RESEARCH & DEVELOPMENT

Evaluation of Locomotive Emissions Reduction Strategies

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16. Abstract

Older diesel locomotives may have higher per passenger mile emission rates of NO_x and PM compared to other transport modes. Therefore, to reduce human exposure to train-generated air pollution, measures to reduce emissions from existing locomotives are desirable. Fuel use and emission rates (FUER) depend on exhaust after-treatment technology, locomotive operation, and fuels. Variation in locomotive operation results in spatial variation of FUER along the route. Thus, there could be hotspot locations with high emissions. Switching fuels to biodiesel blends affects FUER due to differences in fuel physical and chemical properties. Here, interactions between technology, operation, and fuels were evaluated. Rail yard (RY) and over-the-rail (OTR) measurements were conducted using portable emission measurement system (PEMS) to quantify FUER. Data from multiple measurements were time-aligned and screened for errors. RY measurements included three replicates of a predefined test schedule. OTR measurements included 6 one-way trips on the Piedmont rail route between Raleigh, NC and Charlotte, NC. The retrofit of a selective catalytic reduction-based Blended exhaust After Treatment System (BATS) for controlling NO_x emissions was evaluated based on RY measurements. Simultaneously, PEMS-based emission rates were benchmarked to a Federal equivalent method (FEM). The effect of operation was assessed by comparing one-way trips with the highest and lowest trip total fuel use and emissions. Spatial variability in FUER was compared to spatial variability in train speed, acceleration, rail-grade and rail curves. In prior work, FUER were quantified for several blends of biodiesel and diesel. Less than 1 % of the data were excluded during screening. PEMS-based emission rates of CO_2, NO_x and PM were highly correlated with the FEM. BATS is highly recommended for reducing NO_x emissions. Efficient locomotive operation including fewer notch changes and avoiding rapid accelerations and decelerations is recommended for reducing trip total fuel use and emissions. A 20 percent blend of biodiesel in diesel is effective in reducing CO, HC and PM emission rates. A combination of technology, operation and fuels is highly recommended to simultaneously reduce fuel use and emissions of CO, HC, NO_x and PM. This research demonstrates that PEMS-based measurements are reliable for quantifying the effect of technology, operation and fuels on FUER.

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Executive Summary

Introduction
Diesel locomotives used for passenger rail have a long service life. Purchasing new locomotives with lower emissions is costly. Therefore, to reduce human exposure to train-generated air pollution, measures to reduce emissions from existing locomotives are desirable. Over-the-rail (OTR) measurements of pollutant exhaust concentrations during actual train service were conducted using a portable emission measurement system (PEMS). The objectives of this work are to: (1) quantify the accuracy of PEMS-based FUER; (2) quantify factors affecting FUER of a passenger train; and (3) identify and characterize energy use and emission reduction strategies.

The North Carolina Department of Transportation (NCDOT) owns eight diesel locomotives for Amtrak operated passenger service between Raleigh, NC and Charlotte, NC. Each locomotive has two engines: Prime Mover Engine (PME), and Head End Power (HEP) engine. These engines are typically operated on ultra-low sulfur diesel (ULSD). The PME has a throttle control with eight positions, a high idle, and a low idle position. Each of the throttle positions is called a Notch. The PMEs of NCDOT locomotives are old, lack emission controls and produce high emissions of gaseous pollutants and particulate matter (PM). The NCDOT seeks to quantify the emissions of these locomotives and to identify and evaluate options for emissions reductions to meet increasingly stringent emission standards.

Locomotive FUER depend on factors such as exhaust after-treatment technology, locomotive operation, and fuels. Variation in locomotive operation also results in spatial variation of FUER along the route. Thus, there could be regions with emissions higher than a threshold value. Such regions are known as emission hotspots. Exhaust after-treatment could reduce the frequency and magnitude of hotspots. Changes in operational practices could prevent some emissions. Switching fuels to biodiesel blends affects FUER due to differences in energy intensity and chemical composition.

Methods
Baseline measurements on a locomotive operating on ULSD were conducted. The retrofit of a Blended exhaust After Treatment System (BATS) to an F59PH locomotive was evaluated based on rail yard (RY) measurements. The BATS is a selective catalytic reduction (SCR)-based exhaust after-treatment system that treats the combined (blended) exhaust from the PME and HEP engine.

