

# Ultra-Clean Diesel Locomotive

*SwRI helps develop, implement and verify state-of-the-art emission controls for a new locomotive*



*Dustin T. Osborne is a research engineer in the Emissions Research and Development Department within the Engine, Emissions and Vehicle Research Division. His work focuses on locomotive performance and emissions and the application and evaluation of locomotive aftertreatment products. Christopher A. Sharp is a staff engineer in the Emissions Research and Development Department. His projects include characterization of regulated and unregulated engine emissions to study fuel effects, aftertreatment effects and diesel engine developments to meet future emission standards.*

D17426-5250

D17426-5213

By Dustin T. Osborne and  
Christopher A. Sharp

According to the Federal Railroad Administration, railroads are 1.9 to 5.5 times more fuel-efficient than trucks when it comes to moving freight. In fact, a freight train moves a ton of freight an average of 457 miles on a single gallon of fuel. It comes as no surprise, then, that rail transportation is the most used method of transporting goods in the United States, accounting for 43 percent of all goods transported. To help get this done, more than 24,000 locomotives operate on the seven largest U.S. railroads, which also comprise the U.S. Class I Railroads.

Locomotive exhaust emissions were unregulated in the U.S. until 2000, when the Environmental Protection Agency put in place exhaust emission standards that by 2005 would require locomotive manufacturers to reduce nitrogen oxide (NO<sub>x</sub>) emissions, the leading precursor to the formation of ozone, or smog, by approximately 60 percent. Particulate matter (PM) emissions, a pollutant identified by the state of California as a cancer-causing substance and an irritant to the respiratory system, were to be reduced by approximately 50 percent under the regulations that were implemented in Tier 1 and 2 stages. Despite these significantly cleaner engines, the EPA estimated in 2008 that locomotive and marine diesel engines still accounted for approximately 20 percent of mobile source emissions of NO<sub>x</sub>, and about 25 percent of mobile source diesel PM in the United States.

### New EPA regulations for locomotive emissions

On May 6, 2008, the EPA finalized future Tier 3 and Tier 4 exhaust emission standards for new locomotives. The transition from Tier 2 to Tier 3 will require a 50 percent reduction in PM and will apply to newly manufactured locomotives starting January 1, 2012. This will most likely be achieved by using ultra-low sulfur diesel (ULSD) fuel along with an incremental improvement in engine-out PM. Tier 4 exhaust emission standards for locomotives will take effect in 2015 and will require an additional 70 percent reduction in PM from Tier 3 standards, as well as approximately an 80 percent reduction in NO<sub>x</sub>. Tier 4 standards will not likely be met by

engine design changes alone, but would instead force the transfer into the locomotive sector of exhaust catalyst technology previously developed to control NO<sub>x</sub> and PM from on-highway and non-road heavy-duty diesel engines.

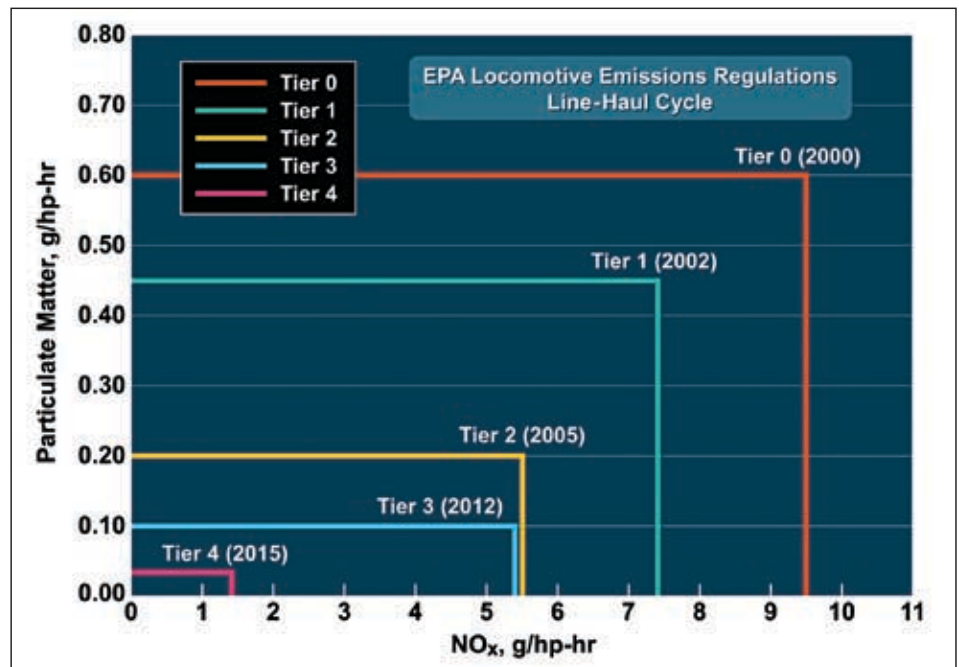
In addition to EPA regulation, the state of California actively promotes effective measures of reducing emissions within that state's nonattainment zones, or areas that do not meet the National Ambient Air Quality Standards (NAAQS), where emission reduction priorities are the highest. The desire for railroads to help meet California's air quality objectives, plus the approach of future EPA regulations, resulted in a demand from manufacturers for ultra-low emission locomotives. Although the number of ultra-low emission switcher locomotives has been increasing in recent years with the introduction of multiple gen-set switchers, the railroads had not yet had an ultra-low emission solution for medium horsepower locomotives operating in helper and short-haul services. Therefore, an opportunity exists to fill a market void with the introduction of an intermediate line-haul locomotive equipped with state-of-the-art selective catalytic reduction (SCR) aftertreatment, which has the potential to reduce NO<sub>x</sub> emissions by more than 80 percent below Tier 2 levels. In the coming months, a supplier of products to the North American rail industry will be delivering five locomotives that



