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Progress Rail PR30C-LoNOx Locomotive with DOC and Urea based SCR: 12-Month Field Demonstration and Emissions Testing at 0, 1500 and 3000 Hours of Operation

Prepared by

Dustin Osborne
Steven G. Fritz, P.E.

FINAL REPORT
PUBLIC DOMAIN

Prepared For

California Air Resources Board
Stationary Source Division
Criteria Pollutants Branch
1001 I Street, 6th Floor
Sacramento, CA 95812

May 2011

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The work reported in this document was performed for the California Air Resources Board and was split into two Phases. Phase 1 of the project, as outlined in SwRI proposal No. 03-51987A, included initial SCR installation and testing at SwRI, and was funded by CARB from an Ultramar/ARB Escrow Account # 1216999-000. Phase 2, funded under CARB contract 07-410, covered one year of tracking SCR system performance during subsequent revenue service operation of the PR30C locomotive in California. The Phase 2 contract between SwRI and CARB was defined under SwRI Proposal 03-51899 and SwRI Project 03.14368.

This project was performed by the Department of Emissions Research and Development within the Engine, Emissions, and Vehicle Research Division under the supervision of Mr. Jeff White. The Project Manager for SwRI was Mr. Steven G. Fritz, manager of medium speed diesel engines in the Department of Emissions Research and Development. The CARB technical contact for this project was Mr. Michael Jaczola, Staff Air Pollution Specialist.

The test locomotive for this project was provided by Progress Rail Services, a Caterpillar company. Caterpillar support for aftertreatment installation and commissioning at SwRI was provided by Mr. Douglas Biagini, Mr. Geary Smith, and Mr. David Stoor.

Union Pacific Railroad Company helped make this project possible by providing a year of revenue service work for the locomotive demonstration. UPRR included the Progress Rail test locomotive in its working fleet from November of 2009 through October of 2010.

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LIST OF ABBREVIATIONS

AESS	Automatic Engine Start/Stop
ASTM	American Society for Testing and Materials
BSFC	Brake Specific Fuel Consumption
CAN	Controller Area Network
CARB	California Air Resources Board
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DEF	Diesel exhaust fluid
DOC	Diesel Oxidation Catalyst
ECM	Engine Control Module
EPA	Environmental Protection Agency
FTIR	Fourier Transform Infrared Spectrometer
FTP	Federal Test Procedure
HC	Hydrocarbons
HCLD	Heated chemiluminescent detector
HFID	Heated Flame Ionization Detector
HP	Horsepower
LFE	Laminar flow element
LTC	Locomotive Technology Center
NDIR	Non-dispersive infrared
NH_3	Ammonia
NO	Nitrogen Oxide
NO_x	Oxides of Nitrogen
NO_2	Nitrogen Dioxide
O_2	Oxygen
PHS	Public Health Service
PM	Particulate Matter
PPM	Parts per million
SCFM	Standard cubic feet per minute
SCR	Selective Catalytic Reduction
SwRI®	Southwest Research Institute®
ULSD	Ultra Low Sulfur Diesel
UPRR	Union Pacific Railroad Company

EXECUTIVE SUMMARY

Progress Rail, a Caterpillar company, recently unveiled their new 3,005 horsepower intermediate line-haul PR30C-LoNOx locomotive equipped with selective catalyst reduction (SCR) and diesel oxidation catalyst (DOC) aftertreatment. Progress Rail provided Union Pacific Railroad Company (UPRR) with five such locomotives for a one-year demonstration. California Air Resources Board (CARB) provided funding for the testing and evaluation of one of these LoNOx locomotives, road number PRLX3004, to investigate the feasibility of combining an advanced engine repower with an aftertreatment system on a medium horsepower freight line-haul locomotive.

Phase 1 of the CARB funded program was conducted at the Southwest Research Institute (SwRI) Locomotive Technology Center, and included engine-out baseline emissions testing, aftertreatment installation, commissioning and aftertreatment degreening, 0-hour aftertreatment emissions testing, and data logging equipment installation. Phase 2 of the program consisted of monitoring and reporting in service operation of the LoNOx locomotive PRLX3004 during a 12-month demonstration while it worked in the UPRR system, as well as performing additional emissions tests at the mid-point and end-point of the demonstration. A summary of the average values for emission test results for both phases are given in Table ES-1.

Triplicate emission tests were run to establish emissions for the engine-out baseline configuration of PRLX3004. Without the aftertreatment, the locomotive produced emission levels within Tier 2 EPA locomotive limits. The aftertreatment system was installed and 40 hours of rated power operation were used to degreen the aftertreatment system. This degreened condition was identified as the 0-hour point for the LoNOx configuration. Triplicate tests at the 0-hour point with degreened aftertreatment indicated a reduction in oxides of nitrogen (NO_x) of 80 percent over the line-haul cycle, and 59 percent over the switcher cycle, as compared to the baseline values. During this test program, ammonia slip volume concentration at the exhaust stack ranged from zero to five parts per million (ppm).

The aftertreatment provided a total hydrocarbon (HC) reduction from baseline of 93 percent over the line-haul cycle and 94 percent over the switcher cycle, and a carbon monoxide (CO) reduction of 72 percent over the line-haul cycle and 81 percent over the switcher cycle. The particulate matter (PM) reduction from baseline at the 0-hour testing was 43 percent over the line-haul cycle and 64 percent over the switcher cycle. Emission test results for the 0-hour PR30C-LoNOx configuration achieved Tier 4 line-haul NO_x, CO, HC, and smoke emission levels, as well as Tier 3 PM levels. With completion of 0-hour testing of PRLX3004 in the PR30C-LoNOx configuration, the locomotive was released to begin Phase 2, the field demonstration period.

Phase 2 of the CARB funded program (CARB contract NO. 07-410) started in December 2009 when the locomotive was released from SwRI to UPRR for revenue service. Throughout the field demonstration, SwRI provided weekly updates of in use operation and performance data of locomotive PRLX3004 in the PR30C-LoNOx configuration. The locomotive was worked back to San Antonio for emissions testing in March of 2010 after accumulating approximately 1,500 hours of operation, and again in November after accumulating approximately 3,000 hours of operation. For the 1,500 and 3,000-hour test points, emission results were similar to those of the 0-hour point. HC, CO, and NO_x remained below Tier 4 limits, and PM remained below Tier

3 limits. CO emissions were slightly lower for the 1,500-hour and 3,000-hour points as compared to the 0-hour point, and the HC cycle composite values increased slightly from the 0-hour point. Test results indicated a small decrease in PM emissions at the 1,500-hour point, and again at the 3,000-hour point.

Results from this project indicate that the PR30C-LoNOx locomotive has demonstrated the ability to operate within a Class 1 railroad and maintain Tier 4 NO_x, HC, and CO emissions, as well as Tier 3 PM emissions over the course of a 12-month in-service field demonstration, during which PRLX3004 accumulated a total of 3,082 hours of engine operation.

TABLE ES-1. SUMMARY OF SWRI EMISSON TEST RESULTS FOR PROGRESS RAIL PR30C LOCOMOTIVE PRLX3004 IN BASELINE AND LONOX CONFIGURATIONS

	Locomotive Line-haul Cycle Composite Emissions				Locomotive Switcher Cycle Composite Emissions				Smoke Opacity		
	HC	CO	Corr. NO_x	PM	HC	CO	Corr. NO_x	PM	Max SS	30 Sec	3 Sec
Test Description	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	percent opacity	percent opacity	percent opacity
Tier 2 Limits	0.30	1.5	5.5	0.20	0.60	2.4	8.1	0.24	20	40	50
Tier 3 Limits	0.30	1.5	5.5	0.10	0.60	2.4	5.0	0.10	20	40	50
Tier 4 Limits	0.14	1.5	1.3	0.03	NA	NA	NA	NA	20	40	50
Baseline Average	0.26	0.7	4.8	0.09	0.45	1.1	5.2	0.16	7	8	22
0-hour Average	0.02	0.2	0.9	0.05	0.03	0.2	2.2	0.06	4	5	13
1,500-hour Average	0.02	0.2	0.9	0.05	0.03	0.1	2.2	0.05	3	4	7
3,000-hour Average	0.02	0.1	0.9	0.04	0.03	0.1	2.1	0.04	3	4	5

1.0 INTRODUCTION AND BACKGROUND

Progress Rail Services, a Caterpillar subsidiary, recently developed a new model locomotive for intermediate line-haul applications. The model PR30C-LoNOx locomotive was designed to achieve EPA Tier 4 Line-haul locomotive NO_x levels that will be required for new locomotives in the United States starting in 2015. The 3,005 horsepower PR30C, six-axle locomotive is an EMD SD40-2 chassis originally manufactured in the 1970's, but repowered with a Tier 2 Caterpillar 3516C-HD diesel engine. When the engine is equipped with a Caterpillar developed advanced exhaust aftertreatment system that includes urea based selective catalytic reduction (SCR) technology, as well as diesel oxidation catalyst (DOC) technology, the unit is designated PR30C-LoNOx.

Progress Rail Services supplied Union Pacific Railroad (UPRR) with a set of five PR30c-LoNOx locomotives for a 12-month field evaluation period. As part of a research initiative to determine the feasibility of combining an advanced engine repower with an aftertreatment system to meet Tier 4 requirements on a medium horsepower freight line-haul locomotive, California Air Resources Board (CARB) funded emissions testing and remote monitoring for one of the locomotives during the evaluation period. Locomotive road number PRLX3004 was selected for the CARB funded testing and remote monitoring.

Phase 1 of the project was conducted at the Southwest Research Institute (SwRI) Locomotive Technology Center, and included the baseline emissions testing, aftertreatment installation and commissioning, 0-hour emissions testing, and data-logging equipment installation. Phase 2 of the project started when locomotive PRLX3004 was released to the Union Pacific Railroad Company (UPRR) for revenue service, and included remote monitoring of the locomotive during the field demonstration, emissions testing after 1,500 hours of engine operation, and again after 3,000 hours of engine operation.

This report documents the results of both Phase 1 and Phase 2 of this CARB funded project. The report includes a description of the LoNOx test locomotive PRLX3004, baseline exhaust emission test results, aftertreatment system installation, exhaust emission test results for the 0-hour, 1,500-hour, and 3,000-hour test points, and a summary of the remote monitoring of PRLX3004 during the field demonstration.

2.0 TECHNICAL APPROACH

SwRI performed locomotive exhaust emission tests using the Federal Test Procedure (FTP) for locomotives, as detailed in Subpart B of 40CFR92, 40CFR1033, and 40CFR1065. In accordance with the FTP, emissions of hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), oxides of nitrogen (NO_X), and particulate matter (PM) were measured at each throttle notch setting.

2.1 Test Locomotive

The locomotive used for this work was a Progress Rail model PR30C-LoNOx locomotive provided by Progress Rail Services with road number PRLX3004, and is shown in Figure 1. This was one of five 3,005 horsepower, six-axle, intermediate line-haul locomotives that were manufactured by Progress Rail Services for product evaluation by UPRR. The locomotive is an EMD SD40-2 locomotive chassis repowered with a 3,005 horsepower, Caterpillar, 3516C-HD engine. Engine details are listed in Table 1. At the time of baseline testing, the engine had accumulated approximately 500 hours of operation.

FIGURE 1. PR30C-LONOX TEST LOCOMOTIVE

TABLE 1. LOCOMOTIVE AND ENGINE SPECIFICATIONS

Locomotive Number	PRLX3004
Locomotive Model	PR30c
Engine Model	Caterpillar 3516C-HD
Engine Serial No.	SDX00101
Rated Brake Power	3,005 hp
Cylinder arrangement	60° V-16
Bore	170 mm
Stroke	215 mm
Displacement/Cylinder	4.88 L
Rated engine speed	1,800 rpm

2.2 Aftertreatment

For the LoNOx configuration, the engine was equipped with a Caterpillar patent pending advanced aftertreatment emission control system. SwRI installed the aftertreatment system - shipped separately, after performing engine-out baseline emissions testing. The Caterpillar locomotive aftertreatment system consisted of three major components: the diesel exhaust fluid (DEF) tank, the dosing cabinet, and the reactor. Figure 2 shows the location of these components on the locomotive. DEF is an aqueous solution of 32.5 percent urea by weight, and is the NO_x reducing agent used by the aftertreatment system.

A diagram of the reactor is shown in Figure 3. The reactor fits on the locomotive such that the two engine exhaust outlets enter the reactor as separate exhaust streams and are directed through separate DOC elements. The two exhaust gas streams are then redirected to the center of the reactor and combined into one stream. Swirl and turbulence are added to the exhaust stream by mixer vanes just before the DEF is injected into the center of the exhaust stream from an air assisted nozzle. The mixture of exhaust gas and DEF travels through the mixing tube before the stream is divided in two and sent through separate SCR catalyst banks. The outlet of each SCR bank serves as the final exhaust outlet to atmosphere.

A combination of feed forward and feedback algorithms control DEF injection to maintain target NO_x reductions while minimizing ammonia slip. The SCR control system uses a total of three NO_x sensors: one positioned just upstream of the DEF injector to measure SCR inlet NO_x, and two that measure SCR outlet NO_x and are positioned at each of the two SCR bank outlets.

The dosing cabinet, shown in Figure 4, contains the SCR controller, the DEF dosing pump, and the DEF dosing manifold. These components supply and control the flow of DEF and compressed air to the DEF injector. Supply and return lines are routed from the dosing cabinet to the DEF tank, and DEF and compressed air supply lines are routed from the dosing cabinet to the injector.

