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EMISSION TEST REPORT

Vehicle/Engine:	**North Carolina Department of Transportation** **Locomotive No. 1859** **Equipped with Rail Propulsion Systems' BATS Aftertreatment System**
Test Sponsor:	**North Carolina Department of Transportation**
Supv. Engineer:	**C.S. Weaver**
Test Dates:	**June 28-29, 2021**
Date of this Report:	**August 4, 2021**

The North Carolina Department of Transportation (NCDOT) has contracted with Rail Propulsion Systems (RPS) to develop a selective catalytic reduction (SCR) emission control system suitable for NCDOT's fleet of passenger locomotives. The result of this project was the RPS blended after-treatment system (BATS), which is installed on NCDOT locomotive number 1859. With the locomotive's current operating hardware and standard EPA test procedures, the BATS reduces NOx emissions 90% and PM emissions 64% below the Tier 0+ standard to which the engine is certified. In addition, NOx emission are 45% below the Tier 4 standard and the PM emissions are 42% below the Tier 3 standard.

The locomotive was also tested with a manually controlled airbox bypass valve. When emissions were calculated with a duty cycle more realistic for passenger locomotives, the NOx emissions were compliant with CARB's proposed Tier 5 standard for locomotives. It was demonstrated that this modification would allow continuous operation at idle with better than Tier 5 NOx emissions.

Locomotive under test

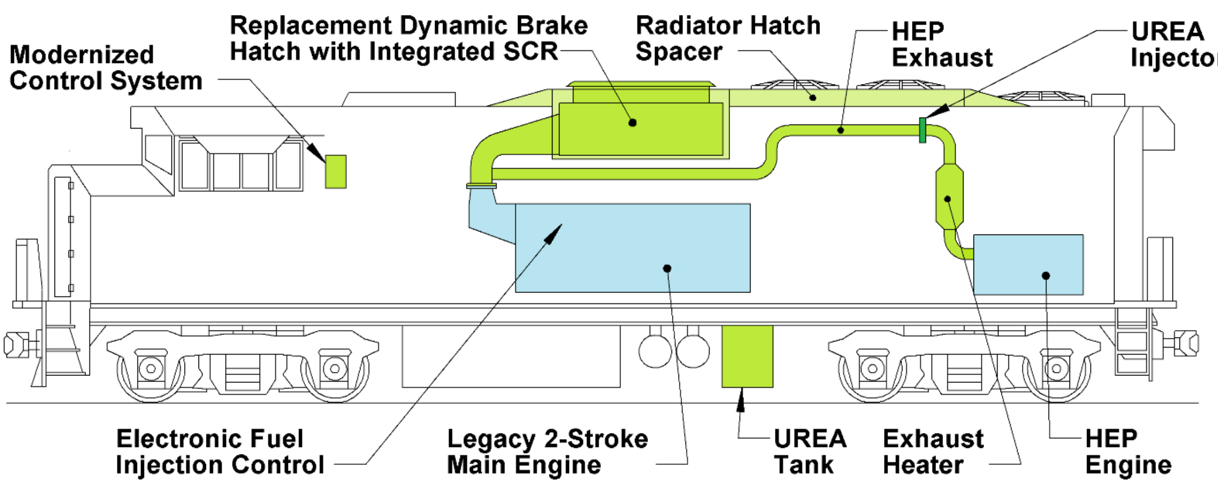
NCDOT 1859 is an EMD model F59 PH passenger locomotive manufactured in 1988. The main propulsion engine is an EMD 12-710E3B two-stroke diesel nominally rated at 3,000 tractive horsepower. The engine was remanufactured in 2011 with a kit certified to the EPA Tier 0+ emission standard using engine family number 9EMDKO710TMA. The certification emission results for that remanufacture kit are shown in Table 1.

Like many passenger locomotives, the EMD F59 PH is equipped with a separate diesel engine-generator set to provide electric power for heating, lighting, air conditioning and other "hotel" requirements in the passenger cars. In the case of NCDOT 1859, this head-end power (HEP) engine is a Caterpillar C18 certified to Tier 2 emission non-road emission standards. The HEP engine typically runs at moderate to high load whenever a passenger train is connected to the locomotive, even when the main propulsion engine is idling or turned off.