The role of variability in train operations and its effect on fuel use and emissions was assessed by comparing one-way trips with highest and lowest trip total fuel use and emissions. Further, spatial variability in these rates was compared to spatial variability in train speed, acceleration, rail-grade and rail curves. In prior work, the locomotive was operated on several blends of biodiesel and diesel and FUER for each fuel blend were quantified. Here, interactions between technology, operation, and fuels were evaluated. Emission hotspots were identified based on 0.25-mile segments of the 173-mile route that had the top 20th percent frequency range of segment total emissions.

Typically, one RY test and six OTR one-way trips per locomotive were conducted to quantify notch average FUER for each of baseline, operation, and fuels. Exhaust gas and PM concentration measurements were conducted using an Axion PEMS. RY tests included running the locomotive at each of the PME throttle notch positions for a pre-defined time duration, known as a test schedule. RY tests included three replicates of the test schedule. Baseline RY measurements of the HEP engines were conducted in prior work. OTR tests were conducted on the revenue generating Amtrak Piedmont passenger rail service between Raleigh, NC and Charlotte, NC. A typical train consist included 1 locomotive, 2 passenger cars, and 1 baggage/café car. Each one-way trip had a different fraction of time spent in each throttle notch position, also known as a duty cycle, due to differences in driver behavior. Notch average FUER were weighted to selected duty cycles to estimate cycle average FUER. The U.S. Environmental Protection Agency (EPA) specifies the Line-Haul duty cycle for regulatory purposes. A typical duty cycle on the Piedmont route had a higher fraction of time at Notch 8, and a lower fraction of time at idle, compared to the Line-Haul cycle.

The PEMS-based measurement method was benchmarked to a reference method that satisfies EPA requirements for certification testing. The benchmarking was based on four replicates of railyard measurements.

Technology

To quantify notch average FUER for technology and to benchmark Axion PEMS, RY measurements were conducted in October 2016 for a first-generation BATS that was installed on locomotive NC 1859. A "zero hour" compliance test was conducted by Engine Fuels and Emissions Engineering (EF&EE) using their locomotive emission measurement system (LEMS). The LEMS provides 40 CFR 1065 Subpart J compliant measurements of CO_2, CO, HC, NO_x and PM. Combined fuel use rate of the PME and HEP engine was measured gravimetrically at each notch change, and PEMS- and LEMS-based emission rates were estimated. NCSU used PEMS to conduct measurements simultaneously with LEMS. Using the LEMS as a baseline reference, the precision and accuracy of the FUER estimated based on the Axion PEMS was evaluated.

Operation

Factors affecting train energy use and emissions include train activity and track geometry. Train activity includes train speed and acceleration. Track geometry includes track grade and curvature. The trips with highest fuel use and emissions were compared to trips with lowest fuel use in terms of locomotive speed and acceleration, track grade and curvature. Typically, the trip with highest fuel use also had the highest emissions of CO_2, CO, HC, NO and PM. Thus, comparison amongst the trips with highest and lowest fuel use was used to quantify the effect of locomotive operation that led to variation in FUER. The rail-route was divided into equal length segments of 0.25 mile. Segment average speed, acceleration, grade and curve radii were compared to segment total fuel use and emissions. These comparisons help identify fuel use and emission hotspots along the rail route.

Fuels

NCSU conducted a prior multi-year study of the effect of biodiesel fuel on emissions of selected NCDOT locomotives with sponsorship from the Federal Railroad Administration and in collaboration with NCDOT. Using PEMS, cycle average NO_x, HC, CO, PM and CO_2 emission rates were previously estimated for three locomotives operating on ULSD and soy-based B10, B20, and B40 biodiesel blends. Measurements were conducted in the RY and OTR during passenger service. Compared to ULSD, B20 biodiesel had statistically significant average emission rate reductions in the RY of 58 percent for CO, 45 percent for PM, and 6 percent CO_2 and OTR of 59 percent for HC, 50 percent for CO, 26 percent for PM, and 5 percent for CO_2. The average differences in notch average NO_x emission rates for both the RY and OTR, and HC in the RY, were not statistically significant. The OTR findings typically agreed qualitatively with the RY findings; however, OTR provides a better basis for estimating the real-world impact of fuel switching. The results indicate substantial potential to reduce in-use locomotive emissions for existing older locomotives, with the exception of NO_x. FUER of an average locomotive were derived from the above study were used here to quantify interactions amongst technology, operation, and fuels.

