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LOCOMOTIVE EXHAUST TEMPERATURES DURING HIGH ALTITUDE TUNNEL OPERATION IN DONNER PASS

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ABSTRACT

Locomotives in heavy-haul operation at high elevation and within unventilated tunnels function under some of the most extreme conditions encountered in the U.S. with regards to high ambient temperatures and high locomotive exhaust temperatures. Consideration of such conditions is crucial to the design of future catalytic emission control systems for locomotives. Field testing was conducted with two locomotives certified to U.S. Federal Tier 2 Locomotive Emissions Standards that were operating as part of a four-locomotive consist pulling a heavy-freight train west-bound through the Donner Pass Region in late August 2007. The highest post-turbine exhaust temperatures observed over the entire test route occurred within Union Pacific Tunnel #41, which is an approximately two-mile-long unventilated tunnel located near Norden, California. Engine protection measures within the electronic locomotive and engine management systems of both locomotives limited the peak exhaust temperatures encountered during the tests to below 560 °C.

INTRODUCTION

On April 3, 2007 the U.S. Environmental Protection Agency (U.S. EPA) proposed new Tier 3 and Tier 4 exhaust emissions standards for new locomotives.[1] The Tier 4 standards are expected to require the use of catalytic exhaust emission control systems on new diesel electric locomotives in the U.S. A critical first step in the design of such systems is to characterize the operational conditions that will be encountered within these applications. Thermal sintering is one of the primary degradation mechanisms for exhaust catalysts. Operation at high altitudes and within unventilated tunnels was identified by locomotive manufacturers and Class 1 railroads as representative of some of the most extreme conditions encountered with respect to ambient temperatures, coolant temperatures, lubricant temperatures and exhaust temperatures. It has been suggested to EPA that post-turbine exhaust temperatures as high as 700 °C could be encountered under such test conditions.

Sustained exhaust temperatures that are near 700 °C are important from the standpoint of exhaust catalyst design, particularly when considering methods for controlling NO_x emissions from diesel-electric locomotives in line-haul applications. The sustained exhaust temperatures at which significant thermal degradation can occur differs for the available types of selective catalytic reduction (SCR) systems used with urea reductant for lean-NO_x exhaust emission control. Extruded vanadium catalysts and coated vanadium-tungsten-titanium mixed oxide (VWT) catalysts have maximum operating temperatures of 540 °C and 600 °C, respectively, for heavy-duty diesel applications.[2,3] Coated base-metal-zeolite catalysts have maximum operating temperatures in the 650 °C to 750 °C range depending on the base metals and coatings that are used.[4,5] Following discussions with the two major manufacturers of large 6-axle line-haul locomotives in the U.S., EPA decided that coordinated field testing of instrumented locomotives in heavy-haul operation at high altitudes and in unventilated tunnels would provide critically needed data for assessing NO_x emission control system designs for locomotive applications.

TEST PROCEDURES

Test Route

The U.S EPA worked with representatives of Union Pacific Railroad (UP), BNSF Railway (BNSF), the Association of American Railroads (AAR) and researchers at the Southwest Research Institute (SwRI) to identify a train route and train configuration that would provide as close as possible to worse case high ambient temperature, lubricant temperature, coolant temperature and exhaust temperature conditions for locomotive operation. A westbound route operating heavy freight trains from Sparks, Nevada through Donner Pass to Roseville, California was identified as meeting these conditions. The route started at an elevation of approximately 4400 feet (1340 m) at the Union Pacific Railyard in Sparks, Nevada and over the course of approximately 50 miles climbed through Donner Pass to an altitude of approximately 6890 feet (2100 m) near Norden, California. The remaining 70 miles of the route were primarily downhill, terminating at the Union Pacific Railyard in Roseville, California at an altitude of 144 feet (44m). A similar route through the Donner Pass and the tunnels and snow-sheds near Norden California was used by General Electric (GE) for high altitude testing during development of the Evolution Series of locomotives.[6,7] The test route is summarized in Table 1. Data was acquired primarily between Sparks, Nevada and Soda Springs, California on August 29, 2007 (see map in Figure 1).

Locomotive and Freight Train Configuration

Two locomotives certified to meet the current Tier 2 U.S. Federal locomotive emissions standards were selected for the tests and were instrumented with data acquisition systems. One of the locomotives instrumented for the tests, UP8353, was an Electro-Motive Diesel (EMD) SD70ACe. The other instrumented locomotive, BNSF7736, was an ES44DC produced by GE. EPA has monitored the emissions data of both locomotives through their participation in annual in-use emissions testing conducted by the Association of American Railroads at SwRI in San Antonio, TX.

The instrumented locomotives were operated in two positions three and four of a four-locomotive consist, behind two uninstrumented Tier 0 locomotives. A fifth uninstrumented Tier 2 locomotive was operated at the rear of the freight train as an unmanned distributed power unit. During the west-bound test, the freight train consisted of 62 cars weighing 8,347 tons. (Table 2) contains a summary of the locomotives' specifications.