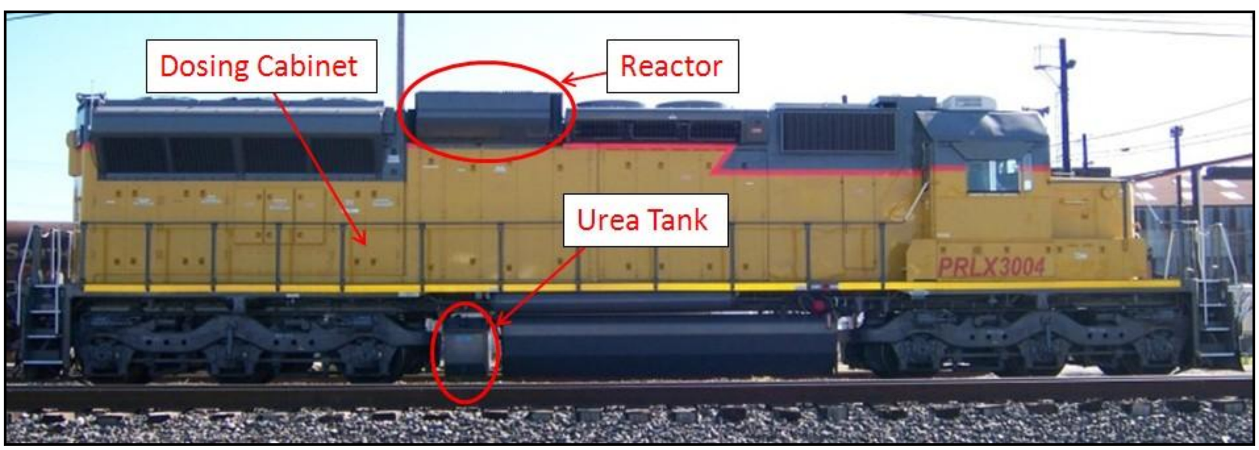


FIGURE 2. LOCATION OF AFTERTREATMENT SYSTEM COMPONENTS

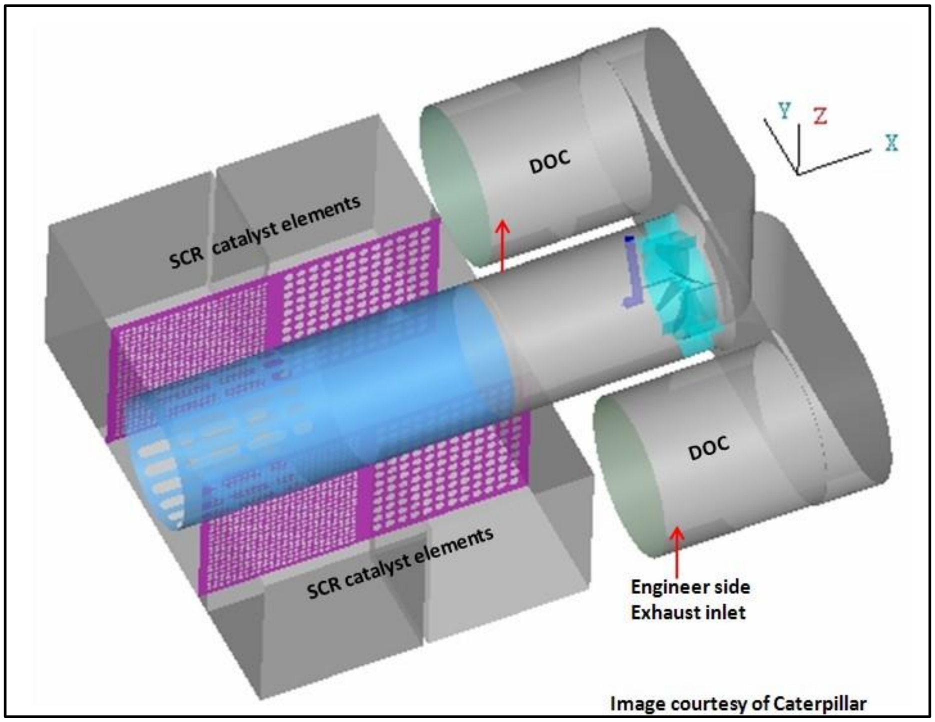


FIGURE 3. DIAGRAM OF AFTERTREATMENT REACTOR

FIGURE 4. SCR DOSING CABINET

2.3 Power Measurements

Most locomotives are equipped with a "dynamic brake" feature in which the electric motors used for traction are reverse-excited to become generators for slowing the train. The electric power generated is dissipated in resistance grids. Locomotives with the self-load feature can also dissipate the main alternator power into these "dynamic brake" resistance grids.

Although PRLX3004 was equipped with dynamic brake grids, an external resistive load grid was used to load the stationary locomotive during testing.

Locomotive electric power was determined by direct measurement of the main alternator voltage and current, plus auxiliary power measurements made from a watt meter. The efficiencies of the main alternator, rectifier, and companion alternator for each operating point were provided by Caterpillar, and used for calculation of shaft power at the flywheel, or engine brake power.

2.4 Test Fuel and Fuel Consumption Measurements

Properties of each test fuel are listed in Table 2 along with the EPA test fuel specifications and ASTM test methods. All emission tests were performed using an Ultra Low Sulfur Diesel (ULSD) containing a sulfur concentration less than or equal to 15 parts per million (ppm) and meeting EPA certification fuel specifications.

Diesel fuel consumption was measured on a mass flow basis, using a Micro Motion® mass flow meter. The system was equipped with a heat exchanger to control fuel supply temperature. Hot return fuel which would normally return to the locomotive fuel tank was cooled before returning to the fuel measurement reservoir ("make-up tank") to ensure a consistent fuel supply temperature at the engine.

TABLE 2. TEST FUEL PROPERTIES

Determinations	ASTM Test Method	Baseline and 0-hour Fuel EM-3137N-F	1500-hour Fuel EM-3137O-F	3000-hour Fuel EM-3137Q-F	EPA Loco. Cert. Diesel Spec.
API Gravity @ 15°C Specific gravity Density (gram/L)	D4052	33.9 0.8555 855	34.4 0.8529 852	35.7 0.8463 846	32 – 37 NS NS
Viscosity @ 40°C (cSt)	D445	2.745	2.522	2.488	2.0 - 3.2
Sulfur (ppm)	D5453	10.7	14.0	12.4	Depends on Tier Level
Cetane Number	D976	44.9	44.7	46.4	40 – 48
Cetane Index	D4737	44.2	43.9	46.4	NS
Heat of Combustion Gross (MJ/kg) Net (MJ/kg)	D240	45.444 42.673	45.442 42.694	45.460 42.646	NS NS
Carbon-Hydrogen Ratio % Carbon % Hydrogen Hydrogen/Carbon Ratio	D5291	87.05 13.06 1.79	86.89 12.95 1.78	86.86 13.26 1.82	NS NS NS
SFC Aromatics Total Mass % Total Volume % [a] PNA Mass %	D5186	29.2 28.1 4.9	30.5 29.3 4.6	29.3 28.2 5.2	27 min
Hydrocarbon by FIA (volume %) Aromatics Olefins Saturates	D1319	32.8 1.7 65.5	33.6 1.6 64.8	29.7 2.9 67.4	
Distillation, °C (Pressure Corrected)	D86 IBP 10% 50% 90% FBP	187 214 264 318 342	185 211 259 311 336	185 214 257 313 341	171 – 204 204 – 238 243 – 285 293 – 332 321 – 366

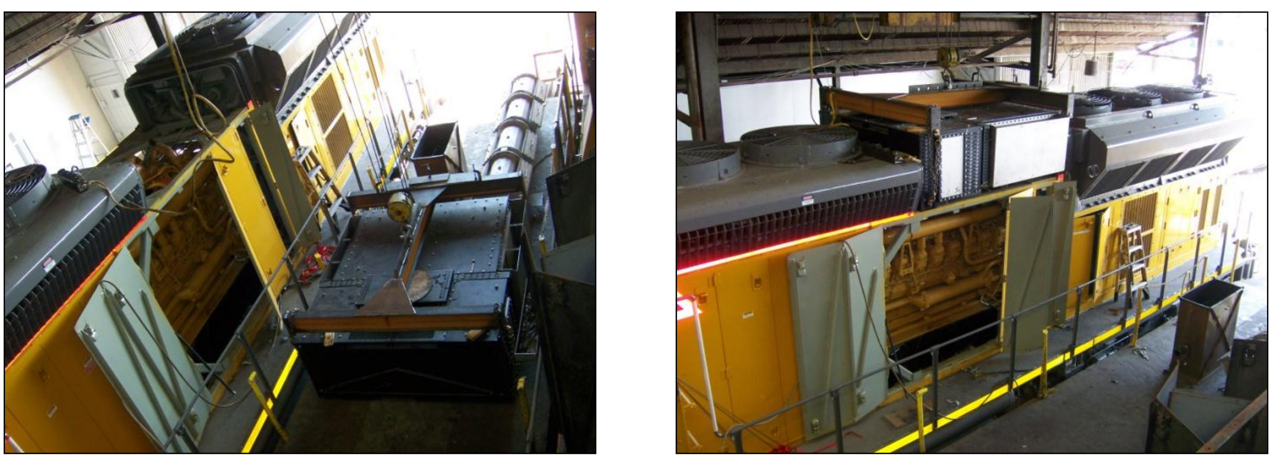
Notes:
[a] – Aromatic hydrocarbons expressed in percent volume = 0.916 x (aromatic hydrocarbons expressed in percent weight) + 1.33, per California Code of Regulations, Title 13, §2282 (c)(1).
NS – not specified

2.5 Exhaust Emissions Test Procedure

PRLX3004 arrived at the SwRI Locomotive Technology Center in August of 2009 without the aftertreatment installed. The exhaust and crankcase ventilation were routed into a conventional style locomotive exhaust stack. The conventional stack allowed for the standard SwRI locomotive exhaust stack extension to be used for baseline emissions testing in the engine-out configuration. Figure 5 shows the setup for baseline testing. Triplicate FTP's were completed with the locomotive in the baseline configuration.

FIGURE 5. BASELINE TEST SETUP

After baseline testing was completed, the existing exhaust outlet and muffler were removed from the locomotive and the exhaust aftertreatment was installed. The installation process was completed in one week and consisted of the following tasks: mounting the aftertreatment reactor above the engine (shown in Figure 6), installing instrumentation and wiring for the SCR controls and communications network, installing DEF and compressed air plumbing, and reworking the crankcase ventilation routing to exit into the post-SCR exhaust.



a. reactor about to be lifted into position **b. reactor placed in position above engine**

FIGURE 6. MOUNTING THE AFTERTREATMENT REACTOR ON PRLX3004

After installing the aftertreatment, the locomotive was moved to the test station, where the aftertreatment catalysts were degreened by operating the locomotive with ULSD fuel at rated power for approximately 40 hours. During this time the SCR was not operating because it was not necessary to dose DEF during catalyst degreening. Exhaust backpressure and exhaust temperature at various locations were recorded continuously at a rate of one Hertz during the degreening process.

After degreening, the DEF dosing control system was commissioned under the guidance of on-site Caterpillar personnel. Emission testing instrumentation was then installed. A custom exhaust collector was used to combine the two exhaust outlets into one to allow sampling the total exhaust from a single exhaust stream. Figure 7 shows the PRLX3004 test set-up for emissions testing in the LoNOx configuration (with aftertreatment).

A preliminary test was completed to verify correct operation of the system and to identify correct gaseous analyzer ranges at each test mode. Triplicate FTP's were performed to establish 0-hour emissions. Triplicate FTP's were also performed after approximately 1,500 hours of engine operation were accumulated while in revenue service, and again after approximately 3,000 hours of revenue service engine operation.

FIGURE 7. TEST SETUP FOR PRLX3004 WITH AFTERTREATMENT

2.5.1 Gaseous Emissions Sampling

Gaseous emissions were sampled from within an exhaust stack extension. A heated line was used to transfer the raw exhaust sample to the emission instruments for analysis. Measured gaseous emissions included hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and oxides of nitrogen (NO_X). Steady-state measurements were taken for each discrete mode listed in the EPA locomotive duty cycles.

Hydrocarbon concentrations in the raw exhaust were determined using a California Analytical Instruments Model 300 heated flame ionization detector (HFID), calibrated on propane. NO_X concentration in the raw exhaust was measured with a California Analytical Instruments Model 400 heated chemiluminescent detector (HCLD). NO_X correction factors for ambient air humidity were applied as specified by EPA in 40CFR1065.670. Concentrations of CO and CO_2 in the raw exhaust were determined by non-dispersive infrared (NDIR) instruments made by Horiba, and O_2 concentrations were measured using a Horiba magneto-pneumatic analyzer.

Gaseous mass emission rates were computed using the measured concentration, the observed (measured) fuel consumption rate, and calculated engine airflow. Following the FTP, engine airflow was not directly measured in this test program. Instead, engine airflow was determined using a carbon balance of the carbon-containing constituents in the exhaust (CO_2, CO, and HC) to compute the fuel/air ratio (f/a). Engine airflow rate was then computed using the measured fuel consumption rate and the computed f/a ratio.

2.5.2 SCR Specific Measurements

Post SCR ammonia (NH_3) "slip" in the exhaust was measured using a Thermo Fisher Nicolet 6700 FTIR analyzer. Raw exhaust was sampled from a multi-hole gaseous emissions probe and drawn through a heated sample line to the FTIR analyzer at a target flow rate of 10 liters per minute. Diesel exhaust fluid (DEF) injection rate was measured on a mass flow basis using a micro-motion mass flow meter in line with the injector supply.

2.5.3 Particulate Emissions Sampling

Particulate emissions were measured at each test point with a Sierra Instruments BG-3 Particulate Partial-Flow Sampling System. This "mini-dilution tunnel" device employs a partial flow dilution technique that can be characterized as the "split then dilute" technique, in which a portion of the raw locomotive exhaust is "split" from the total flow and mixed with filtered air in a very small dilution tunnel.

The Sierra BG-3 sampling system used a single ended probe facing upstream in the exhaust to extract a fraction of the raw exhaust. Approximately three inches after the probe terminates, the raw exhaust sample was diluted in a Sierra patented radial inflow dilution tunnel. The diluted exhaust sample was then transferred from the proximity of the locomotive exhaust stack down to near ground level through a 17 foot, one-half inch diameter, stainless steel transfer tube heated to 47°C. The diluted exhaust was then pulled through a Sierra Heat-Pak before being routed through a single 47 mm diameter TX40 sample filter. The Sierra Heat-Pak is a heated enclosure (target temperature of 47°C) that contains a stainless steel cyclonic separator and a residence chamber. This is an optional BG-3 accessory offered by Sierra Instruments as a tool for sampling under 40CFR1065 criteria. The BG-3 measured the dilution air flow using a laminar flow element (LFE), and the total dilute sample was measured by a positive displacement roots meter. The difference between the two measurements is defined as the raw exhaust sample volume, which was used along with the filter mass increase and the calculated engine exhaust flow rate to calculate the PM mass emission rate of the locomotive.

2.5.4 Smoke Opacity

Smoke opacity was measured using a modified Public Health Service (PHS) full-flow opacity meter (smokemeter) mounted above the locomotive exhaust stack. This smokemeter uses standard PHS smokemeter optics and electronics, but was modified to a 40-inch diameter to accommodate larger exhaust plume diameters. The construction, calibration, and operation of the smokemeter adhere to the FTP.

The smokemeter through-exhaust path length was approximately one meter (as determined by the dimensions of the exhaust stack extension). The center of the light beam is positioned 125±25 mm away from the outlet of the exhaust collector. Using the smokemeter control unit, a voltage output proportional to opacity was recorded. Smoke opacity was continuously monitored and recorded during the EPA Locomotive Test Sequence.

2.5.5 Duty Cycle Weighting Factors

For locomotives with a single idle speed, there are ten discrete modes within the locomotive FTP. For each mode, the engine is controlled to a manufacturer specified combination of target engine speed and power. The operating points consist of a no-load idling condition, a dynamic brake condition, and eight power notches that range from low to rated power. During emissions testing, the operator commands the required mode by adjusting the locomotive throttle notch setting. To obtain the weighted composite emissions results that represent a specified duty-cycle, an assigned statistical weight is applied to each individual steady-state discrete mode emission determination and then summed over all the modes. The two duty cycles and composite weightings used for EPA locomotive testing are given in Table 3 (Table B132-1 of 40CFR92.131).

TABLE 3. LOCOMOTIVE DUTY CYCLES

Throttle Notch Setting	EPA Line-Haul Cycle Weighting, Percent	EPA Switcher Cycle Weighting, Percent
Idle	38.0	59.8
Dynamic Brake	12.5	0.0
Notch 1	6.5	12.4
Notch 2	6.5	12.3
Notch 3	5.2	5.8
Notch 4	4.4	3.6
Notch 5	3.8	3.6
Notch 6	3.9	1.5
Notch 7	3.0	0.2
Notch 8	16.2	0.8
TOTAL	100.0	100.0

2.5.6 Diesel Exhaust Fluid

The DEF used during testing for this project was produced by Colonial Chemical Company, and was called C-Blue™. C-Blue is reported by Colonial Chemical Company to meet ISO 22241 specifications, which are given in Table 4. Physical properties of C-Blue are given in Table 5. C-Blue was supplied in 350 gallon totes and was dispensed into the locomotive 250 gallon on-board tank. The DEF urea concentration was verified to be within the specification limits before aftertreatment emissions testing. This was completed using a Misco handheld refractometer calibrated for urea concentration in water.