D017460

meet future EPA Locomotive Tier 4 NO<sub>x</sub> emission requirements. This group of locomotives will operate in revenue service in California for the next year and will provide valuable field data and real-world experience with locomotive SCR aftertreatment that likely will become an integral part of future U.S. line-haul locomotives.

Southwest Research Institute (SwRI) combines a long history of working with the railroad industry and extensive experience in SCR technology and diesel locomotive exhaust emissions. Institute engineers have helped government and industry clients meet engine exhaust emission goals for many years. For this program, SwRI staff expertise and facilities were called on to assist with the aftertreatment development, implementation and validation for the ultra-low NO<sub>x</sub> emitting locomotive.



D017461

Tier 4 NO<sub>x</sub> and PM emission requirements, described by the red box at the extreme bottom left of this chart, are shown in this summary of the progression of PM and NO<sub>x</sub> EPA limits for line-haul locomotives operating in the U.S.

D017463



### Developing SCR controls in the laboratory

The SwRI team initiated the project in the summer of 2008 and immediately began work in the test cell. To establish an emissions starting point, SwRI engineers completed baseline engine-out testing for the locomotive engine, which was certified under applicable EPA Tier 2 locomotive requirements. The laboratory component exhaust aftertreatment system was then fitted to the test cell engine. This system first routes engine-out exhaust through a diesel oxidation catalyst to minimize the organic portion of PM and then routes the exhaust through the SCR portion of the system, where NO<sub>x</sub> is reduced.

Selective catalytic reduction (SCR) is a process that converts NO<sub>x</sub> emissions into the harmless products of water and diatomic nitrogen by introducing a reducing agent into engine exhaust in the presence of a catalytic surface. One efficient reducing agent for the NO<sub>x</sub> SCR process is ammonia (NH<sub>3</sub>). However, due to the hazards of storing and transporting ammonia, an aqueous solution of urea (NH<sub>2</sub>)<sub>2</sub>CO is typically used as a safe alternative. The urea solution is injected into the exhaust, where it is evaporated and mixed with the exhaust gas in front of a catalyst. The decomposition of urea in the exhaust stream and on the catalyst surface provides the ammonia necessary for NO<sub>x</sub> reduction to take place. Urea-based SCR has been

identified by many engine manufacturers as the technology of choice for meeting stringent NO<sub>x</sub> emissions regulations for diesel engines. This NO<sub>x</sub> emission control option also offers fuel savings over alternative options, balanced by the drawback of requiring a separate fluid delivery

and control system. Increases in system complexity are likely necessary at any rate, however, to meet future NO<sub>x</sub> locomotive emission regulations while maintaining acceptable fuel efficiency. Ideally, one molar quantity of ammonia (NH<sub>3</sub>) is required to completely reduce the same quantity of NO<sub>x</sub>. However, the urea decomposition process is difficult to model under all exhaust conditions, and different chemical process paths exist for the reduction of NO<sub>x</sub> with NH<sub>3</sub>, depending on exhaust and catalyst conditions. For these reasons the amount of urea injection necessary to reduce NO<sub>x</sub> down to target levels is often determined experimentally.

For the locomotive SCR, the amount of urea to be injected into the exhaust was empirically mapped in the laboratory over all locomotive operating points, such that NO<sub>x</sub> reduction was maximized while maintaining very low levels of ammonia slip, which is defined as any ammonia left over after the catalytic processes have taken place. A feed-forward control algorithm was then developed from the laboratory data and exhaust flow modeling. With this urea injection control strategy, the system was soon demonstrating 2015 Tier 4 locomotive NO<sub>x</sub> levels in the laboratory.