Table 1: The locomotives were operated pulling a heavy freight train west-bound on a route through Donner Pass from Sparks, Nevada to Roseville, California. Locations, altitudes and map coordinates are summarized below.

Location	Cumulative Distance	Altitude (ft)	Altitude (m)	Map Coordinates		Notes
Sparks, NV (UP Railyard)	0	4404	1342	39° 31' 50" N	119° 45' W	Data acquisition started
Truckee, CA	21	5814	1772	39° 19' 43" N	120° 10' 53" W	
Tunnel 13 (East Portal)		6440	1963	39° 18' 47" N	120° 14' 39" W	
Tunnel 13 (West Portal)	33.5	6420	1957	39° 18' 55" N	120° 14' 43" W	
Snow-shed 47 (East)		6550	1996	39° 18' 41.5" N	120° 16' 04" W	
Snow-shed 47 (West)	34.5	6581	2006	39° 18' 42" N	120° 16' 15" W	
Tunnel 41 (East Portal)	38	6758	2060	39° 18' 03.5" N	120° 18' 00.5 W	UP Tunnel 41 is an unventilated tunnel that extends approximately 2 miles between portals.
Tunnel 41 (West Portal, near Norden, CA)	36	6887	2099	39° 18' 32" N	120° 20" 7" W	
Tunnel 41 (West Portal Including Snow-shed)		6887	2099	39° 18' 34" N	120° 20' 15.5" W	The locomotive consist was observed leaving the Tunnel 41 snow-shed at approximately 4:37 pm. This point was the highest altitude attained along the route.
West Norden Snow-shed (East)		6870	2094	39° 19' 01" N	120° 21' 25" W	
West Norden Snow-shed (West)		6854	2089	39° 19' 05" N	120° 21' 35" W	
Soda Springs, CA	44	6753	2058	39° 19' 21" N	120° 22' 44" W	Data downloaded, GE EMS data terminated
Roseville, CA (UP Railyard)	127	144	44	38° 43' 37" N	121° 18' 36" W	Remaining data acquisition terminated, data downloaded

Figure 1: Map of the East Donner Pass region showing the route from Sparks, NV to Soda Springs, CA and the details of the area near UP Tunnel #41 (courtesy of Union Pacific Railroad).

Table 2: Specifications for the locomotives used in the test train are summarized in the table below.

Locomotive	Manufacturer and Model	Engine	Emissions Level	Relative Position of Locomotive	Instrumented?
UP5559	GE C44AC	GE 7FDL V16, 176 L, 3280 kW @ 1050 rpm (gross power rating)	Tier 0	Lead consist, Position 1, cab facing front	No
UP5571	GE C44AC	GE 7FDL V16, 176 L, 3280 kW @ 1050 rpm (gross power rating)	Tier 0	Lead consist, Position 2, cab facing front	No
UP8353	EMD SD70ACe	EMD 16-710G3C-T2 V16, 186 L, 3200 kW @ 950 rpm (traction power rating)	Tier 2	Lead consist, Position 3, cab facing rear	Yes
BNSF7736	GE ES44DC	GEVO V12, 188L, 3360 kW @ 1050 rpm (gross power rating)	Tier 2	Lead consist, Position 4, cab facing rear	Yes
UP8412	EMD SD70ACe	EMD 16-710G3C-T2 V16, 186 L, 3200 kW @ 950 rpm (traction power rating)	Tier 2	Rear-end unmanned distributed power unit, cab facing front	No

Instrumentation

Independent Data Acquired from the Locomotive

Two Tier 2 locomotives in the third and forth positions in the locomotive consist were instrumented with sensors and data recording equipment to study the engine and ambient air conditions present during tunnel operation in Union Pacific's Donner Tunnel system. Conditions of monitored for this study included:

Ambient Air:

- Temperature (above cab)
- Relative humidity
- Barometric pressure
- NO_x concentration
- Oxygen (O_2) concentration

Engine/Locomotive:

- Exhaust temperature @ exhaust turbine inlet
- Exhaust temperature @ exhaust turbine outlet (stack)
- Radiator inlet air temperature
- Radiator outlet air temperature
- Engine speed
- Exhaust NO_x concentration
- Exhaust O_2 concentration
- Air temperature @ turbo-compressor inlet (air filter box)
- Air temperature inside locomotive auxiliary cab

Each locomotive was equipped with EPA-supplied data recorders known as 'SPOT' units (Simple, Portable, On-vehicle Testing). The SPOT units are equipped with an integral relative humidity sensor and utilize a Campbell CR5000 measurement and control system to record all sensor and thermocouple data at a rate of one sample every 6 seconds. Zirconia NO_x sensors, which also measure O_2 concentration, were installed in the air filter cabinet of each locomotive to measure 'ambient' concentration of these parameters. Zirconia NO_x sensors were also installed post-turbo on the GE unit (on a fixture attached to the muffler) and pre-turbo on the EMD unit (on a modified turbo clean-out/inspection plate) to measure the NO_x and O_2 concentrations in the exhaust. NO_x sensor calibrations were verified before and after testing. All temperature sensors used in this study were K-type thermocouples, with temperature data acquisition via the Campbell CR5000. Preliminary installation of the instrumentation was carried out approximately 1-month prior to the field tests at the SwRI immediately after the completion of the third annual series of in-use emissions tests for these two locomotives. The two locomotives participating in the test were operated by UP along routes that delivered locomotives to Roseville, California by the last week of August 2007. Final installation of the instrumentation was completed in Roseville two days prior to the field tests.