Emission control system

The BATS is diagrammed in Figure 1. The SCR catalyst is integrated into the dynamic brake hatch of the locomotive. The BATS applies SCR to the combined exhausts of the HEP engine and the locomotive's main propulsion engine; taking advantage of the higher temperature of the HEP engine exhaust to evaporate and decompose the diesel exhaust fluid (DEF) reductant and to raise the temperature of the SCR catalyst into the active zone, even when the exhaust from the main engine is too cold to do so. DEF is atomized into the HEP engine exhaust as it passes through an insulated, double-walled tube, so that the water is evaporated and the urea is substantially decomposed before the HEP exhaust mixes with the exhaust from the main engine. The combined exhaust then passes through the SCR catalyst before exhausting from the top of the locomotive.

Figure 1: Blended after-treatment system (BATS) for passenger locomotives



DEF flow to the exhaust is controlled by a programmable logic controller (PLC) driving a variable-speed volumetric metering pump. The flow rate is calculated from the estimated exhaust NOx flow rate, based on the measured power outputs of the main and HEP engines.

Emission results

Emission measurements were performed on the combined exhaust systems of the main and HEP engines. Testing was conducted with the BATS system operative in each of 11 locomotive operating modes: low idle, idle, dynamic brake, and throttle notches 1 through 8, as prescribed in 40 CFR 1033. HEP power was held substantially constant at 172 to 188 kW. Brake-specific emissions were calculated by dividing the weighted sum of hourly emissions in each mode by the weighted sum of the power output in each mode, as provided in 40 CFR 1033. Both the hourly emissions and the power output in each mode are the sum of the contributions of each of the two engines. Power output from each engine was measured separately, using an appropriate resistive load bank in each case. The engine was fueled with commercial California ultra-low sulfur diesel fuel from a local fuel supplier.

Two complete 11-mode emission tests were performed with the engine and BATS in normal operation. Table 1 compares the emission test results from this work with the certification data for the remanufactured engine, and with the Tier 4 emission standard. Compared to the baseline certification data, the BATS system reduced locomotive NOx emissions by 90 to 91%, and PM emissions by 62 to 65% in the line haul and 70 to 75% in the switch locomotive cycles. The resulting NOx emissions are well under the Tier 4 standard. The PM emissions are well below the Tier 3 standard, but exceed the Tier 4 standard by 0.02 to 0.03 g/BHP-hr.

Table 1: Summary of Emission Test Results

	Emissions g/BHP-hr				% Below Baseline	
	CO	THC	NOx	PM	NOx	PM
Line-Haul Locomotive Cycle						
Tier 4 Standard	1.50	0.14	1.30	0.03		
Tier 0+ Baseline	1.50	0.14	7.70	0.16		
Test 1	0.25	0.01	0.80	0.060	90%	62%
Test 2	0.17	0.02	0.67	0.057	91%	65%
Test 2 w bypass	0.24	0.02	0.43	0.057	94%	65%
Test 2 w hot DB	0.16	0.02	0.52	0.056	93%	65%
Test 2 w bypass and hot DB	0.23	0.02	0.28	0.056	96%	65%
Switch Locomotive Cycle						
Tier 4 Standard	1.50	0.14	1.30	0.03		
Tier 0+ Baseline	0.80	0.25	10.00	0.18		
Test 1	0.25	0.03	1.03	0.054	90%	70%
Test 2	0.13	0.04	0.95	0.045	91%	75%
Test 2 w bypass	0.35	0.04	0.19	0.046	98%	74%