TABLE 4. ISO 22241 SPECIFICATIONS FOR DIESEL EXHAUST FLUID

Characteristic	Unit	Limits	
		Min.	Max.
Urea content	% (m/m)	31.8	33.2
Density at 20°C	kg/m^3	1087.0	1093.0
Refractive index at 20°C	--	1381.4	1384.3
Alkalinity as NH_3	% (m/m)	--	0.2
Biuret	% (m/m)	--	0.3
Aldehydes	mg/kg	--	5
Insoluble matter	mg/kg	--	20
Phosphate (PO_4)	mg/kg	--	0.5
Calcium	mg/kg	--	0.5
Iron	mg/kg	--	0.5
Copper	mg/kg	--	0.2
Zinc	mg/kg	--	0.2
Chromium	mg/kg	--	0.2
Nickel	mg/kg	--	0.2
Aluminum	mg/kg	--	0.5
Magnesium	mg/kg	--	0.5
Sodium	mg/kg	--	0.5
Potassium	mg/kg	--	0.5

TABLE 5. PHYSICAL PROPERTIES OF C-BLUE DIESEL EXHAUST FLUID

Characteristic	Specification
Appearance	Clear liquid
pH value	7-9
Specific Gravity	1.09 @ 15°C
Water Solubility	Soluble
Crystallization Point	-11°C (12°F)

3.0 BASELINE AND SCR 0-HOUR TEST RESULTS

This section includes the results from the SwRI locomotive FTP exhaust emissions testing for the engine-out baseline configuration, and for the initial testing of the locomotive equipped with the Caterpillar aftertreatment.

The EPA weighted composite results for PRLX3004 in the engine-out baseline configuration are displayed in Table 6 for the three baseline emission tests. Also included in the table are the average composite emission values from the three tests. Baseline testing of PRLX3004 showed that the locomotive was within Tier 2 emissions criteria at the start of this program.

TABLE 6. BASELINE PRLX3004 LOCOMOTIVE DUTY CYCLE COMPOSITE EMISSIONS

Test Description	EPA Line-haul Cycle Emissions, g/hp-hr				EPA Switcher Cycle Emissions, g/hp-hr			
	HC	CO	NO_x	PM	HC	CO	NO_x	PM
Tier 2 Limits	0.30	1.5	5.5	0.20	0.60	2.4	8.1	0.24
Baseline 1	0.26	0.7	4.9	0.08	0.46	1.0	5.3	0.15
Baseline 2	0.25	0.7	4.8	0.09	0.45	1.1	5.2	0.16
Baseline 3	0.25	0.7	4.8	0.09	0.45	1.0	5.2	0.17
Average	**0.26**	**0.7**	**4.8**	**0.09**	**0.45**	**1.1**	**5.2**	**0.16**
Std. Deviation	0.004	0.012	0.068	0.003	0.004	0.022	0.047	0.009

The initial testing of PRLX3004 with aftertreatment installed is referred to in this discussion as the "0-hour" test point. The 0-hour testing was performed immediately after degreening the catalyst for 40 hours at Notch-8 operation, and prior to any revenue service hour accumulation. The 0-hour test results, displayed in Table 7, show that the aftertreatment yielded NO_x emissions that were below the EPA Tier 4 line-haul locomotive standard that will be required for new locomotives starting in 2015. Composite HC and CO emissions were well below the Tier 4 limits, and PM was approximately half of the EPA Tier 3 limits that will go into effect in 2012. All of the regulated emissions were significantly reduced with the aftertreatment. Over the line-haul cycle, composite HC was reduced by an average of 93 percent, CO by 72 percent, NO_x by 80 percent, and PM was reduced by 43 percent. Over the switcher cycle, composite HC was reduced by 94 percent, CO by 81 percent, NO_x by 59 percent, and PM by 64 percent.

TABLE 7. LOCOMOTIVE COMPOSITE EMISSIONS FOR PRLX3004 WITH AFTERTREATMENT AT 0-HOUR TEST POINT

Test Description	EPA Line-haul Cycle Emissions, g/hp-hr				EPA Switcher Cycle Emissions, g/hp-hr			
	HC	CO	NO_x	PM	HC	CO	NO_x	PM
Tier 3 Line-Haul Locomotive Limits [a]	0.30	1.5	5.5	0.10	0.60	2.4	8.1	0.13
Tier 4 Line-Haul Locomotive Limits	0.14	1.5	1.3	0.03	NA	NA	NA	NA
0-hour Run 1	0.02	0.2	1.0	0.06	0.03	0.2	2.1	0.06
0-hour Run 2	0.02	0.2	1.0	0.05	0.03	0.2	2.2	0.05
0-hour Run 3	0.02	0.2	0.9	0.05	0.03	0.2	2.2	0.05
Average	**0.02**	**0.2**	**0.9**	**0.05**	**0.03**	**0.2**	**2.2**	**0.06**
Std. Deviation	0.001	0.005	0.009	0.007	0.001	0.009	0.042	0.005
Avg. Reduction from Baseline	**93%**	**72%**	**80%**	**43%**	**94%**	**81%**	**59%**	**64%**

[a] Tier 3 Line-Haul locomotives must also meet Tier 2 switcher standards.

Smoke test results for both baseline and 0-hour testing of PRLX3004 are listed in Table 8, along with the U.S. EPA maximum values. Smoke levels were well below EPA limits for all of the testing of PRLX3004. In general, PRLX3004 smoke levels were reduced with the addition of the aftertreatment, and a significant reduction in 3-second smoke was measured during 0-hour testing as compared to baseline testing.

TABLE 8. SMOKE TEST SUMMARY FOR BASELINE AND 0-HOUR PRLX3004 TESTING

Test Description	Maximum Steady-State Smoke, Percent Opacity	30-Second Peak, Percent Opacity	3-Sec. Peak, Percent Opacity
EPA Tier 2,3 Max	20	40	50
Baseline 1	7	8	22
Baseline 2	8	9	23
Baseline 3	7	7	22
Baseline Average	**7**	**8**	**22**
0-hour Run 1	4	6	10
0-hour Run 2	4	4	14
0-hour Run 3	5	5	13
0-hour Average	**4**	**5**	**13**

HC and CO emission rates were reduced at all notches with the aftertreatment installed, suggesting that the oxidation catalyst was active even during low load modes and idle when exhaust temperatures were relatively low. Following the locomotive FTP test sequence, the engine was warmed up at Notch 8 for six minutes prior to starting the idle mode. It is likely that the catalyst retained sufficient heat from the test warm-up for oxidation to occur throughout the low notches of the test.

The SCR controller is programmed to inject DEF only when exhaust temperatures are sufficient for complete urea decomposition to occur within the SCR mixing tube. The temperature threshold used for the SCR system is reached at the Notch 2 throttle setting. The effect of the DEF dosing temperature threshold is evident in Notch 2 which was the first test mode with a significant NO_x reduction from baseline values. At this and every following test mode, a reduction in NO_x mass flow from baseline of at least 85 percent was recorded.

The DOC was effective at reducing the soluble organic portion of PM, which consists of unburned fuel and lubricating oil. Therefore, the relative impact of a DOC on PM is generally limited by the amount of soluble organic PM present in engine-out exhaust.

The average observed brake specific fuel consumption (BSFC) for each configuration and the associated standard deviation are given in Table 9. There is no statistically significant difference in the BSFC between the two configurations, suggesting there was no fuel penalty associated with the aftertreatment.

DEF consumption, listed in Table 10 for 0-hour testing, increased slightly for each test, and reached a maximum of 4.1 percent volume of the fuel consumption over the line-haul locomotive duty cycle, and 3.0 percent volume of the fuel consumption over the switcher cycle.

The DEF injection rate is proportional to engine-out NO_x flow into the SCR, and therefore can be indirectly affected by parameters that typically drive engine-out NO_x, such as intake air humidity. The increase in DEF injection rates between runs can be attributed to progressively lower locomotive intake air humidity levels for each run and the corresponding increase in engine-out NO_x flow.

TABLE 9. OBSERVED BRAKE SPECIFIC FUEL CONSUMPTION OVER LOCOMOTIVE DUTY CYCLES FOR BASELINE AND 0-HOUR TESTING

Test Description	EPA Line-haul Cycle Observed BSFC, lb/hp-hr		EPA Switcher Cycle Observed BSFC, lb/hp-hr	
	Average	Std. Deviation	Average	Std. Deviation
Baseline	0.364	0.001	0.399	0.001
0-hour	0.362	0.002	0.400	0.001

TABLE 10. DEF CONSUMPTION AS PERCENTAGE OF VOLUMETRIC FUEL CONSUMPTION AT 0-HOUR TESTING

Test Description	Volumetric DEF Consumption as percent of fuel consumption over the EPA Line-haul cycle	Volumetric DEF Consumption as percent of fuel consumption over the EPA Switcher cycle
0-hour Run 1	3.4	2.3
0-hour Run 2	3.8	2.9
0-hour Run 3	4.1	3.0
0-hour Average	3.8	2.8

4.0 1,500-HOUR AND 3,000-HOUR TEST RESULTS

This section includes results from SwRI locomotive FTP exhaust emission testing of locomotive PRLX3004 in the LoNOx configuration at the mid-point and end-point of the field demonstration, which occurred after accumulating approximately 1,500 hours and 3,000 hours of revenue service engine operation.

The EPA weighted composite results for the 1,500-hour and 3,000-hour points are given in Table 11. Regulated emissions at 1,500 and 3,000 hours remained below Tier 4 limits for HC, CO, and NOx, and Tier 3 limits for PM. Relative changes from 0-hour test results are also listed in the table.

TABLE 11. EPA CYCLE WEIGHTED EMISSIONS AFTER 1,500 HOURS OF ENGINE OPERATION IN REVENUE SERVICE

Test Description	EPA Line-haul Cycle Emissions, g/hp-hr				EPA Switcher Cycle Emissions, g/hp-hr			
	HC	CO	NO_x	PM	HC	CO	NO_x	PM
Tier 3 Line-haul Locomotive Limits [a]	0.30	1.5	5.5	0.10	0.60	2.4	5.0	0.10
Tier 4 Line-haul Locomotive Limits	0.14	1.5	1.3	0.03	NA	NA	NA	NA
0-hour Average	**0.02**	**0.2**	**0.9**	**0.05**	**0.03**	**0.2**	**2.2**	**0.06**
1,500-hour Run 1	0.02	0.1	1.0	0.04	0.03	0.1	2.3	0.05
1,500-hour Run 2	0.02	0.2	0.9	0.05	0.04	0.2	2.2	0.05
1,500-hour Run 3	0.02	0.2	0.9	0.05	0.03	0.2	2.2	0.05
1,500-hour Average	**0.02**	**0.2**	**0.9**	**0.05**	**0.03**	**0.1**	**2.2**	**0.05**
1,500-hour Std. Dev.	0.001	0.005	0.009	0.007	0.001	0.009	0.042	0.005
Rel. Change from 0-hour	+13%	-24%	-3%	-9%	+21%	-30%	+2%	-9%
3,000-hour Run 1	0.02	0.1	0.9	0.04	0.04	0.1	2.1	0.04
3,000-hour Run 2	0.02	0.1	0.9	0.03	0.03	0.1	2.1	0.04
3,000-hour Run 3	0.02	0.1	1.0	0.04	0.03	0.1	2.3	0.04
3,000-hour Average	**0.02**	**0.1**	**0.9**	**0.04**	**0.03**	**0.1**	**2.1**	**0.04**
3,000-hour Std. Dev.	0.002	0.003	0.090	0.001	0.005	0.010	0.109	0.001
Rel. Change from 0-hour	+11%	-32%	-2%	-29%	+30%	-30%	0%	-24%

[a] Tier 3 Line-haul locomotives must also meet Tier 2 switcher standards.

The chart shown in Figure 8 displays cycle composite HC results for 0-, 1,500-, and 3,000-hour points, where the error bars show the standard deviation of each data set. The average line-haul composite HC for each test interval is within one standard deviation of each other, suggesting there is no statistical difference between these average HC values. However, switcher cycle composite HC increased slightly over the 1,500-hour and 3,000-hour intervals. Variability was high for HC at the 0-hour and 1,500-hour test intervals, which can be traced back to a HC spike that occurred for one out of the three 0-hour tests and for each of the 1,500-hour tests. Similar HC events occurred for each of the 3,000-hour tests, but in a more consistent manner and at a larger magnitude. This HC behavior was not observed during engine-out baseline testing, and is likely an effect of the aftertreatment heating up.

Figure 9 shows the average cycle composite CO results for 0-hour, 1,500-hour, and 3,000-hour testing, as well as the standard deviation associated with each set of data. Line-haul cycle composite CO at the 1,500-hour point was 24 percent lower than at the 0-hour point, and 32 percent lower at the 3,000-hour point. The switcher cycle CO values at 1,500-hour and 3,000-hour were both 30 percent lower than the 0-hour point.

