

## **Tier 4 Diesel Emission Reduction Strategies**

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### **Introduction**

This presentation is intended to provide an overview of technologies that contribute to reducing diesel exhaust emissions to the levels mandated in the EPA Tier 4 locomotive emission regulations. It also begins with a description of the composition of diesel exhaust, and a brief summary of the EPA locomotive emission regulations.

### **Composition of Diesel Exhaust**

Diesel exhaust is the result of burning diesel fuel and air under the high pressures and temperatures present inside the cylinder of a diesel engine. For a typical pre-regulatory engine, the principal components of diesel exhaust (by volume) are:

- N<sub>2</sub> - 74.1%
- O<sub>2</sub> - 8.8%
- H<sub>2</sub>O - 8.6%
- CO<sub>2</sub> - 7.5%
- Ar - 0.87%
- Pollutants - approx. 0.13%

Aside from the pollutants - and CO<sub>2</sub>, to be discussed below - these gases are completely harmless. In fact, they are naturally occurring in Earth's atmosphere in more-or-less similar proportions:

- N<sub>2</sub> - 78%
- O<sub>2</sub> - 21%
- H<sub>2</sub>O - varies (typically ~ 1%)
- Ar - 0.93%

- CO<sub>2</sub> - 0.04%

The decreased oxygen (O<sub>2</sub>) in diesel exhaust - and the increased water (H<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>) - are due to the oxygen in the air reacting with hydrogen and carbon in diesel fuel during combustion in the engine cylinder.

A quick note on carbon dioxide: It is considered a greenhouse gas, and is believed by some to be a significant contributor to possible global warming. However, it is not among the pollutants regulated by the EPA locomotive emission regulations. In fact, some technologies to meet these emission regulations actually cause increased carbon dioxide emissions, through increased fuel consumption. Because carbon dioxide is not a pollutant regulated by the EPA locomotive emission regulations, any further discussion is outside the scope of this presentation.

The pollutants governed by the EPA regulations fall within the 0.13% of the typical diesel emissions mentioned above. These pollutants contribute to localized air quality problems. Their proportions, by volume, in typical pre-regulatory diesel emissions, are:

- NO<sub>x</sub> - 0.1%
- CO - 0.02%
- HC - 0.01%
- PM - 0.001%

NO<sub>x</sub> - or nitrogen oxides - result from nitrogen (N<sub>2</sub>) reacting with oxygen (O<sub>2</sub>). While nitrogen is normally quite stable, the high temperatures inside a diesel engine cylinder cause it to react with oxygen. The simplest way to reduce NO<sub>x</sub> formation is to reduce in-cylinder temperatures. However, this can also decrease the efficiency of the engine, resulting in reduced power and increased fuel consumption.

Carbon monoxide (CO), unburned hydrocarbons (HC) and diesel particulate matter (PM) result from incomplete combustion of the fuel. CO is formed when insufficient oxygen is present at a specific molecule for it to form the more preferable carbon dioxide. HC is leftover portions of diesel fuel molecules that do not burn, typically due to localized low-temperature regions in the cylinder. Finally, PM consists of microscopic particles of soot, or

carbon, from diesel fuel that does not fully react with oxygen to form carbon dioxide. PM also includes ash from the small amount of lubricating oil that slips past the piston rings, and sulfur compounds from sulfur in the diesel fuel (more on this later).

### **EPA Locomotive Emission Regulations**

To reduce the effects of the above-mentioned pollutants, the Environmental Protection Agency has implemented regulations to limit the emission of these pollutants from diesel engines in many applications, including locomotives. The locomotive emission regulations vary with the date of original manufacture of the locomotive (applying retroactively to locomotives built as far back as 1973), and whether the locomotive is a “line haul” or a “switch” locomotive. The EPA distinguishes between “line haul” and “switch” locomotives based on whether or not the total power from all engines aboard the locomotive exceeds 2300 hp. Initial regulations were adopted in 1997, establishing Tier 0, Tier 1 and Tier 2 standards based on the date of original manufacture of the locomotive. Further regulations were adopted in 2008, further tightening the Tier 0, 1 and 2 limits for existing locomotives (applicable when the locomotive is remanufactured) and introducing new Tier 3 and 4 limits for locomotives to be built starting in 2011 / 2012 (Tier 3) and 2015 (Tier 4). A brief summary of the locomotive emission standards is given in Tables 1 and 2. More detail is available in the presentation “EPA Emission Requirements for Locomotives” by Chuck Moulis, John C. Hedrick and Ted E. Stewart P.E., presented at the 70<sup>th</sup> Annual Meeting of the LMOA in 2008. The full regulations themselves are available on the EPA website at <http://www.epa.gov/otaq/locomotives.htm>. (Nothing in this paper is to be construed as supplanting or replacing the EPA regulations. In the case of a conflict, the regulations govern.)

### **Engine-Based Emission Reduction**

Up to and including the current Tier 2 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).

### **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 combustion chamber size and shape through piston crown shaping and designing the optimum compression ratio, to improve interaction between air and fuel during combustion,
- 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 NO<sub>x</sub> 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 NO<sub>x</sub> 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 NO<sub>x</sub> 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<sub>x</sub> 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 NO<sub>x</sub> 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.