EMS Data Acquired from the Locomotive

Engineering staff from the manufacturers of both locomotives assisted with the acquisition of engine and locomotive data via the engine management system (EMS) on the locomotives and provided the EMS data to EPA. The EMS data provided general information about the impact of specific engine operating parameters on some of the measured properties acquired using the SPOT units and also allowed additional calculations in combination with the SPOT data. The EMS data was not reported directly within the final results of this work to due to its proprietary nature.

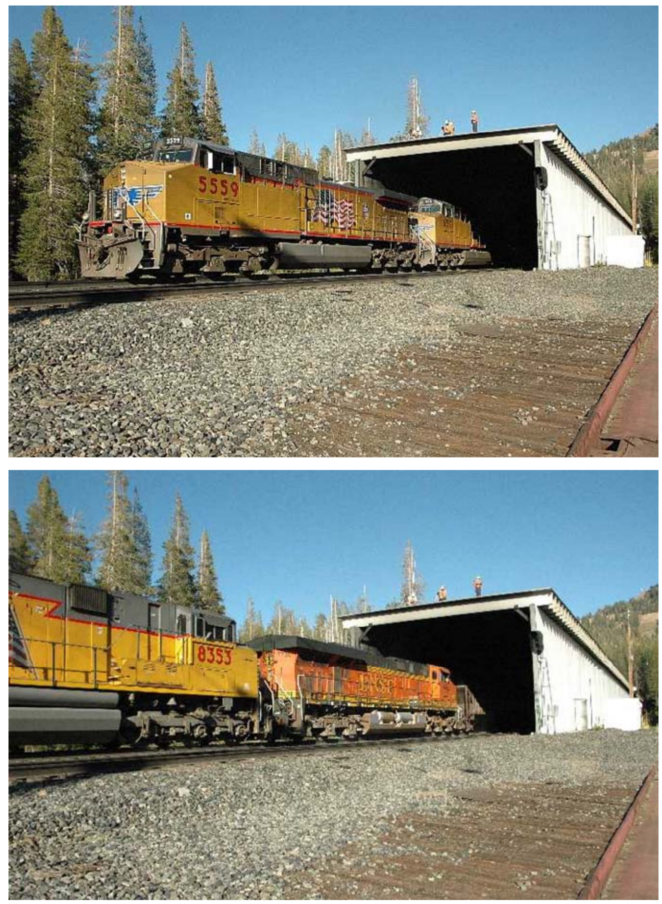


Figure 2: The above photos show the lead units in a four-locomotive consist leaving the 210 m (690') long snow-shed located at the west portal of Tunnel #41. The lower photo shows the two instrumented locomotives (UP8353 and BNSF7736). The thermographic camera and its operator can be seen near the top-center of the snow-shed. Ventilation of the snow-shed is through open slots located immediately below the roof supports. The west portal of Tunnel 41 is a the far (east) end of the snow-shed in these photographs

NO_x Emissions Calculations

Measured NO_x concentrations acquired by via SPOT were combined with EMS data to calculate NO_x mass emission rates and brake-specific NO_x emissions using a chemical mass balance approach:[8]

$$\dot{n}_{exhaust} = \frac{\dot{m}_{fuel} * w_C}{M_C * x_{C\_comb\_wet}}$$

where:

$\dot{n}_{exhaust}$ = molar exhaust flow (mol/hr)

$\dot{m}_{fuel}$ = fuel mass flow (g/hr)

w_C = carbon mass fraction of the fuel

M_C = molecular weight of carbon

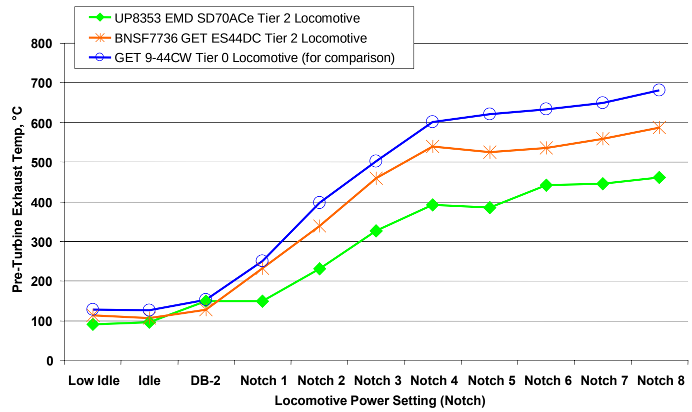
$x_{C\_comb\_wet}$ = the molar fraction of carbon from fuel per mol of wet exhaust based on chemical mass balance based on H:C ratio of fuel and exhaust-λ measurement. From this, NO_x emissions rate in g/hr was calculated as:

$$\dot{m}_{NO_x} = M_{NOx} * x_{NOx} * \dot{n}_{exhaust}$$

and brake-specific NO_x emissions over an interval of the route were then calculated from the integrated NO_x mass emissions divided by the locomotive work determined from the EMS data collected over the tested route. NO_x emissions were corrected for measured humidity.[9]