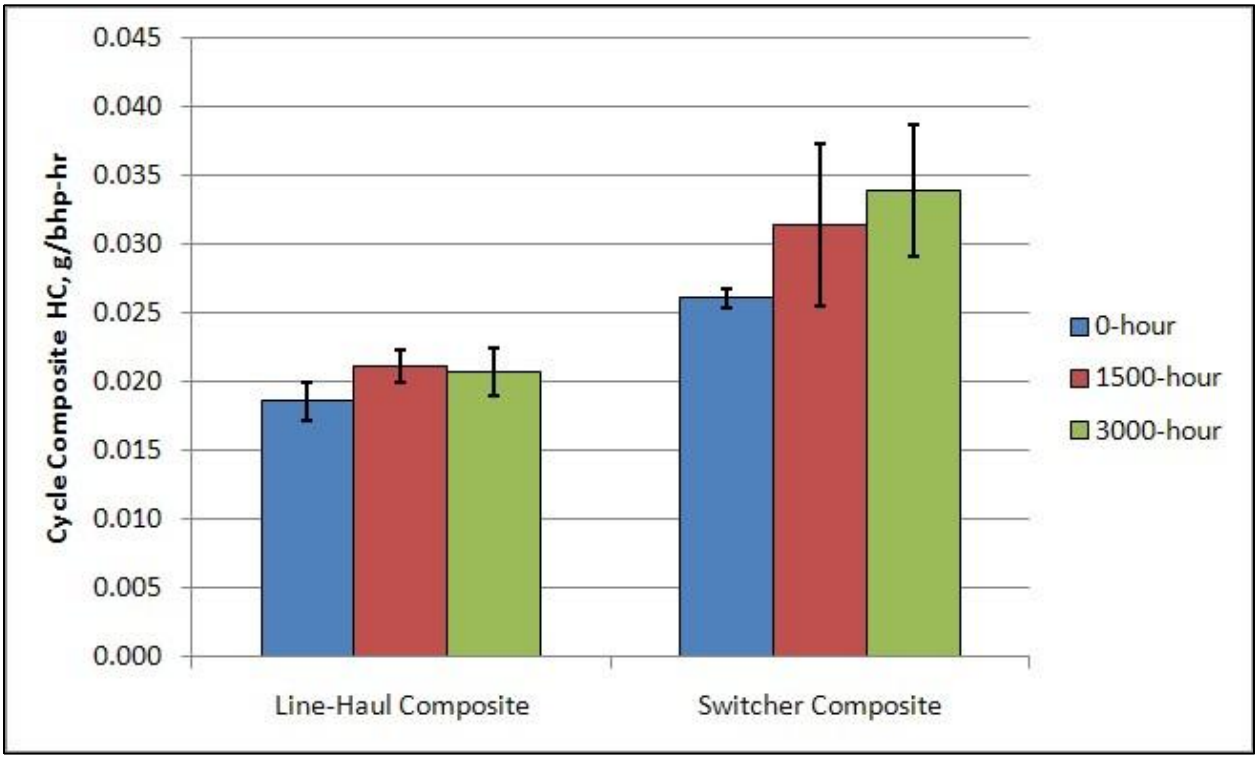


FIGURE 8. AVERAGE CYCLE COMPOSITE HC VALUES AT 0-HOUR, 1,500-HOUR, AND 3,000-HOUR TEST POINTS

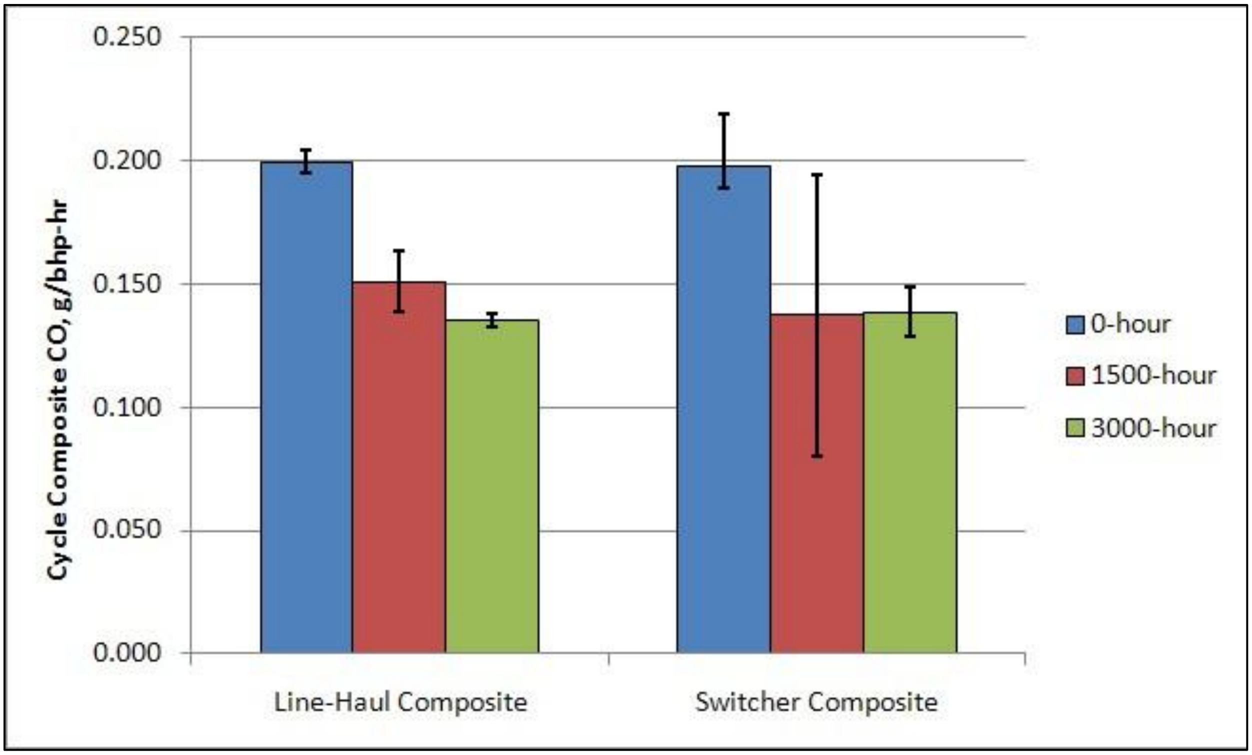


FIGURE 9. AVERAGE CYCLE COMPOSITE CO VALUES AT 0-HOUR, 1,500-HOUR, AND 3,000-HOUR TEST POINTS

The average cycle composite NO_x results, shown in Figure 10, were within one standard deviation of each other. Figure 11 shows the average cycle composite PM values for 0-hour, 1,500-hour and 3,000-hour testing. PM decreased slightly from previous results for both the 1,500-hour and the 3,000-hour points.

Smoke test results for 1,500-hour and 3,000-hour points of PRLX3004 are listed in Table 12. Smoke opacity for the locomotive with aftertreatment was consistent throughout this program, remaining well below EPA limits. Smoke during load transitions, characterized by the maximum 3-second peak average opacity, was lower for the 1,500-hour and 3,000-hour points than it was for 0-hour point.

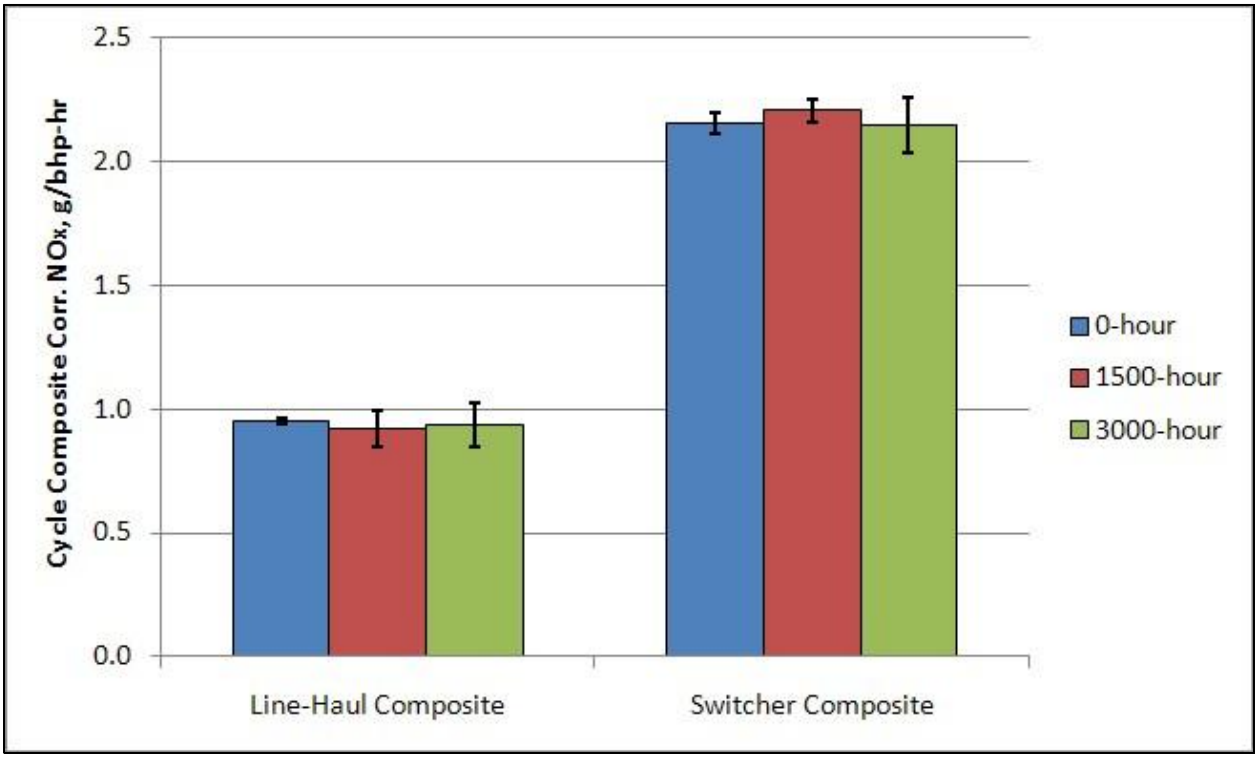


FIGURE 10. AVERAGE CYCLE COMPOSITE CORRECTED NO_X VALUES FOR 0-HOUR, 1,500-HOUR, AND 3,000-HOUR TEST POINTS

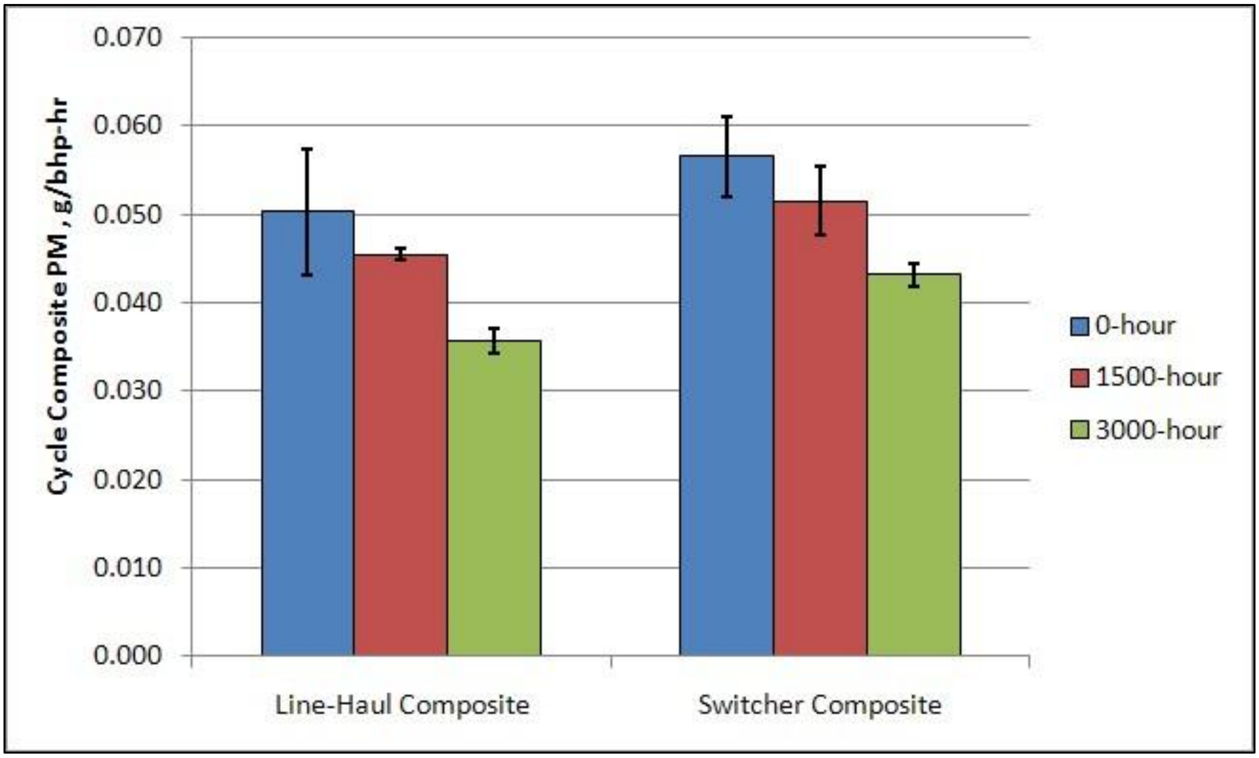


FIGURE 11. AVERAGE CYCLE COMPOSITE PM VALUES AT 0-HOUR, 1,500-HOUR, AND 3,000-HOUR TEST POINTS

TABLE 12. SMOKE TEST RESULTS FOR PRLX3004 1,500-HOUR AND 3,000-HOUR TESTING

Test Description	Maximum Steady-State Smoke, Percent Opacity	30-Second Peak, Percent Opacity	3-Sec. Peak, Percent Opacity
EPA Tier 2,3 Max	20	40	50
0-hour Average	**4**	**5**	**13**
1500-hour Run 1	4	5	8
1500-hour Run 2	2	3	7
1500-hour Run 3	4	4	7
1500-hour Average	**3**	**4**	**7**
3000-hour Run 1	4	4	5
3000-hour Run 2	3	3	6
3000-hour Run 3	4	4	5
3000-hour Average	**3**	**4**	**5**

A relatively small drop in flywheel power at the higher notches occurred at the 1,500-hour and 3,000-hour points. This was a result of different auxiliary power requirements, and can be attributed to one less radiator fan running during the 1,500-hour and 3,000-hour points. Note, however, that duty cycle emission test results are reported as brake-specific values, and are therefore normalized for small differences in power. Figure 12 shows a chart comparing the cycle composite observed brake specific fuel consumption (BSFC) for each configuration, and shows slight changes in fuel economy between test points. This data is also tabulated in Table 13.

The overall DEF consumption for each test point is expressed in Table 14 as the volumetric percentage of fuel consumption over the EPA line-haul and switcher duty cycle. DEF consumption increased slightly at each test point, and at the 3,000-hour point, reached a maximum of 4.8 percent volume of the fuel consumption over the line-haul locomotive duty cycle, and 3.2 percent volume of the fuel consumption over the switcher cycle. The upward trend in DEF consumption was accompanied with a downward trend in locomotive intake air humidity levels during testing, and was likely a result of increased engine-out NO_x flow.

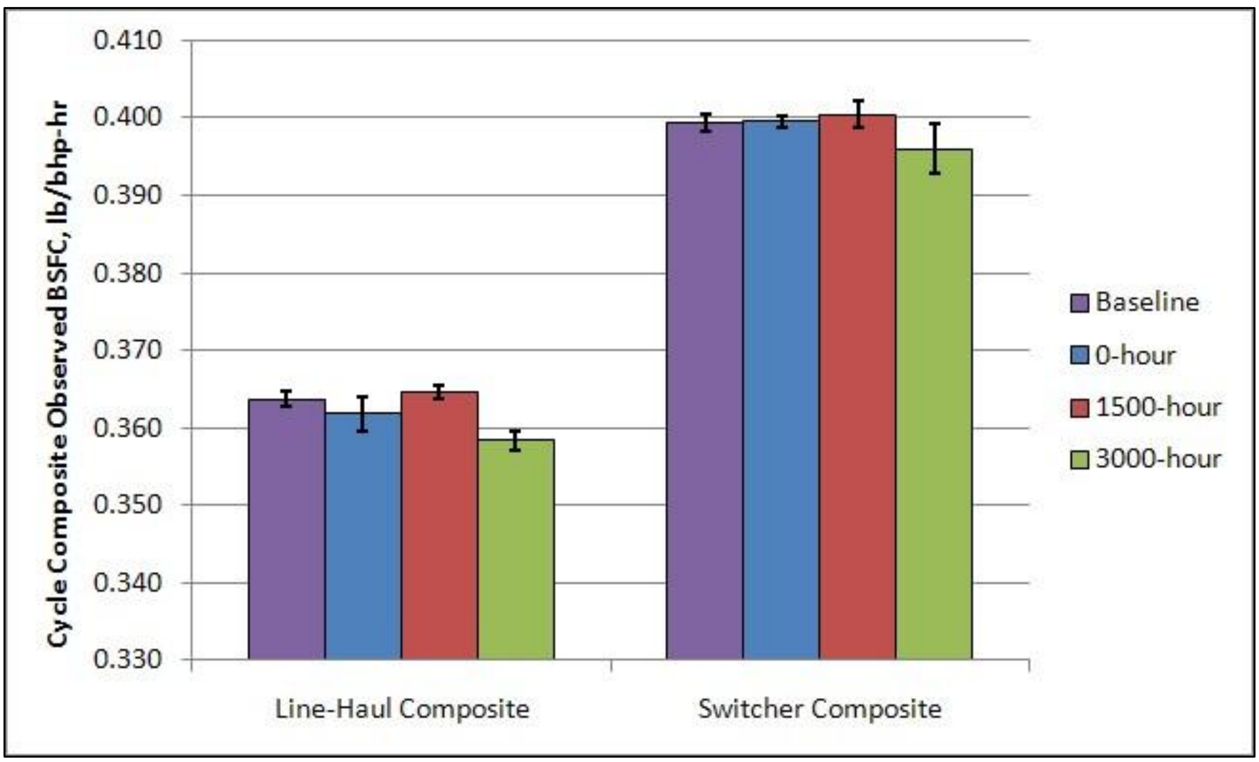


FIGURE 12. AVERAGE CYCLE COMPOSITE OBSERVED BSFC FOR 0-HOUR, 1,500-HOUR, AND 3,000-HOUR TEST POINTS

TABLE 13. AVERAGE CYCLE COMPOSITE OBSERVED BSFC FOR 0-HOUR, 1,500-HOUR, AND 3,000-HOUR TEST POINTS

Test Description	Average EPA Line-haul cycle weighted Observed BSFC, lb/hp-hr		Average EPA Switcher cycle weighted Observed BSFC, lb/hp-hr	
	Average	Std. Deviation	Average	Std. Deviation
0-hour	0.362	0.002	0.400	0.001
1,500-hour	0.365	0.001	0.400	0.002
3,000-hour	0.358	0.001	0.396	0.003

