oxygen-poor exhaust from a spark-ignition engine, this can be accomplished by a passive "three-way" catalyst. However, in the relatively oxygen-rich exhaust of a diesel engine, another strategy is used: Selective catalytic reduction (SCR).

In SCR, an additional fluid is added to the exhaust as a "reductant". This reductant is then mixed with the exhaust, before entering the SCR's catalyst chamber. There, the reductant reacts with the NO_x to convert it to N_2. In existing mobile diesel engine applications, an aqueous solution of urea (commonly known as diesel emission fluid, or DEF, or in Europe as "AdBlue") is used as the reductant. While mixing with the hot exhaust, the DEF breaks down into ammonia, which in turn reacts in the SCR chamber to reduce the NO_x. The amount of DEF injected must be carefully controlled based on the engine's operation (load, speed, temperature, etc.) to maximize the reduction of NO_x, and to minimize the release of unreacted ammonia from the SCR. This "ammonia slip" is also prevented by using a "slip catalyst" to convert any remaining ammonia into harmless N_2 and H_2O.

The use of DEF in SCR requires procuring, storing, dispensing and carrying onboard the locomotive another fluid besides those already used. Typically, an SCR-equipped locomotive can expect to use between 5% and 10% as much DEF as it does diesel fuel. An alternative being developed uses hydrocarbons such as diesel fuel as the reductant, rather than DEF. This avoids the infrastructure needed to support a separate fluid, though it increases the consumption of diesel fuel aboard the locomotive.

As with some other catalyst-based systems, SCR can be "poisoned" by sulfur in the fuel. This means that sulfur compounds in the exhaust attach permanently to the catalyst, eliminating its ability to reduce NO_x. This is another reason why only ULSD (Ultra-Low Sulfur Diesel) can be used in most if not all locomotives designed to meet the Tier 4 emission standards.