Infrared Thermography

A limited set of thermography data was acquired using an Infrared Solutions IR Flexcam T thermographic full-motion video camera. The FlexCam T has a NIST-traceable calibration from 0 °C to 600 °C with an accuracy of 2 °C or 2% of reading (whichever is greatest). The thermographic camera was operated in tandem with a full motion video camera, both of which were mounted on top of the UP Tunnel #41 west portal snow-shed. The cameras were aimed approximately 45° from horizontal and the Flexcam T was focused near the focal distance of the roofs of the locomotives just after exiting the west portal of the snow-shed (Figure 2). Thermographic results were compared to the SPOT/thermocouple measurements and to previous exhaust temperature measurements obtained during locomotive emissions tests at SwRI which are summarized in Figure 3.



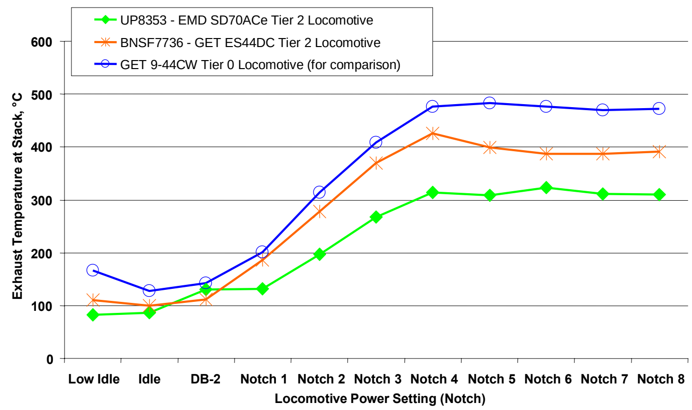


Figure 3: The charts above show laboratory measurements of pre-turbine and exhaust stack temperatures for both locomotives participating in the field tests compared to a representative GE Tier 0 locomotive.

RESULTS

SPOT Data

A summary of the measured parameters over the most heavily loaded portion of the route is shown in Figure 4. The highest ambient, coolant, and exhaust temperatures that occurred over the tested route were inside the west portal of Tunnel #41. Prior to entering the first tunnel (tunnel #13), air inlet temperatures and air temperatures at the radiator inlets were approximately 35 °C (95 °F). Post-turbine exhaust stack temperatures for both locomotives prior to Tunnel #13 were approximately 50 °C higher than temperatures previously observed during static locomotive FTP emissions tests at SwRI.[10] The highest observed ambient temperatures, pre-turbine exhaust temperatures and exhaust stack temperatures occured near the west portal of Tunnel #41 near the transition from the unventilated tunnel into the passively-ventilated snow-shed. Very high peak ambient air temperatures of approximately 95 to 110 °C (200 to 230 °F) were observed at the radiator air inlets for the trailing two locomotives in the locomotive consist near the west portal of Tunnel #41.

Turbocharger compressor intake air temperatures were similarly high (90 to 100 °C). The peak exhaust temperature reached by BNSF7736 was 560 °C near the west portal of Tunnel #41 just prior to reaching the snow-shed. The peak exhaust temperature for the UP8353 was 430 °C and was reached at approximately the middle of Tunnel #41. In both cases, exhaust temperatures were self-limited by active EMS engine and locomotive protection measures designed by the locomotive manufacturers to prevent excessively high coolant and oil temperatures. This was accomplished by the EMS via de-rating of engine power by the electronic controls as monitored coolant and oil temperature limits and turbocharger speed limits were approached or exceeded. The engine de-rate events are marked within Figure 5. The amount of engine power available during these conditions and the exact conditions triggering engine de-rate are considered proprietary information by the locomotive manufacturers, and thus are not reported in this paper. In general, an engine de-rate to 50% of rated power or less is possible under these types of extreme operating conditions. Although operator demand was for full power (“throttle notch 8”) for the entire length of Tunnel #41, the combination of locomotive engine de-rating for engine protection and the grade in Tunnel #41 caused a significant decrease in train speed between the east and west portals. Train speed was approximately 21 mph (34 km/h) as the lead consist entered the east portal of Tunnel #41 and had reduced during the two miles within the tunnel to approximately 6.5 mph (10 km/h) at the west portal.