TABLE 14. DEF CONSUMPTION AS PERCENT OF VOLUMETRIC FUEL CONSUMPTION

Test Description	Average Volumetric DEF Consumption as percent of fuel consumption over EPA Line-haul cycle	Average Volumetric DEF Consumption as percent of fuel consumption over EPA Switcher cycle
0-hour	3.8	2.8
1,500-hour	4.2	3.0
3,000-hour	4.8	3.2

5.0 PRLX3004 REMOTE DATA LOGGING

Locomotive PRLX3004 was instrumented by SwRI with a data logging system that continually monitored the parameters listed in Table 15 during revenue service. Figure 13 shows the inside of the electrical cabinet for the data logger. Data was recorded every minute using a Campbell Scientific data acquisition system. A cellular phone package was installed to remotely monitor and periodically download the data via the internet. A GPS receiver was used to monitor and record locomotive location.

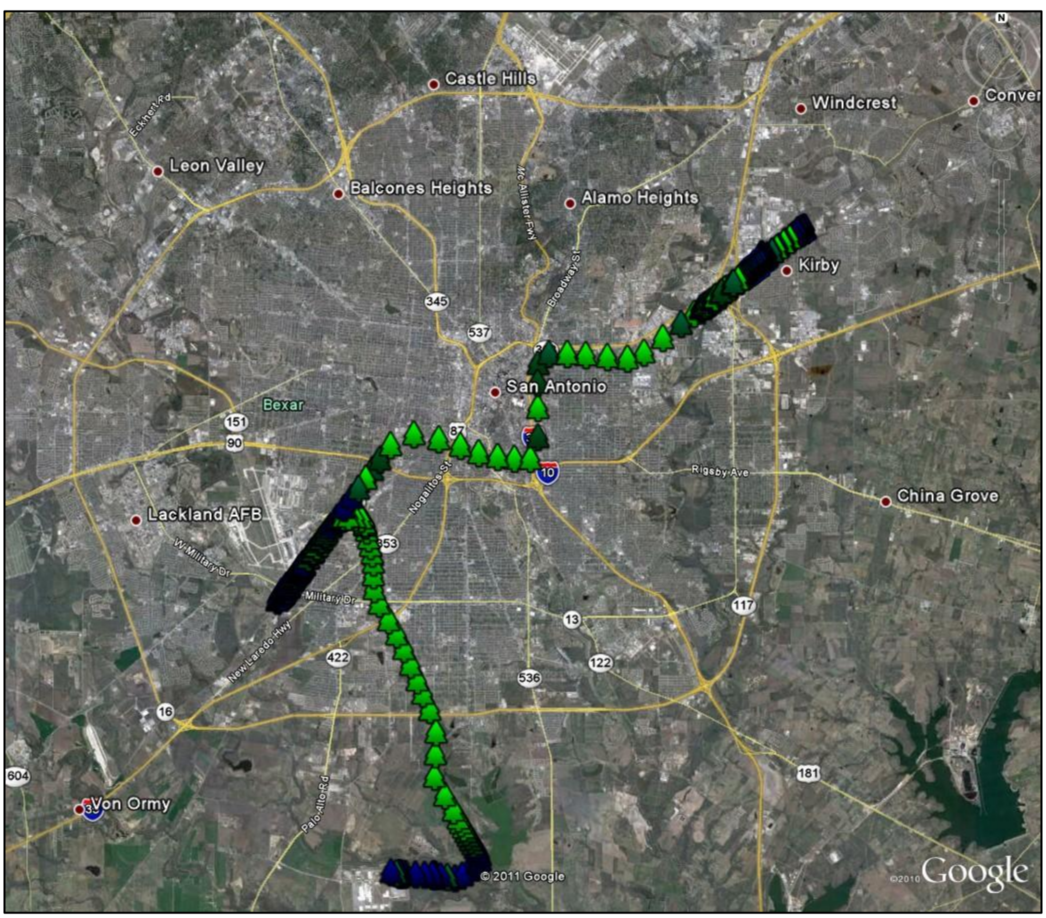
SwRI provided a year of locomotive data logging, monitoring, and weekly status updates for PRLX3004 as part of Phase 2 of the project. The updates were circulated via e-mail to those involved with the project and included tracking the position of the locomotive, total hours of engine operation, the duty cycle experienced by the locomotive during the week, and the estimated effectiveness of the aftertreatment system. Figure 14 shows an illustration of the data logger tracking during early operation of PRLX3004 in San Antonio. The place marks are shaded according to the NO_x reduction recorded for that point, with the bright green representing a NO_x reduction greater than 85 percent, dark blue is 0-20 percent NO_x reduction, and intermediate NOx reductions are shaded proportionately between the two colors. Note that the areas of little or no NO_x reduction were due to exhaust temperatures being below the threshold of DEF dosing.

A SwRI client FTP site was generated and updated weekly during the field demonstration with the latest data downloaded from the locomotive, along with appropriate summary spreadsheets and documents.

TABLE 15. PRLX3004 DATA LOGGING PARAMETERS

Channel	Parameter
1	Date/Time stamp
2	Latitude
3	Longitude
4	Locomotive Speed
5	Engine Speed
6	Exhaust Backpressure
7	Ground Fault Indicator
8	SCR Fault Indicator
9	Engineer side exhaust outlet temp
10	Conductor side exhaust outlet temp
11	Engine room temp
12	DEF tank level
13	Engine-out NOx sensor concentration
14	Conductor side tail-pipe NOx sensor concentration
15	Engineer side tail-pipe NOx sensor concentration
16	CAN: Total engine hours
17	CAN: Total fuel burn

FIGURE 13. REMOTE DATA LOGGER CABINET



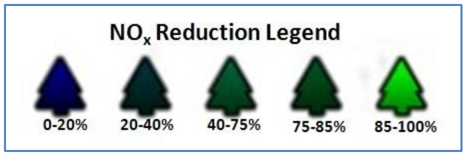


FIGURE 14. EXAMPLE OF PRLX3004 TRACKING

5.1 PRLX3004 12-Month Revenue Service Summary

After 0-hour testing was completed for PRLX3004, the engine hour-meter reading was recorded as the starting point for the demonstration and a fresh clock began for the 3,000 hour field demonstration. PRLX3004 was placed outside the SwRI gate on November 4, 2009 to be picked up by UPRR and placed into revenue service. The locomotive was kept close to the SwRI facility for the first two months of service and was used in helper hauler service on a local San Antonio route while system operations were verified to be in good working order. PRLX3004 was placed in a California bound intermodal train and left San Antonio on January 18, 2010 and arrived in the Los Angeles basin on January 20 having already accumulated 986 hours of engine operation for the field demonstration.

The first service route PRLX3004 worked on in California was between West Colton and the Port of Long Beach. This route uses the Alameda Corridor and runs through the heart of an extreme ozone nonattainment metropolitan area where NO_x reduction is very desirable. Figure 15 is a graphic generated in Google Earth software illustrating the NO_x reduction achieved by PRLX3004 during the west bound trip from West Colton to Long Beach. Below the map is the elevation profile of the route. The west bound trip from Colton to Long Beach is mostly downhill and as a result the locomotive was in dynamic brake for a large portion of the time; however, there were some stretches of significant engine load during the trip where exhaust temperatures were conducive for SCR activity. These areas are characterized by green place marks representing good SCR NO_x reduction.

A similar illustration for the east bound return trip from Long Beach to West Colton is shown in Figure 16. Most of this trip was a climb with a total elevation gain of over 1,000 feet, resulting in a high load factor for the locomotive. Logged NO_x data revealed good SCR effectiveness for almost the entire trip, as indicated by the mostly green place marks. A typical week for PRLX3004 on this service loop consisted of two to three round trips between West Colton and Long Beach, as well as extended engine idling and brief periods of yard movement and switching. Figure 17 shows the total operation duty cycle for all PRLX3004 operation that was within the West Colton – Long Beach route. Most of this portion of the demonstration was marked with inconsistent usage and workload for PRLX3004. Many instances of extended engine idling were recorded, along with service trips where PRLX3004 did not provide power, but appeared to be isolated, or “cut-out”, from the working locomotives. This resulted in a relatively low load factor with approximately 78 percent of engine-hours being accumulated at idle.

After accumulating a total of 1,498 hours of engine operation for the field demonstration, PRLX3004 began to work back to San Antonio on March 20, 2010 for scheduled emissions testing. The locomotive arrived at SwRI on March 28 having completed 1,575 hours of engine operation in the field demonstration. At the conclusion of the 1,500-hour testing and inspections, PRLX3004 worked back to California and continued service on the West Colton/Long Beach route until May 16. PRLX3004 was assigned to the West Colton/Long Beach route for a total of 89 days, and accumulated 626 hours of operation while assigned to this service route.