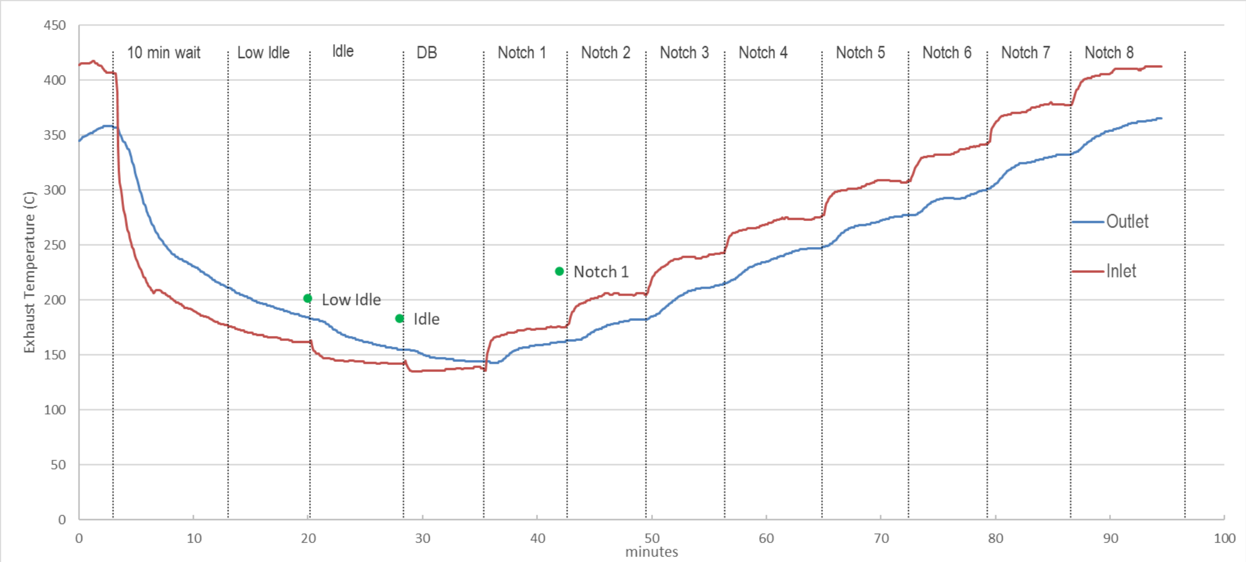
Exhaust temperature effects

Under low engine load (low idle, idle, dynamic brake and Notch 1 test modes), the main propulsion engine operates with a great deal of excess air, so that stabilized exhaust temperatures from the main engine are too low to support the SCR reaction. The situation is different under the 11-mode EPA test cycle, as the exhaust temperatures in the two idle modes do not have time to stabilize.

Figure 2 shows SCR catalyst inlet and outlet temperatures during a typical 11-mode test. The EPA test cycle begins with the engine and exhaust system warmed up to full operating temperature. The engine is then allowed to idle for 10 minutes before beginning emission measurements. Emissions are successively measured for five minutes each in low idle, idle, dynamic brake, and power Notches 1 through 7 before measuring for 10 minutes in Notch 8. (A maximum of five additional minutes are allowed for processing between test modes).

The BATS SCR catalyst has enough heat capacity that it remains fully active during the first, low idle test mode. That, with the low space velocity due to low exhaust volume, results in nearly 100% NOx conversion efficiency. The catalyst activity drops off rapidly during the idle mode, remains low in dynamic brake, and increases gradually during Notch 1 operation. Thus, NOx emissions in these modes are relatively high – accounting for 60 to 70% of the weighted NOx emissions during the 11-mode test.

Figure 2: SCR catalyst inlet and outlet temperature during 11-mode emission test



The placement of the dynamic brake test mode immediately after the idle modes in the EPA test procedure is not representative of passenger locomotive operation. Typically, locomotives accelerate at Notch 8 leaving each station, then slow for the next station using the dynamic brake. It would be more realistic, therefore, to place the dynamic brake test mode after Notch 8 in the test sequence. The effect of this change on modal emissions is shown in Table 2, and the effect on the 11-mode results is shown on the "hot DB" line in Table 1. Starting dynamic brake mode with the SCR catalyst at operating temperature reduced NOx emissions in that mode by 85%, and by 23% over the complete 11-mode test.