A comparison between exhaust stack versus ambient temperatures along with a comparison of exhaust concentrations of NO_x and O_2 to ambient NO_x and O_2 concentrations suggests an exhaust dilution ratio with air of approximately 5:1 in the area near the two trailing locomotives in the lead consist as it approached the west portal of Tunnel #41. It is likely that the amount of air physically displaced by the train within the tunnel may have caused a “piston effect” that pushed air and exhaust in front of the lead consist and contributed to the high ambient temperatures observed at the radiator air-inlets, turborcharger compressor inlet and on top of the locomotive.

Extended full-load operation in “throttle notch 8” without engine de-rate was observed for both instrumented locomotives while climbing through Donner Pass prior to the entrance to Tunnel #13. Exhaust stack temperatures over this part of the route were still lower than those observed with engine de-rate within Tunnel #41.

Infrared Thermography

Thermographic measurements of external exhaust stack surfaces (Figure 6) showed good agreement with post-turbine temperatures measured via K-type thermocouples for UP8353 (~214 °C via IR vs. 231 °C via thermocouple). Similar measurements with BNSF7736 showed IR thermographic results that were approximately 100 °C less than post-turbine exhaust stack measurements with K-type thermocouples. The shape and construction of the muffler used within the exhaust stack of the GE ES44DC locomotive may have contributed to this difference. The IR thermographic measurements are non-contact line-of-sight measurements. The UP85353 EMD SD70ACe locomotive had a fairly simple, open exhaust stack configuration that allowed a relatively unobstructed line of sight directly into the exhaust stack for the IR measurements. The BNSF7736 GE ES44DC locomotive used an exhaust stack with double-wall construction extended above the cab while the UP8353 exhaust stack was flush with the cab. BNSF7736 also had a large muffler with a high-surface-area baffle obstructing the line-of-sight into the exhaust stack and possibly contributing to exhaust-stack heat rejection.

The two GE C44AC uninstrumented lead units in the consist, UP5559 and UP5571, both had double-wall exhaust stack configurations that were similar to that of the GE ES44DC except that they did not appear to use the same type of muffler baffle arrangement within the exhaust stack. Thermographic measurements of the exhaust surfaces of the two lead units indicated that they were operating at a de-rated power output that may have been similar to that of the BNSF7736. It should be noted that because the thermographic images were acquired at the snow-shed exit, temperatures had already declined considerably from their peak values. Exhaust stack configurations for UP5559, UP8353 and BNSF7736 are compared in Figure 7.