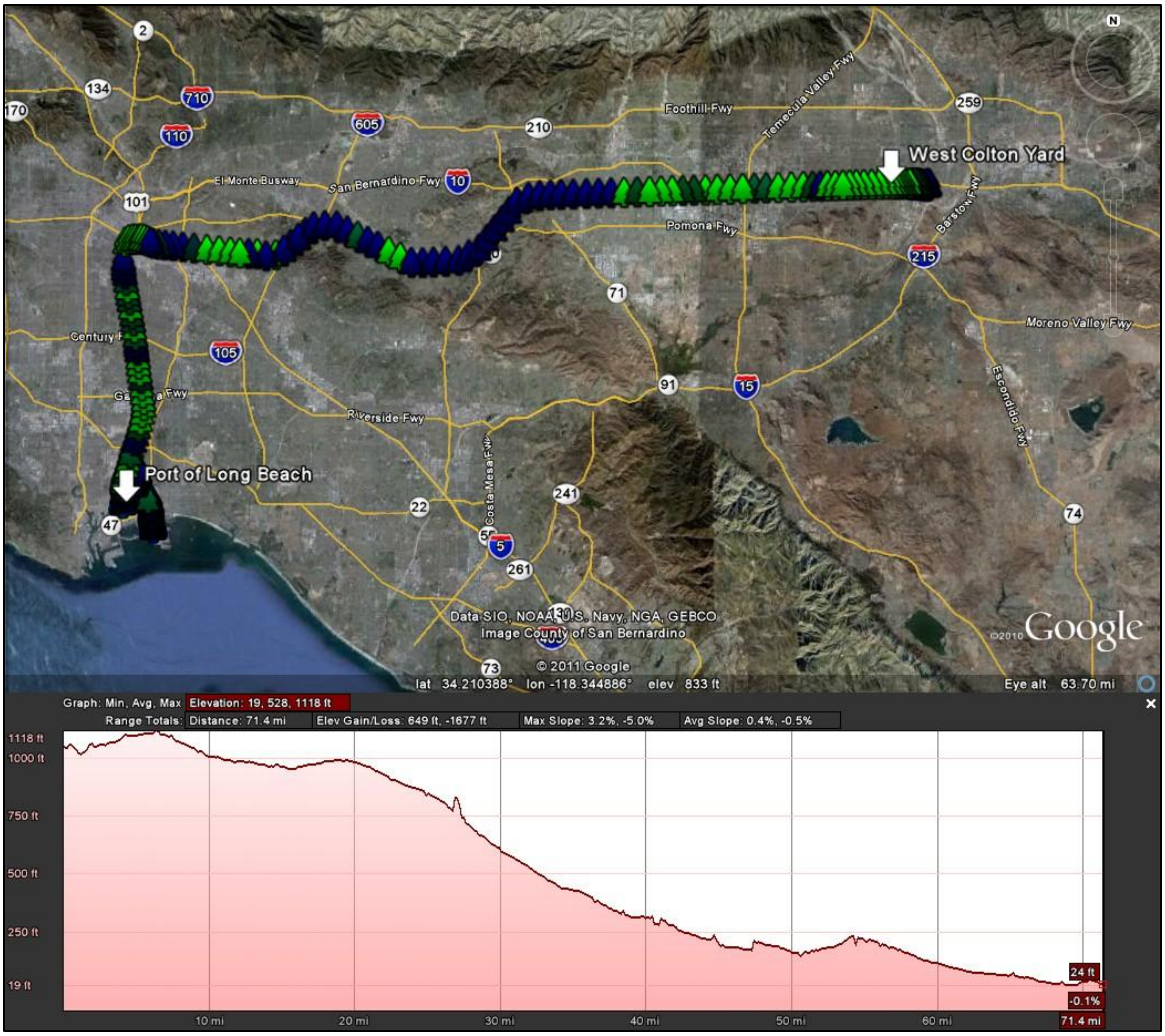


FIGURE 15. NO_X REDUCTION MAP AND ELEVATION PROFILE OF TRIP FROM WEST COLTON TO LONG BEACH

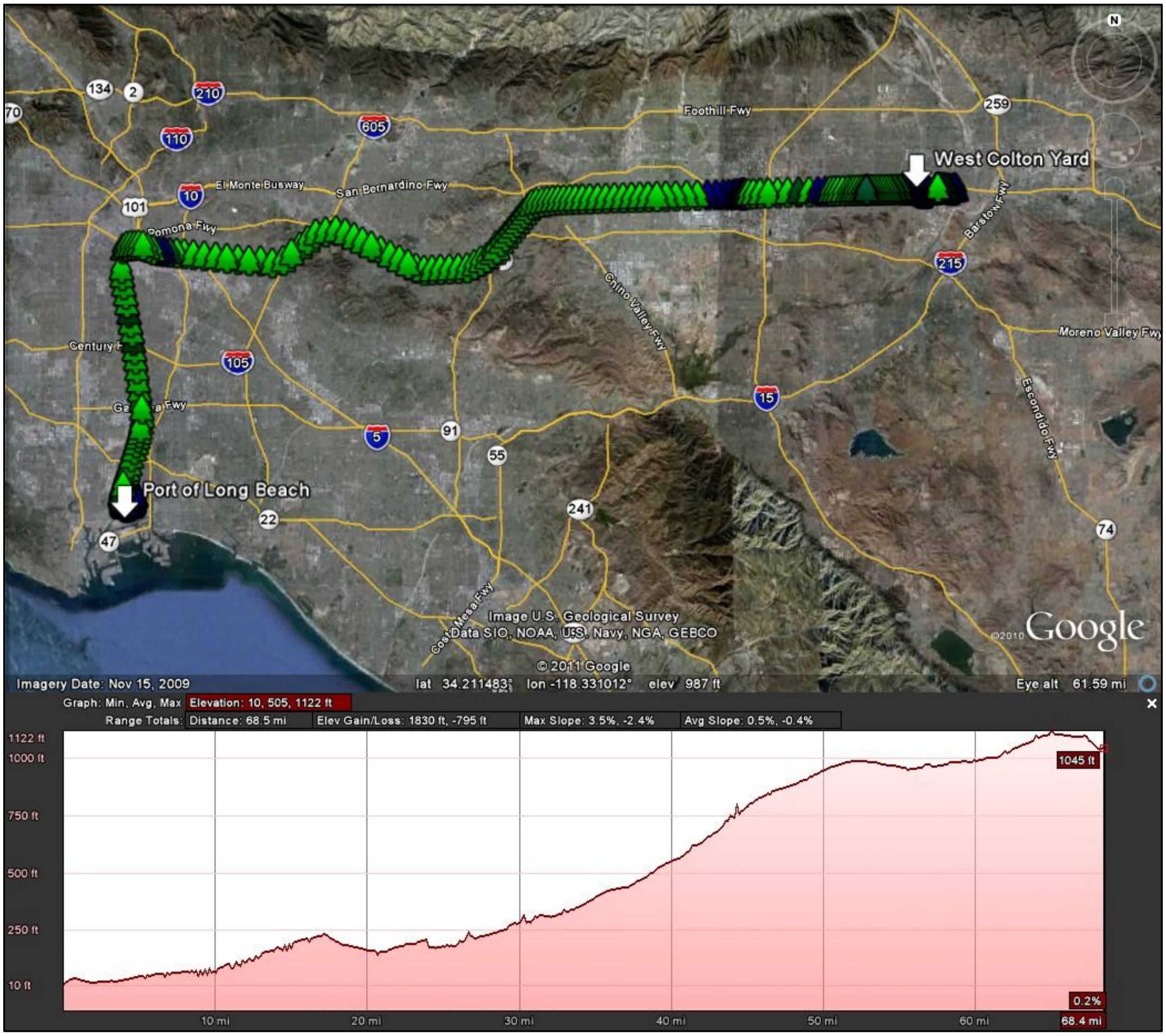


FIGURE 16. NO_X REDUCTION MAP AND ELEVATION PROFILE OF TRIP FROM LONG BEACH TO WEST COLTON

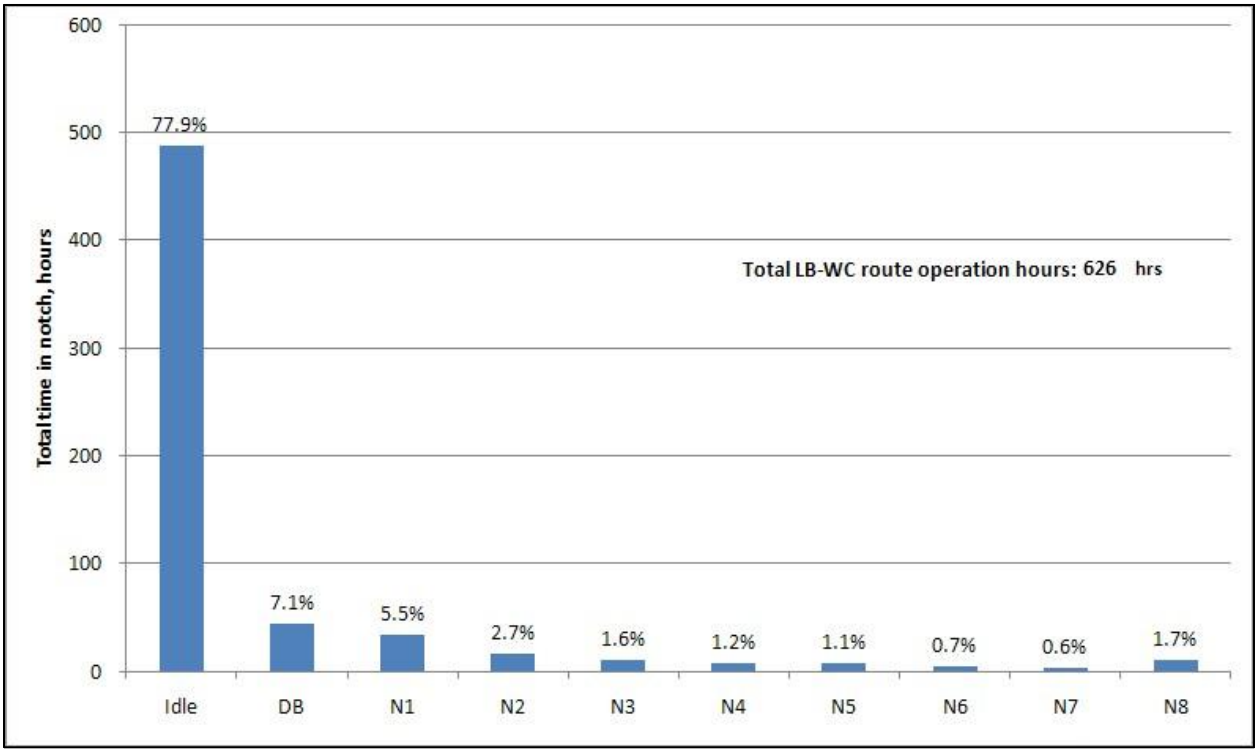


FIGURE 17. PRLX3004 TOTAL TIME IN EACH NOTCH AND DUTY CYCLE FOR WEST COLTON – LONG BEACH SERVICE ASSIGNMENT

On May 16, 2010 PRLX3004 changed service route assignments and began to operate between West Colton and El Centro. This is a 164 mile trip from the Los Angeles basin to a desert town near the California/Mexico border. This service was less frequent than the previous assignment; however, the new route was longer and offered higher overall utilization and load factor. Figure 18 is an illustration generated in Google Earth software showing the overall route along with the elevation profile. Typical NO_x reduction data for PRLX3004 on the trip is illustrated in Figures 19 through 24. The south bound trip to El Centro from West Colton starts off with a 1,600 foot elevation gain over 25 miles as the train is pulled up out of the basin. This portion of the trip is shown in Figure 19. The locomotive was operated at Notch 8 almost immediately after leaving the West Colton yard, and remained at Notch 8 until reaching Beaumont ("A" on map). The SCR reduced approximately 90 percent of engine-out NO_x during this portion of the trip. The rest of the trip to El Centro is either downhill or flat. Operation between Beaumont ("A" on map) and near the Salton Sea ("B" on map), shown in Figure 20, was mostly dynamic braking and only required brief periods of engine loading near Palm Springs and alongside the Salton Sea. The final leg of the south bound trip, shown between place mark "B" and El Centro in Figure 21, consisted of significant engine loading and good SCR NO_x reduction. The NO_x reduction map for the north bound return trip from El Centro back to West Colton is shown in Figures 22 through 24. The 2,600 foot climb in elevation through the middle section of the return trip, displayed between place marks "B" and "A" of Figure 23, is a stretch for high SCR activity with extended periods of Notch 8 engine operation.