Results

This section summarizes baseline measurements and quantifies the individual effects of technology, operation, and fuels on FUER. The combined effect of technology, operation, and fuels on FUER is also described here.

Benchmark Axion PEMS

PEMS-based fuel use rates were highly correlated with the gravimetric measured fuel use rates, with a mean error ranging from only 7 percent at idle to 1 percent at notch 8. The range of errors in fuel use rates for individual notch average rates from a given replicate were from –1.5 g/s to + 1.2 g/s. The CO_2 and NO_x emission rates from the PEMS measurements also agreed well with those from the LEMS, with mean errors less than 4 percent for CO_2 and NO_x emission rates, respectively. The Axion PEMS-based PM emission rates were correlated with LEMS-based PM emission rates with a correlation coefficient of 0.8. Because CO and HC emission rates were low and generally based on concentrations below the detection limit, a direct comparison between PEMS and LEMS was not possible for these two pollutants.

Baseline Measurements

The baseline RY measurements on locomotive NC 1859 were conducted on November 18, 2015. The baseline OTR PME exhaust concentration measurements on locomotive NC 1859 were conducted during April 2016. The train consist included one locomotive, two passenger cars and one baggage/café car. Notch average FUER were estimated and weighted to the EPA line-Haul and an Average Piedmont cycle. The average Piedmont duty cycle was estimated based on 48 one-way trips conducted in prior work. Cycle average FUER for RY and OTR measurements are given in Table ES-1.

For RY tests, the EPA line-haul cycle typically had higher FUER than the Piedmont cycle except for CO emissions. The measured cycle average NO_x emission rate was higher than the level of the Tier 0+ standard for each of the three replicates for both cycles. Cycle average CO emission rates were lower than the level of the Tier 4+ standards. Cycle average HC emission rates were lower than the level of the Tier 3+ standards. The estimated cycle average PM emission rate was higher than the level of the Tier 0+ standard.

TABLE ES-1. Baseline Cycle Average Emission Rates for the Prime Mover Engine of NC 1859 operated on Ultra-Low Sulfur Diesel Based for the Rail Yard and Over-the-rail measurements.

(a) Rail Yard Measurements conducted on 11/18/2015.

Property	Cycle	Replicate 1 (g/bhp-hr)	Replicate 2 (g/bhp-hr)	Replicate 3 (g/bhp-hr)	Average (g/bhp-hr)	Std Dev (g/bhp-hr)	CV[a]
Fuel	EPA Line-Haul	162	156	161	160	3	0.02
	Average Piedmont	158	150	157	155	4	0.03
CO_2	EPA Line-Haul	506	488	502	499	10	0.02
	Average Piedmont	494	470	490	484	13	0.03
CO	EPA Line-Haul	0.21	0.24	0.23	0.23	0.01	0.06
	Average Piedmont	0.26	0.30	0.29	0.28	0.02	0.07
HC[b]	EPA Line-Haul	0.28	0.35	0.35	0.33	0.04	0.12
	Average Piedmont	0.18	0.27	0.27	0.24	0.05	0.22
NO_x[b]	EPA Line-Haul	9.6	9.4	9.1	9.4	0.2	0.02
	Average Piedmont	8.7	8.4	8.1	8.4	0.3	0.03
PM[b,c]	EPA Line-Haul	0.41	0.42	0.41	0.41	0.00	0.01
	Average Piedmont	0.36	0.36	0.35	0.36	0.01	0.02

(b) Over-The-Rail Measurements conducted between April 6 and April 20, 2016.