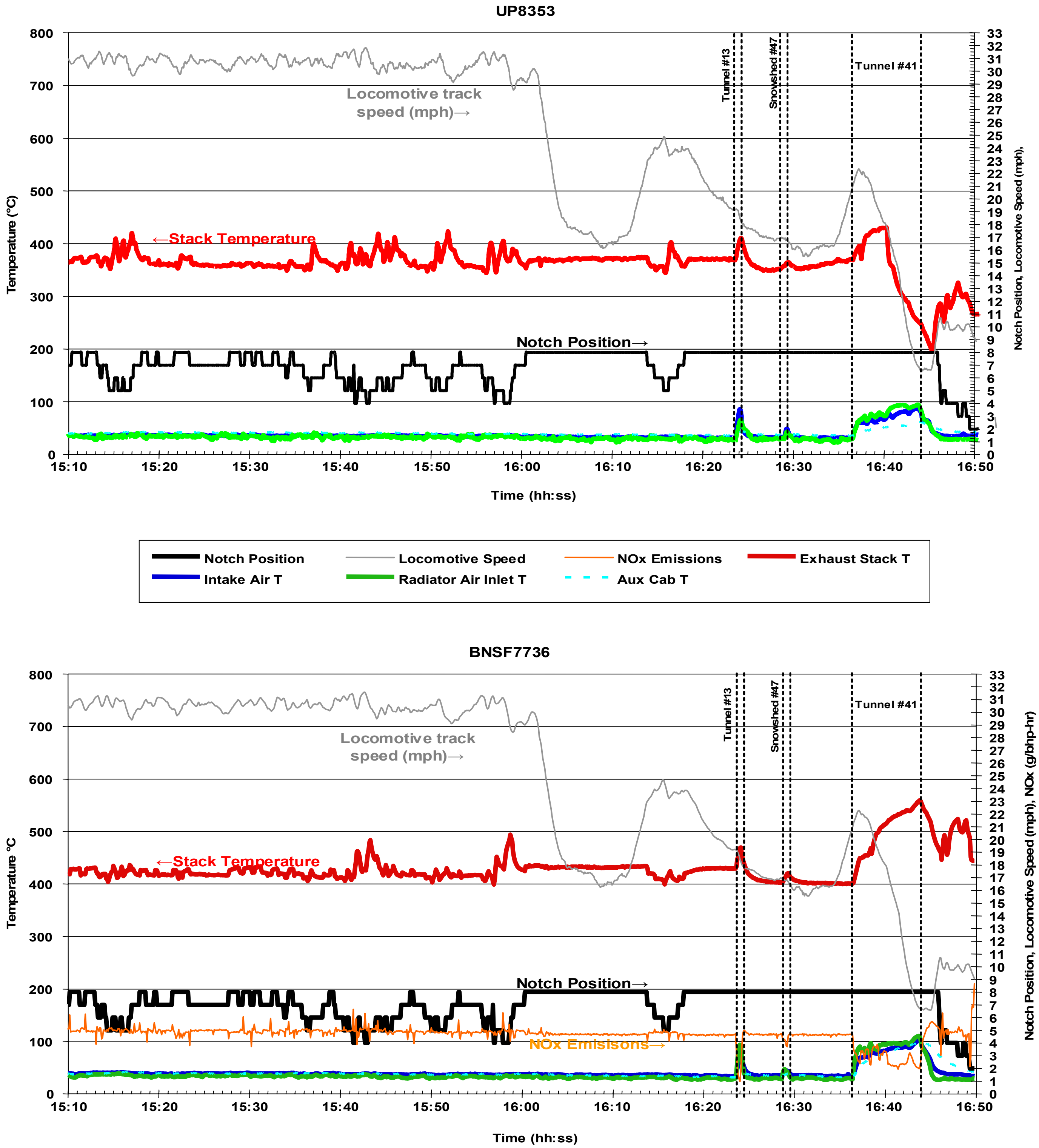


Figure 4: Summary of parameters measured from locomotives UP8353 and BNSF7736. The time shown is U.S. Pacific Time on August 29, 2007. The lead consist was under load for this entire portion of the trip.

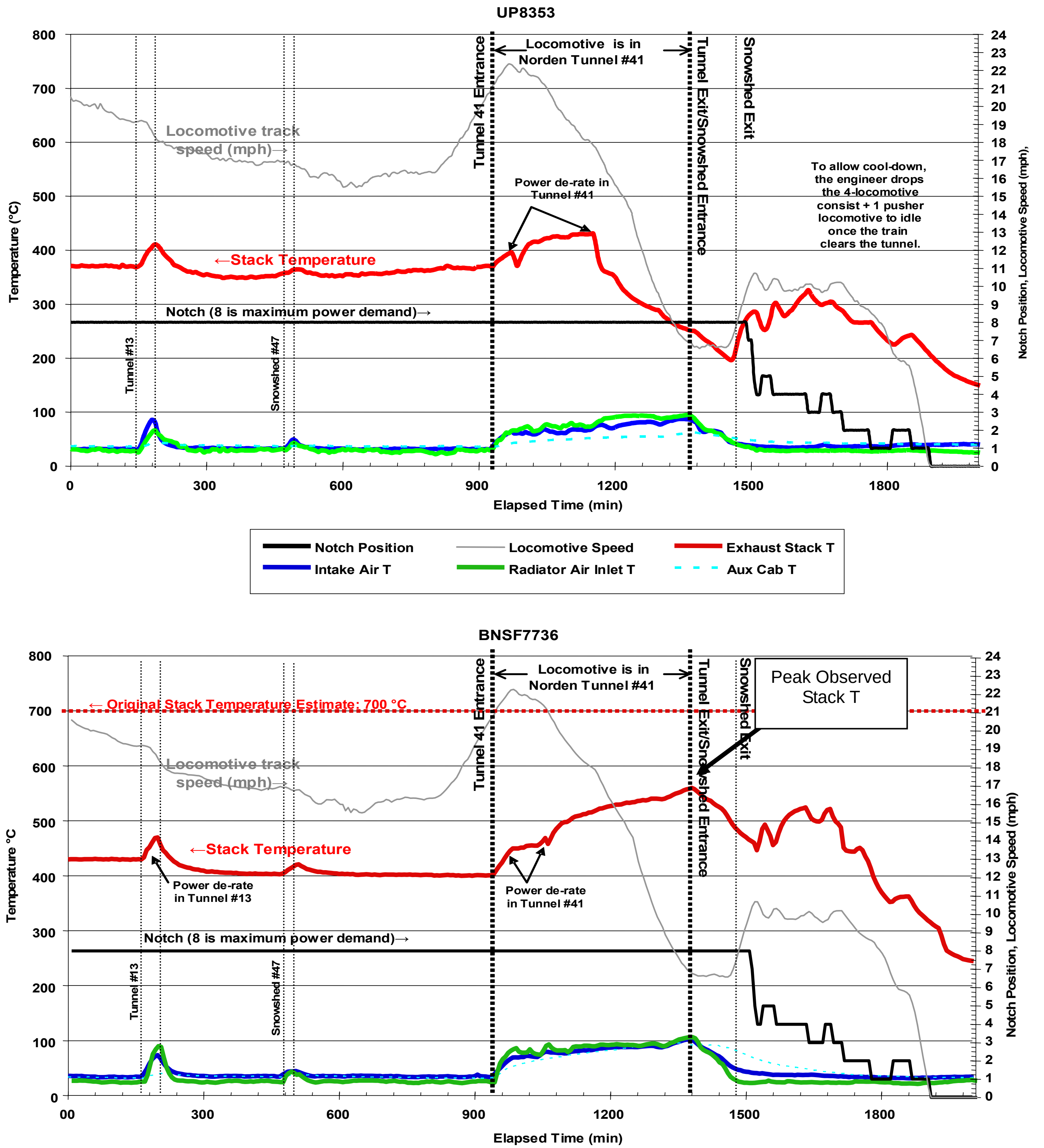


Figure 5: Additional details of the measured parameters during operation in Tunnel #41. Time shown is the time elapsed from train's the approach to Tunnel #13.