D017462



*The SCR exhaust aftertreatment equipment that was developed by the manufacturer and SwRI engineers was implemented in a locomotive engine.*



The SwRI Locomotive Technology Center, located near a commercial railyard in downtown San Antonio, provides the space and convenience needed to perform emissions collection and analysis on locomotives, such as PRLX3004 shown here, as they are brought in from line haul service.

The next task was to incorporate the NO<sub>x</sub> feedback control system. Post-SCR exhaust NO<sub>x</sub> concentration data feedback to the controller helped to fine-tune the SCR and adjust urea dosing for optimum SCR performance at any operating condition. This feature reduced NO<sub>x</sub> emissions even further and also lowered ammonia slip to near zero.

### Locomotive emissions reduction equipment installed

The SwRI team installed the first SCR in 2009 and performed locomotive emission testing at the SwRI Locomotive Technology Center (LTC) near downtown San Antonio. This facility was established in cooperation with the Association of American Railroads (AAR) in 1992. SwRI has performed more than 250 locomotive exhaust emission tests at the center in projects for EPA, the California Air Resources Board (CARB), locomotive manufacturers, engine component suppliers, the AAR, and individual railroads.

Emissions testing using the exhaust aftertreatment resulted in NO<sub>x</sub> levels below the 2015 Tier 4 limits. In addition, hydrocarbon (HC) and carbon monoxide (CO) emissions were a fraction of the Tier 4 emissions limits. The aftertreatment system was also effective in reducing PM emissions from the previous Tier 2 category to roughly one-half of the Tier 3 limit.

The locomotive was initially put into revenue service in June 2009, operating first locally between Kirby and South San Antonio, then between San Antonio and Fort Worth. Before leaving SwRI, it was instrumented with a data logging system to continually monitor and log parameters pertinent to SCR operation and locomotive use during revenue service. A Global Positioning System (GPS) receiver was also installed to monitor locomotive location, and a cellular phone package was used to remotely monitor and periodically download data via the Internet.

SwRI engineers monitored operations of the locomotive and SCR system and tracked its hours of operation. The locomotive worked its way back to SwRI for emissions tests after reaching 500 hours of revenue service, and it did so again at 1,000 hours of operation. Results from these tests, along with the revenue service data logging, showed that the locomotive so far is capable of meeting the high demands of line-haul locomotives while also sustaining Tier 4 levels of NO<sub>x</sub>, CO and HC and Tier 3 levels of PM.

In the fall of 2009, the second of the five SCR-equipped locomotives that are scheduled to operate in California was delivered to SwRI, where the aftertreatment equipment was installed and commissioned, and exhaust emission evaluations completed. This locomotive was likewise instrumented to track its usage, SCR performance and engine operation.

### In service in California

The two locomotives left Texas in January 2010, working their way to California pulling an intermodal freight train, and they are currently operating in revenue service in the Los Angeles basin of California. SwRI engineers will continue to monitor and report usage and performance data to CARB for one year. The second locomotive tested at SwRI is scheduled to return for repeat emission tests and inspections after six months of revenue service in California, and again after a year of revenue service.

Results from SwRI emissions testing of the two locomotives were provided to CARB to verify that any locomotive of this model can be recognized by the state of California as an ultra-low emission locomotive (ULEL), thereby qualifying for California incentive programs. This will

accelerate the introduction of these ultra-clean locomotives into service, displacing older, higher-emitting locomotives. ❖

Questions about this article? Contact Osborne at (210) 522-4243 or [dustin.osborne@swri.org](mailto:dustin.osborne@swri.org), or Sharp at (210) 522-2661 or [chris.sharp@swri.org](mailto:chris.sharp@swri.org).



An illustration of data logger tracking during early operation of the SCR equipped locomotive in San Antonio shows placemarks shaded according to the NO<sub>x</sub> reduction recorded at each point. Areas of little or no NO<sub>x</sub> reduction are due to exhaust temperatures being below the threshold of SCR activity.

### References

- "Class I Railroad Statistics," Association of American Railroads, September 10, 2009; online document available at [www.aar.org](http://www.aar.org)
- "EPA Locomotive Emission Standards: Regulatory Support Document," United States Environmental Protection Agency Office of Mobile Sources, April 1998, p96.
- "40 CFR Parts 9,85, et al., Control of Emissions of Air Pollution From Locomotive Engines and Marine Compression-Ignition Engines Less Than 30 Liters per Cylinder; Final Rule," Federal Register, Vol. 73, No.126, Monday, June 30, 2008, Rules and Regulations, p37097.