FIGURE 18. PATHWAY AND ELEVATION PROFILE OF WEST COLTON - EL CENTRO SERVICE ROUTE

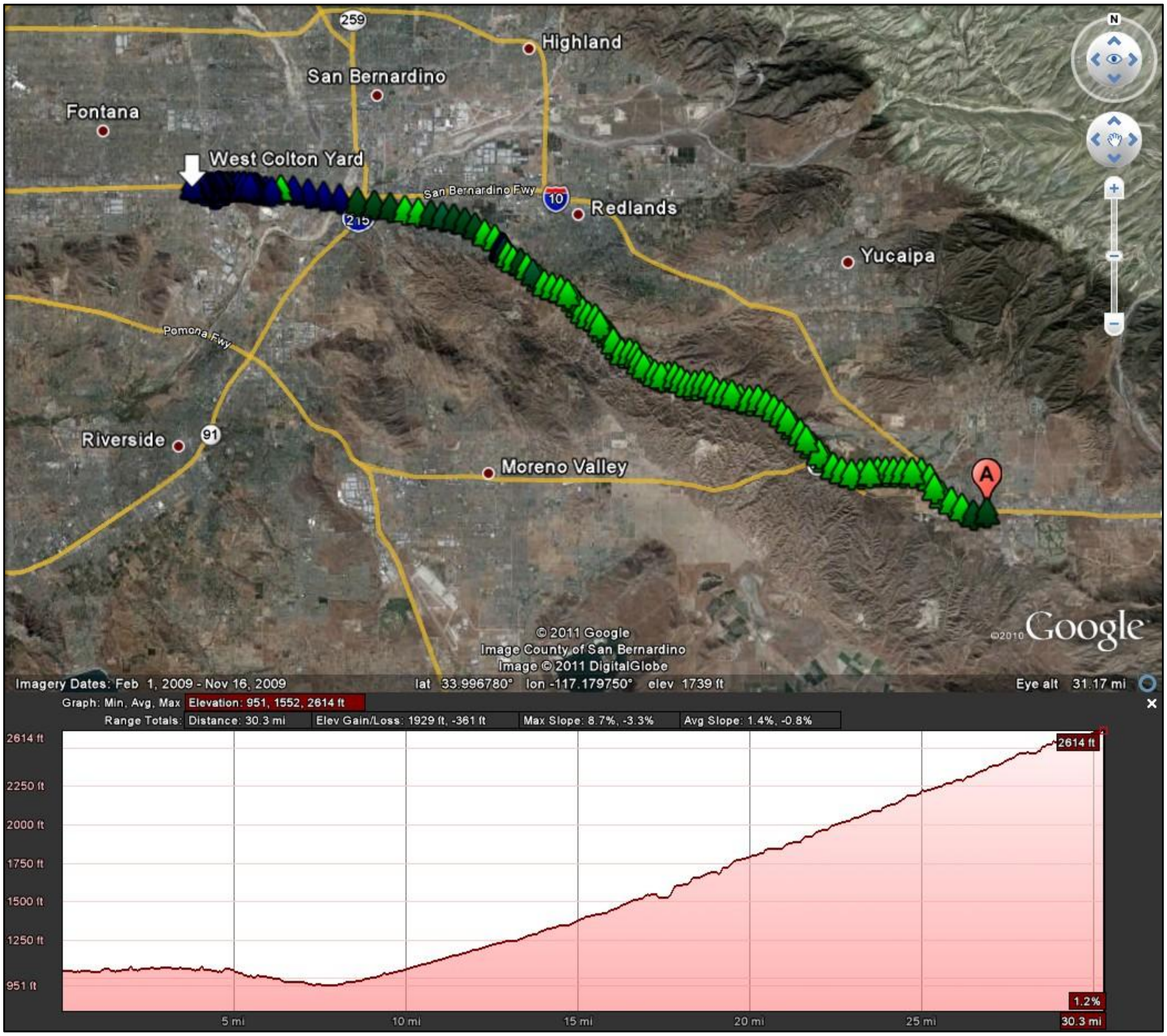


FIGURE 19. NO_X REDUCTION MAP AND ELEVATION PROFILE OF TRIP FROM WEST COLTON TO EL CENTRO, SEGMENT 1 OF 3

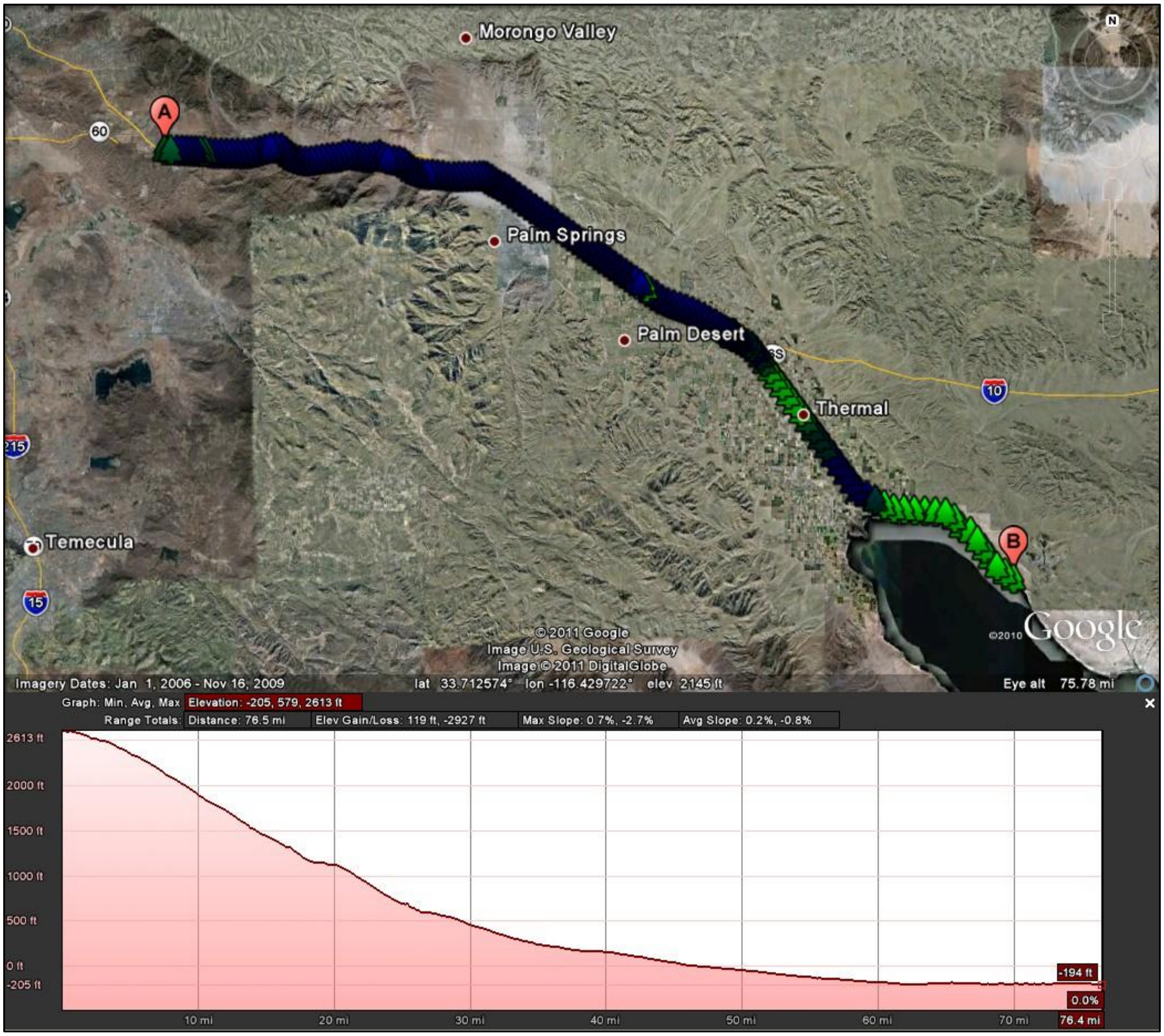


FIGURE 20. NO_X REDUCTION MAP AND ELEVATION PROFILE OF TRIP FROM WEST COLTON TO EL CENTRO, SEGMENT 2 OF 3

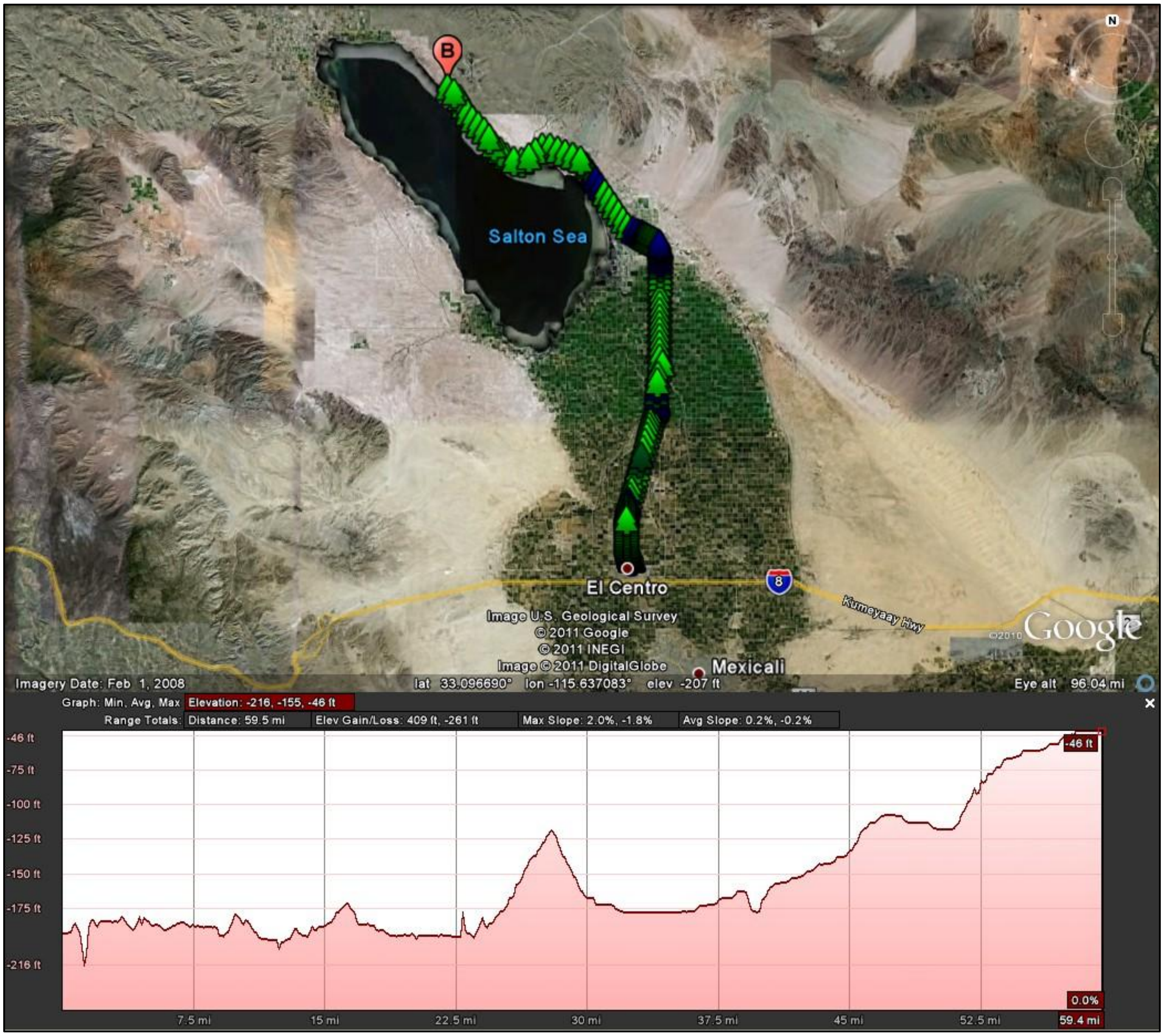


FIGURE 21. NO_X REDUCTION MAP AND ELEVATION PROFILE OF TRIP FROM WEST COLTON TO EL CENTRO, SEGMENT 3 OF 3

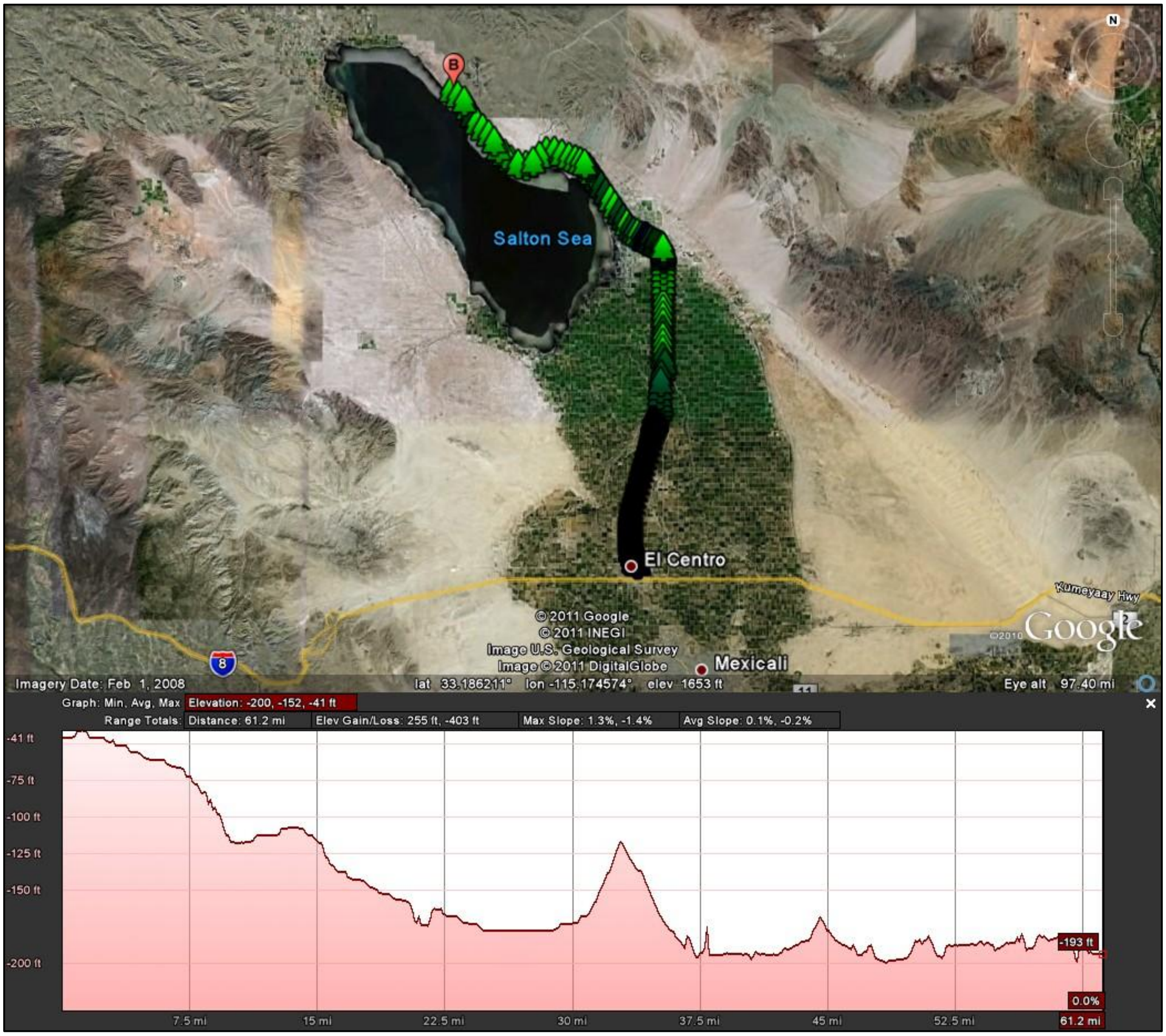


FIGURE 22. NO_X REDUCTION MAP AND ELEVATION PROFILE OF TRIP FROM EL CENTRO TO WEST COLTON, SEGMENT 1 OF 3

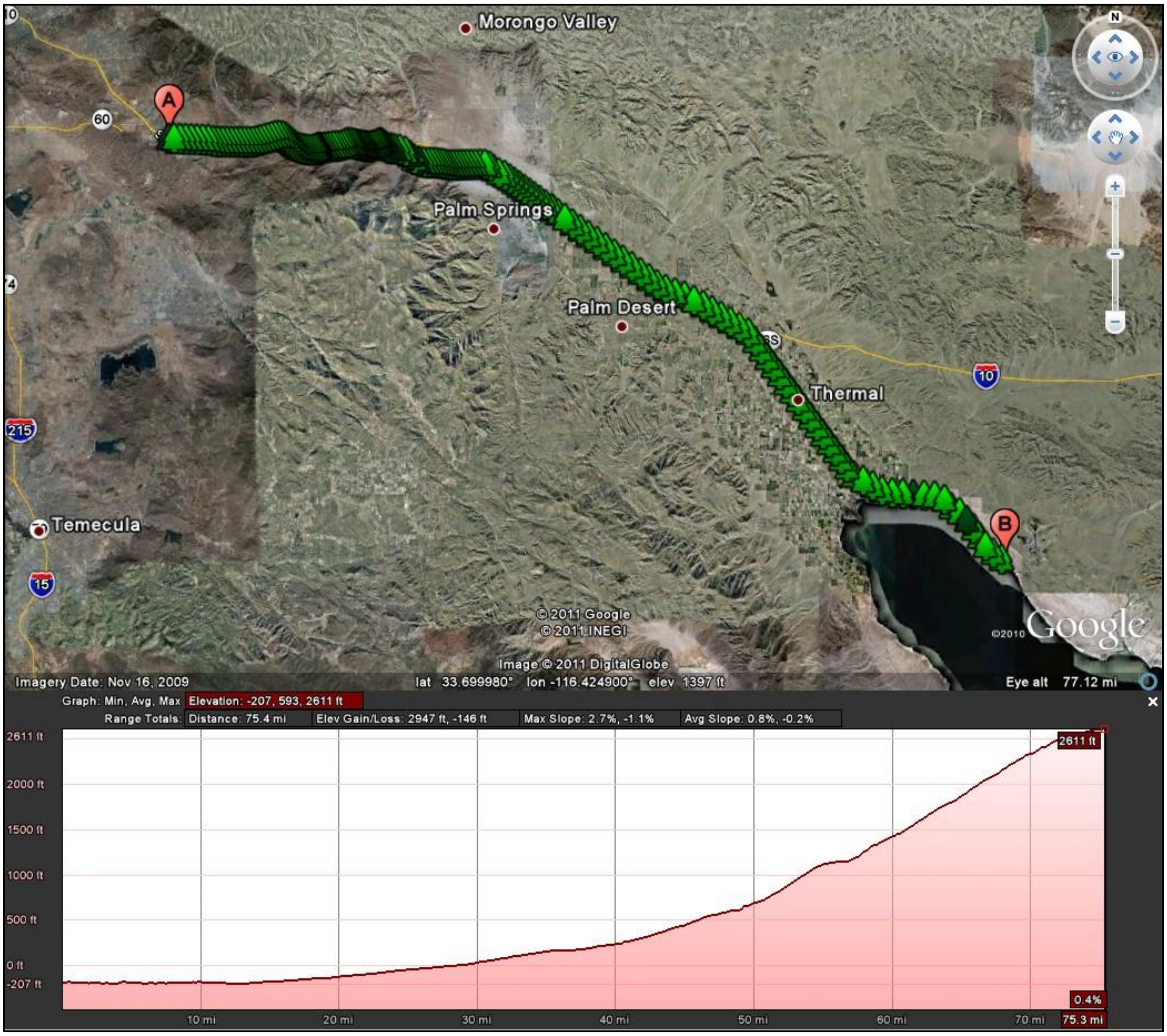


FIGURE 23. NO_X REDUCTION MAP AND ELEVATION PROFILE OF TRIP FROM EL CENTRO TO WEST COLTON, SEGMENT 2 OF 3

FIGURE 24. NO_X REDUCTION MAP AND ELEVATION PROFILE OF TRIP FROM EL CENTRO TO WEST COLTON, SEGMENT 3 OF 3

PRLX3004 left West Colton on November 3 to begin the trip back to SwRI for the final set of emission tests, thus completing the El Centro service assignment. PRLX3004 was assigned to the El Centro service for a total of 171 days and accumulated an additional 1,167 hours of operation. Figure 25 shows the total time in each mode and duty cycle during the El Centro service assignment. The locomotive utilization improved slightly for the El Centro service as compared to the Long Beach service. Idling was reduced from 78 percent of the total engine operation while servicing Long Beach, to 65 percent for the El Centro service, and operation time at Notch 8 increased from two percent to six percent.

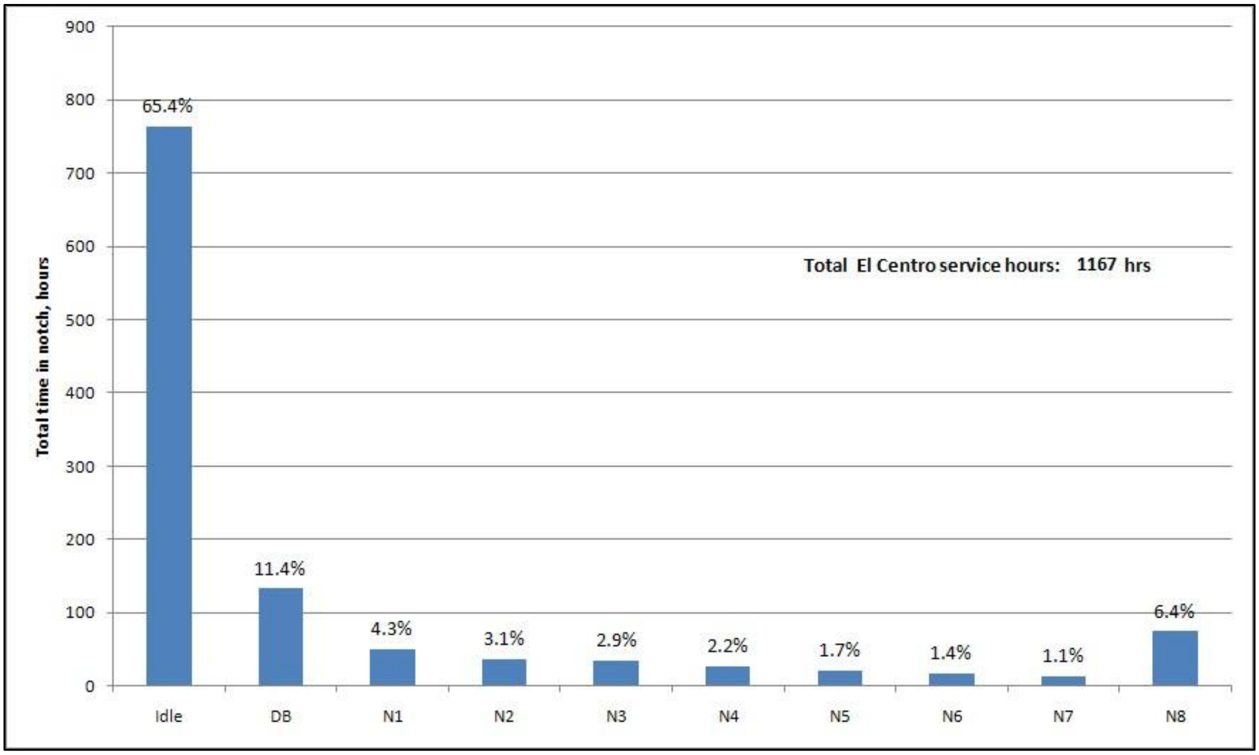


FIGURE 25. TOTAL TIME IN EACH NOTCH AND DUTY CYCLE FOR WEST COLTON – EL CENTRO SERVICE ASSIGNMENT

PRLX3004 arrived at SwRI on November 12, 2010 completing the demonstration with a total of 3,082 hours of operation. The total time in each mode and the resulting duty cycle for the entire demonstration are shown in Figure 26. Engine idling and dynamic braking accounted for 80 percent of the total demonstration hours. Figure 27 shows the total hours of operation and the resulting duty cycle when only the modes producing traction power are included. The power producing modes contributed 611 hours to the total demonstration hours, making up 20 percent of the total duty cycle. The total elapsed time from the start of the demonstration on November 4, 2009, to the end on November 12, 2010, was 8,952 hours. The engine was off 66 percent of the total elapsed time, and provided power seven percent of the time.