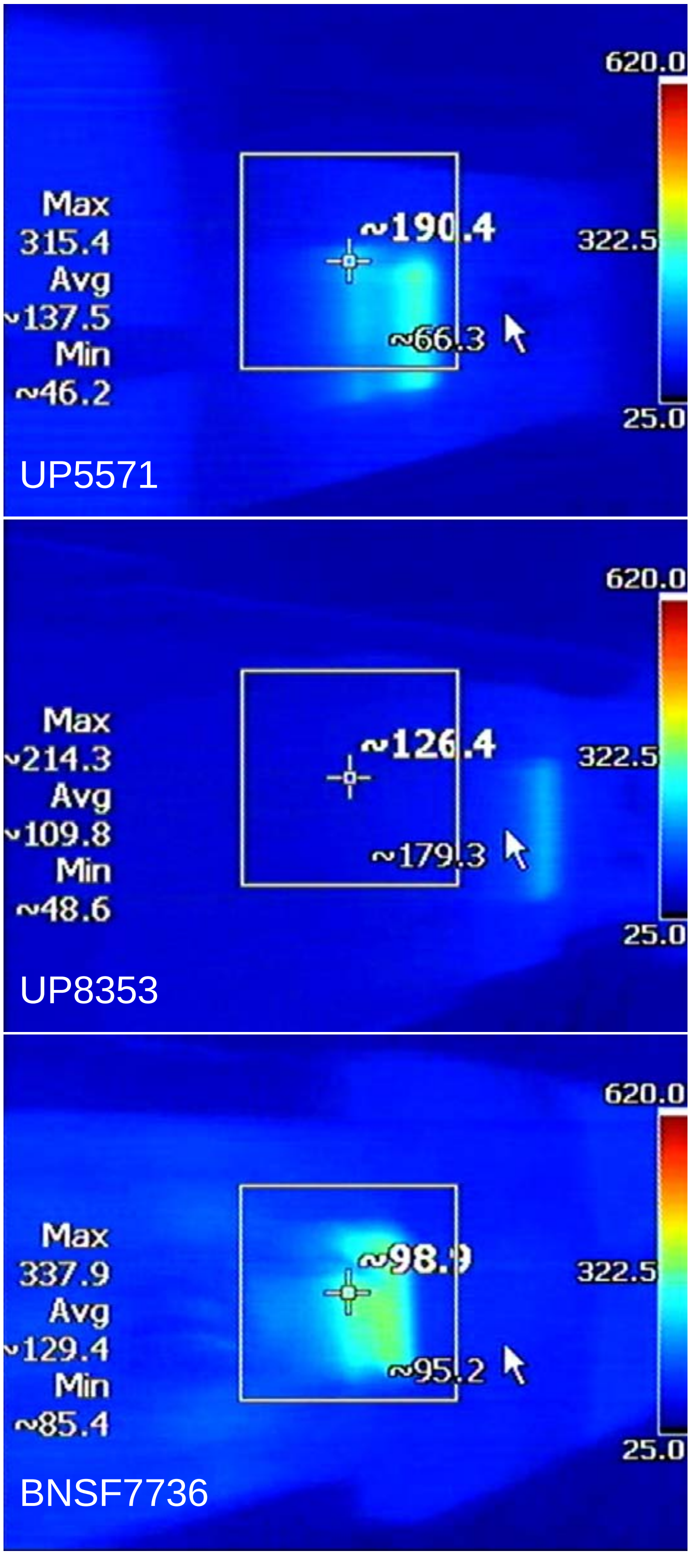


Figure 6: Thermographs of the roofs and exhaust stacks of UP5559 (upper image), UP8353 (middle image) and BNSF7736 (lower image) immediately after emerging from the snow-shed at the west portal of Tunnel #41.