Table 2: Effect of blower bypass and sequencing of dynamic brake on modal emissions

	NOx (g/hr)		PM (g/hr)	
	Normal	**Bypass**	**Normal**	**Bypass**
Low Idle	34.1	16.0	13.7	9.9
Idle	774.4	5.4	19.3	20.6
Notch 1	1,012.9	6.4	15.9	24.6
	After idle	**After N8**	**After idle**	**After N8**
Dynamic Brake	1,217.6	183.9	16.3	11.8

Below Notch 6, the turbo-supercharger on the traction engine is mechanically driven by the engine gear train. The resulting air flow greatly exceeds the engine's requirements in idle and Notch 1. Venting some of the excess air from the airbox – thus bypassing the cylinders – raised the stabilized exhaust temperatures significantly, as shown by the green points in Figure 2. This and the lowered space velocity in the SCR catalyst greatly reduced NOx emissions. NOx emissions were reduced by 52% in low idle and by more than 99% in idle and Notch 1, resulting in a 36% reduction in NOx over the 11-mode test. Combining the airbox bypass with realistic test conditions during dynamic brake reduced 11-mode NOx emissions by 58%. With these changes, the BATS system gave a 96% reduction in NOx from the Tier 0 baseline.

With a fully functioning excess airbox bypass system, a BATS-equipped passenger locomotive could operate continuously at low idle with near-zero NOx emissions. This is in stark contrast to currently marketed Tier 4 locomotives, for which certification data show NOx emissions at idle through Notch 2 to be as much as 9 grams of NOx per BHP-hour – six times the Tier 4 NOx standard.

Passenger Locomotive Duty Cycles

Neither the EPA line-haul nor switch cycle much resembles passenger locomotive operation. We developed a more representative cycle from analysis of monitoring data on a Metrolink commuter locomotive. Table 3 compares this cycle based on actual passenger locomotive operations to the EPA-specified cycles. The commuter cycle includes even more idle time than the switch cycle, as locomotives are often left idling with the HEP engine running even when the train is not in service, in order to supply power to the passenger cars. Most of this idle time is for relatively long periods, so that the condition is mostly low idle. Passenger locomotives spend more time in high-load operation than do switchers, although not as much as the EPA line-haul cycle.

Table 4 shows the effect of reweighting the emission measurements for NCDOT 1859 according to the commuter locomotive schedule, compared to the line-haul schedule. This shows the importance of the idle modes in the overall emissions. At 0.20 g/BHP-hr, the commuter-weighted NOx emissions are consistent with the proposed Tier 5 standard that ARB is petitioning the EPA to incorporate into a revised locomotive emissions rulemaking.

Table 3: Comparison of EPA test cycles and typical passenger locomotive duty cycle

	Percent weighting		
Test Mode	EPA Line-haul	EPA Switch	Metrolink Commuter
Low Idle	19.0%	29.9%	61.8%
Hi Idle	19.0%	29.9%	10.0%
Dynamic Brake	12.5%	0.0%	6.1%
Notch 1	6.5%	12.4%	2.9%
Notch 2	6.5%	12.3%	1.6%
Notch 3	5.2%	5.8%	1.3%
Notch 4	4.4%	3.6%	3.8%
Notch 5	3.8%	3.6%	0.4%
Notch 6	3.9%	1.5%	1.3%
Notch 7	3.0%	0.2%	2.6%
Notch 8	16.2%	0.8%	8.3%

Table 4: NCDOT 1859 emissions reweighted to passenger locomotive duty cycles

	Emissions g/BHP-hr			
	CO	**THC**	**NOx**	**PM**
Metrolink Commuter Cycle				
Test 1	0.22	0.01	0.65	0.068
Test 3	0.13	0.02	0.53	0.055
Test 3 w bypass	0.24	0.02	0.33	0.051
Test 3 w hot DB	0.09	0.03	0.53	0.047
Test 3 w bypass and hot DB	0.26	0.03	0.20	0.043
Line-Haul Locomotive Cycle				
Test 1	0.25	0.01	0.80	0.060
Test 2	0.17	0.02	0.67	0.057
Test 2 w bypass	0.24	0.02	0.43	0.057
Test 2 w hot DB	0.16	0.02	0.52	0.056
Test 2 w bypass and hot DB	0.23	0.02	0.28	0.056