### **Homogeneous Charge Compression Ignition**

Homogeneous Charge Compression Ignition consists of injecting fuel into the cylinder early in the compression stroke, so that the fuel and air become well mixed as the piston approaches top dead center. Once the temperature and pressure are high enough, combustion ignites spontaneously throughout the fuel-air mixture. The lack of localized high-temperature zones and oxygen-poor regions during combustion leads to greatly reduced NO<sub>x</sub> and PM formation. However, it is extremely challenging to control the fuel injection amount for engine speed, load and temperature to achieve the desired ignition timing and to control the engine operation. Although this technology is under development and testing, it is not yet available commercially.

### **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<sub>2</sub> and H<sub>2</sub>O. 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<sub>x</sub>.

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<sub>2</sub>.

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  $\text{NO}_x$  back to harmless nitrogen ( $\text{N}_2$ ) 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  $\text{NO}_x$  to convert it to  $\text{N}_2$ . 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  $\text{NO}_x$ . The amount of DEF injected must be carefully controlled based on the engine’s operation (load, speed, temperature, etc.) to maximize the reduction of  $\text{NO}_x$ , 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.

### **Conclusion**

Engine and locomotive manufacturers have a wide variety of technologies available to meet the EPA's upcoming Tier 4 locomotive emission standards. When selecting which products are best suited to your railroad, be sure to speak with your locomotive, engine and aftertreatment suppliers. It is critical to gain a solid understanding of their emission-reduction strategies, and their impact on your operating and maintenance practices.

## Tables

| Year of original manufacture | Tier of standards   | Standards (g/bhp-hr) |                   |      |     |
|------------------------------|---------------------|----------------------|-------------------|------|-----|
|                              |                     | NO <sub>x</sub>      | PM                | HC   | CO  |
| 1973 - 1992 <sup>a</sup>     | Tier 0 <sup>b</sup> | 8.0                  | 0.22              | 1.00 | 5.0 |
| 1993 <sup>a</sup> - 2004     | Tier 1 <sup>b</sup> | 7.4                  | 0.22              | 0.55 | 2.2 |
| 2005 - 2011                  | Tier 2 <sup>b</sup> | 5.5                  | <sup>e</sup> 0.10 | 0.30 | 1.5 |
| 2012 - 2014                  | Tier 3 <sup>c</sup> | 5.5                  | 0.10              | 0.30 | 1.5 |
| 2015 or later                | Tier 4 <sup>d</sup> | 1.3                  | 0.03              | 0.14 | 1.5 |

<sup>a</sup> Locomotive models that were originally manufactured in model years 1993 through 2001, but that were not originally equipped with a separate coolant system for intake air are subject to the Tier 0 rather than the Tier 1 standards.

<sup>b</sup> Line-haul locomotives subject to the Tier 0 through Tier 2 emission standards must also meet switch standards of the same tier.

<sup>c</sup> Tier 3 line-haul locomotives must also meet Tier 2 switch standards.

<sup>d</sup> Manufacturers may elect to meet a combined NOX+HC standard of 1.4 g/bhp-hr instead of the otherwise applicable Tier 4 NOX and HC standards, as described in paragraph (j) of this section.

<sup>e</sup> The PM standard for newly remanufactured Tier 2 line-haul locomotives is 0.20 g/bhp-hr until January 1, 2013, except as specified in 40 CFR 1033.150(a)

**Table 1**

### Line-Haul Locomotive Emission Standards

| Year of original manufacture | Tier of standards   | Standards (g/bhp-hr) |                   |                   |     |
|------------------------------|---------------------|----------------------|-------------------|-------------------|-----|
|                              |                     | NO <sub>x</sub>      | PM                | HC                | CO  |
| 1973 - 2001                  | Tier 0              | 11.8                 | 0.26              | 2.10              | 8.0 |
| 2002 - 2004                  | Tier 1 <sup>a</sup> | 11.0                 | 0.26              | 1.20              | 2.5 |
| 2005 - 2010                  | Tier 2 <sup>a</sup> | 8.1                  | <sup>b</sup> 0.13 | 0.60              | 2.4 |
| 2011 - 2014                  | Tier 3              | 5.0                  | 0.10              | 0.60              | 2.4 |
| 2015 or later                | Tier 4              | <sup>c</sup> 1.3     | 0.03              | <sup>c</sup> 0.14 | 2.4 |

<sup>a</sup> Switch locomotives subject to the Tier 1 through Tier 2 emission standards must also meet line-haul standards of the same tier.

<sup>b</sup> The PM standard for new Tier 2 switch locomotives is 0.24 g/bhp-hr until January 1, 2013, except as specified in 40 CFR 1033.150(a).

<sup>c</sup> Manufacturers may elect to meet a combined NOX+HC standard of 1.3 g/bhp-hr instead of the otherwise applicable Tier 4 NOX and HC standards, as described in 40 CFR 1033.101(j).

**Table 2**  
**Switch Locomotive Emission Standards**