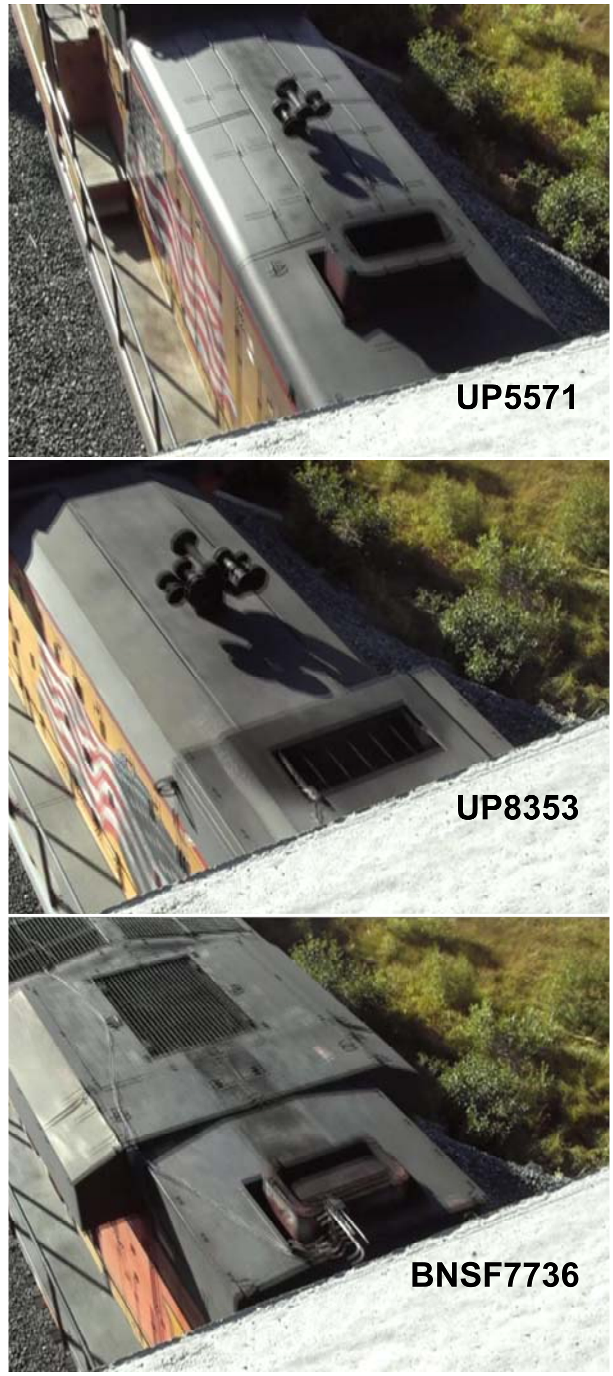


Figure 7: Exhaust stack configurations for UP5571 (UP5559 was identical), UP8353 and BNSF7736.

Brake-specific NO_x Emissions

Problems with a pre-turbine NO_x sensor due to a recessed mounting and subsequent excessive heat-soak resulted in the loss of valid NO_x concentration data for UP8353 during testing. Average brake-specific NO_x emissions for BNSF7736 were 4.2 g/bhp-hr for BNSF7736 over the segment of the route from Sparks, Nevada to Soda Springs, California. The integration of NO_x over this segment of the route included approximately 2 hours and 40 minutes of idle prior to the start of operation under load. With the exception of brief periods during notch transitions, brake-specific NO_x emissions for BNSF7736 were very close to 5.0 g/bhp-hr for most of the loaded operation climbing from Sparks, Nevada to Soda Springs, California (Figure 4), which included a change in elevation of nearly 2,500 feet (760 m) climbing to nearly 7,000 feet (2134 m) near the Tunnel #41 West Portal. The Tier 2 NO_x standard in the U.S is 5.5 g/bhp-hr over the EPA Line-haul locomotive test cycle and the maximum elevation for locomotive emissions compliance in the U.S. is 7,000 feet.

CONCLUSION

Tier 2 locomotive exhaust temperatures were monitored continuously over the west-bound route from Sparks, Nevada through Donner Pass to Soda Springs California. The test route climbed to nearly 7,000 (2134 m) elevation. Two Tier 2 locomotives that operated as part of a four-locomotive consist pulling a heavy freight train over this route encountered peak ambient and post-turbine exhaust stack temperatures within or near the west portal of Union Pacific Tunnel #41. Peak exhaust stack temperatures of 560 °C and 430 °C were observed for locomotives BNSF7736 GE ES44DC and UP8353 EMD SD70ACe, respectively. Ambient temperatures exceeding 100 °C (212 °F) were observed as the lead locomotive consist approached the west portal of Tunnel #41. Engine protection measures implemented within the electronic locomotive and engine management systems of both locomotives limited the peak exhaust temperatures encountered during the tests. Such engine protection measures are typically set to prevent exceeding temperature limits for materials, lubricants and engine coolant. Considering the severe nature of the operational conditions encountered over the tested route and the observed intervention of the electronic engine management system, the post-turbine exhaust stack temperatures observed are likely very close to an upper bound of temperatures that can be encountered during heavy-haul operations. The temperatures encountered during locomotive field testing were significantly less than temperatures currently encountered during forced PM trap regeneration in 2007 model year and later U.S. over-the-road Class 8 truck operation, and were below the temperatures at which significant thermal degradation occurs for base-metal zeolite urea SCR systems now under consideration for U.S. Tier 4 locomotive applications.[11]

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