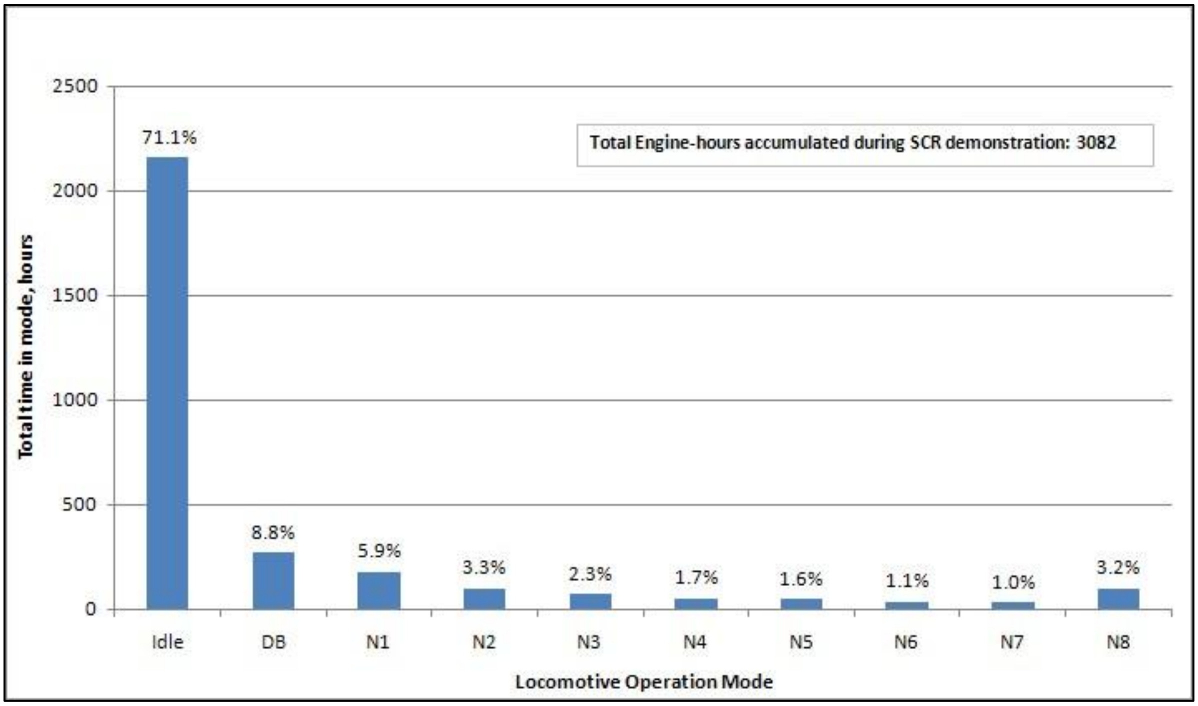


FIGURE 26. TOTAL TIME IN EACH OPERATING MODE AND RESULTING DUTY CYCLE DURING FIELD DEMONSTRATION

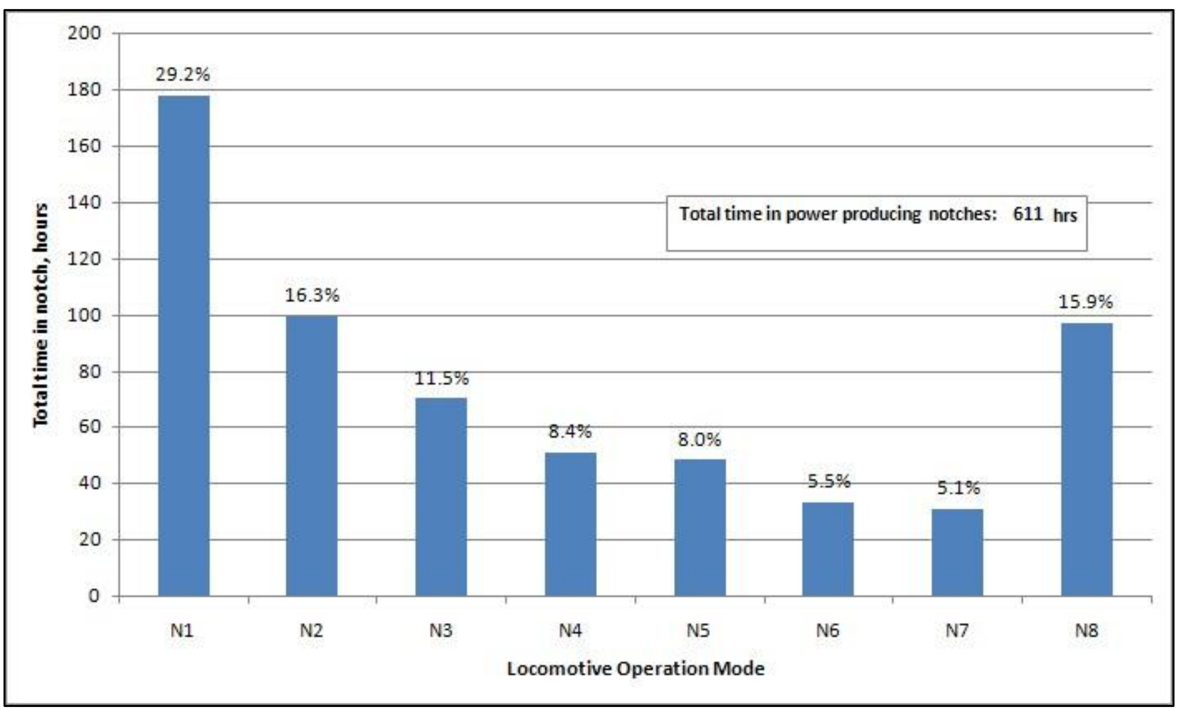


FIGURE 27. TOTAL TIME IN EACH TRACTION POWER PRODUCING MODE AND RESULTING DUTY CYCLE DURING DEMONSTRATION

Figure 28 shows a plot of the totalized engine-hour accumulation as a function of the calendar date, as well as a plot of the totalized estimated megawatt-hour (MW-hour) accumulation as a function of calendar date. The SwRI data logger did not record in-use power for PRLX3004; however, engine-brake power was established for each mode during emissions testing at SwRI, and these values were used along with the recorded time in each mode to estimate MW-hours accumulated during the demonstration. The graph in Figure 28 helps to visualize true PRLX3004 utilization and overall demonstration progress. For example, although the rate of increase for total operation hours was greater while assigned to the Long Beach service, the plot of total MW-hours reveals that PRLX3004 experienced better utilization during the El Centro service, as characterized by rate of change in total MW-hrs.

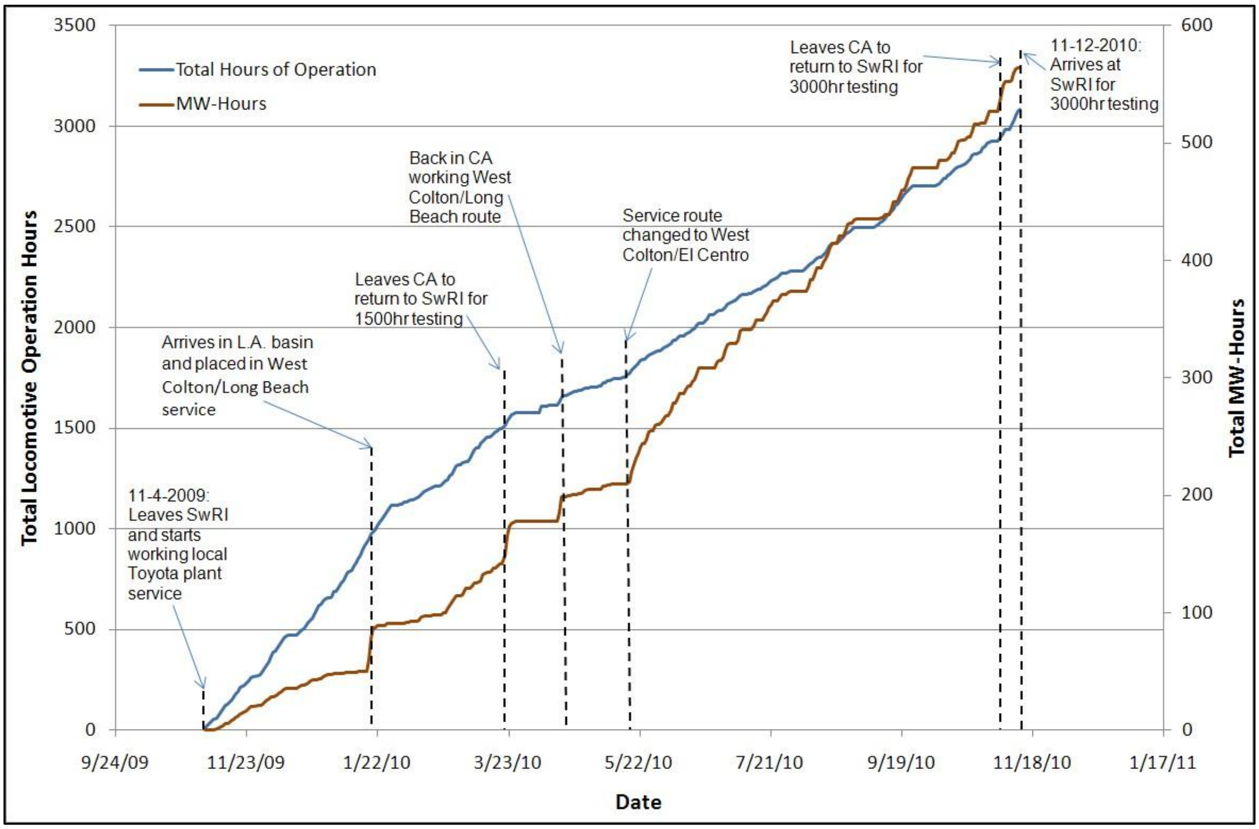


FIGURE 28. ENGINE HOUR AND MW-HOUR ACCUMULATION DURING FIELD DEMONSTRATION

The estimated total MW-hours accumulated by PRLX3004 over the demonstration was 572 engine-brake MW-hours. When estimated using the net traction power instead of engine-brake power (flywheel), the demonstration total was 484 MW-hours. Fuel consumption rates measured by SwRI during emission tests were used along with the total demonstration time in each mode to estimate that 140,318 kg (309,348 lbs, or 44,192 gallons) of diesel fuel was consumed during the demonstration. The engine ECM also broadcasts a CAN signal for estimated total volumetric fuel burn, which was recorded by the data logger. The total change in this recorded value over the demonstration was 178,494 liters (47,153 gallons).

The NO_x reducing potential for the PRLX3004 SCR is dependent on exhaust temperatures and ultimately engine load factor. To maximize the environmental benefit of such a locomotive the overall utilization and service area of operation must be considered. Ideally, using the PR30C-LoNOx to replace existing locomotives which operate at high load factors within ozone nonattainment areas would provide maximum benefit. To characterize the SCR benefit on PRLX3004 NO_x emissions during the demonstration, the total NO_x reduction was estimated by using average SwRI emission test results from baseline, 0-hour, 1,500-hour, and 3,000-hour testing, and also using the demonstration time in each mode. From this estimate the PRLX3004 SCR eliminated 2,438 kg of NO_x over the entire demonstration, or 54 percent of the total NO_x produced by the engine.

6.0 SUMMARY

California Air Resources Board (CARB) funded the emission testing and in service evaluation of a PR30C-LoNOx locomotive, road number PRLX3004, to investigate the feasibility of combining an advanced engine repower with an aftertreatment system on a medium horsepower freight line-haul locomotive. Phase 1 of the CARB funded program was conducted at the Southwest Research Institute (SwRI) Locomotive Technology Center, and included the baseline emissions testing, aftertreatment installation and commissioning, 0-hour emissions testing, and data logging equipment installation.

Emissions test results from PRLX3004 show that the PR30C-LoNOx locomotive achieved Tier 4 Line-Haul NO_x, CO, HC, and smoke emission levels, as well as Tier 3 PM levels. When tested in the baseline configuration, which is without the aftertreatment, the locomotive produced emission levels within Tier 2 EPA locomotive limits. At the 0-hour test point the aftertreatment provided a NO_x reduction of 80 percent over the line-haul cycle, and 59 percent over the switcher cycle, as compared to the engine-out baseline values. The aftertreatment (SCR and DOC) provided a total HC reduction from baseline of 93 percent over the line-haul and 94 percent over the switcher cycle, and a CO reduction of 72 percent over the line-haul and 81 percent over the switcher cycle. Locomotive exhaust PM emissions were sampled using a Sierra Instruments BG-3 partial dilution sampling system. With the aftertreatment, a PM reduction of 43 percent over the line-haul cycle, and 64 percent over the switcher cycle, as compared to baseline values, was measured.

No fuel penalty was detected for the aftertreatment, and the maximum diesel exhaust fluid (DEF) consumption was 4.8 percent of fuel consumption by volume over the line-haul duty cycle, and 3.2 percent of the fuel consumption by volume over the switcher cycle.

Phase 2 of the program started in December 2009 when the locomotive was released from SwRI after 0-hour testing with aftertreatment. Throughout the field demonstration SwRI provided data logging and regular updates regarding the utilization of the locomotive, and operation of the engine and aftertreatment. The locomotive was worked back to San Antonio for emissions testing in March of 2010 after accumulating approximately 1,500 hours of operation, and again in November after accumulating approximately 3,000 hours of operation. The results from the 1,500-hour and 3,000-hour emission test points were similar to the 0-hour test point. Cycle composite HC, CO, and NO_x remained below Tier 4 limits, and PM remained below Tier 3 limits. CO emissions were slightly lower at the 1,500-hour and 3,000-hour test points, as compared to the 0-hour point. HC emissions at Notch 2 were higher for the 1,500-hour and 3,000-hour points, causing slight increases in the duty cycle composite results. PM emissions were lower at the 1,500-hour and 3,000-hour points as compared to the 0-hour point. These results suggest there was no significant degradation in aftertreatment performance during the field demonstration, which included a total of 3,082 hours of engine operation and generated an estimated 572 MW-hours of power over the period of approximately one year.