Property	Cycle	Baseline Cycle Average Emission Rates (g/bhp-hr)								CV[a]
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Average	Std Dev	
Fuel	EPA Line-Haul	175	172	156	162	166	162	165	7	0.04
	Average Piedmont	170	167	159	164	164	162	164	4	0.02
CO_2	EPA Line-Haul	547	536	505	507	518	505	520	18	0.03
	Average Piedmont	531	523	502	512	512	506	514	11	0.02
CO	EPA Line-Haul	58	41	49	62	33	57	50	11.0	0.22
	Average Piedmont	31	24	26	37	21	32	28	6.0	0.20
HC[b]	EPA Line-Haul	0.77	0.65	0.55	0.61	0.44	0.79	0.63	0.13	0.21
	Average Piedmont	0.56	0.51	0.37	0.43	0.28	0.54	0.45	0.11	0.24
NO_x[b]	EPA Line-Haul	10.2	10.8	9.6	9.9	8.7	9.6	9.8	0.7	0.07
	Average Piedmont	9.1	9.7	8.8	9.2	7.9	8.8	8.9	0.6	0.07
PM[b,c]	EPA Line-Haul	0.36	0.37	0.40	0.36	0.45	0.45	0.40	0.04	0.10
	Average Piedmont	0.30	0.32	0.34	0.31	0.40	0.41	0.34	0.05	0.14

[a] *CV = Coefficient of Variation (CV = Standard deviation divided by the mean)*

[b] *HC was measured using non-dispersive infrared (NDIR) of Axion PEMS, which accurately measures some compounds but responds only partially to others. NO_x includes NO and NO_2. Only NO was measured using Axion PEMS. NO_x is always reported as equivalent mass of NO_2. THC and NO_x were estimated from Axion measurements by applying bias correction factors given in Table 4-1. PM was measured using a light scattering technique, which provides useful relative comparisons of particle levels in the exhaust. Results include multiplicative correction factor of 5 to approximate total PM.*

[c] *The PM detection method used here is not a Federal Reference Method. However, notch average PM emission rates are useful to quantify the effect of technology, operation, and fuels on locomotive fuel use and emission rates.*

For OTR tests, the EPA line-haul cycle typically had higher FUER than the Piedmont cycle except for CO emissions. The measured cycle average NO_x emission rate was higher than the level of the Tier 0+ standard for each of the three replicates for both duty cycles. Cycle average CO emission rates were lower than the level of the Tier 4+ standards. Cycle average HC emission rates were lower than the level of the Tier 3+ standards. The estimated cycle average PM emission rate was higher than the level of the Tier 0+ standard.

Technology
RY measurements were conducted after the BATS was installed on locomotive NC 1859. Relative percentage differences in notch average fuel use rate, CO_2 emission rate and NO_x control efficiency due to BATS installation are given in Table ES-2. Fuel use rate increased for all notch positions, except idle. However, the increase was less than 1.6 percent. NO_x emission rates were consistently lower. The BATS was able to achieve a NO_x reduction of 96 percent at Notch 4. The reduction in NO_x emission rates was 80 percent or higher for notches 3 through 8. Overall, cycle average NO_x emission rates were 0.8 g/bhp-hr for the EPA Line-haul and average Piedmont duty cycles, which is lower than the level of Tier 4 standards.

Operation
The effect of locomotive operation on FUER was quantified. On a mass per time basis, FUER are directly related to rail grade, rail curvature, train speed, and train acceleration. Segment total fuel use and emissions were found to be directly related to grade and acceleration, and inversely related to train speed. The effect of higher mass per time fuel use and emissions at high speed was compensated by lower amount of time spent over a segment. Curves also impact fuel use and emission rates directly. However, on this route trains typically operate at reduced speeds of between 30 mph and 50 mph on curves of greater than 3 degrees. Thus, higher FUER due to curves were mitigated by lower train speeds.

The operator of the trip with the lowest trip fuel consumption typically operated the train at zero acceleration and high train speeds for longer periods of time compared to the trip with the highest fuel use. This enabled the operator to operate the locomotive at lower notch positions. The operator also typically coasted the train to a stop. These strategies resulted in a reduction of 30 percent, 20 percent and 18 percent in trip total fuel use, NO_x emissions and PM emissions by mass, respectively.

An example emission hotspot map is shown in Figure ES-1 for the baseline trip. Most of the fuel use hotspots coincided with emission hotspots. Thus, strategies that reduce fuel use will typically also reduce emissions. About 50 percent of the fuel use and emissions hotspots were due to combinations of grade, acceleration and curvature. About 25 percent of the hotspots were due to grade only and 25 percent were due to acceleration only. Curves may serve as potential hotspots, however low train speeds on curves mitigate the effect of curves. Thus, grade and acceleration were key factors for fuel use and emission hotspots. Low train speeds and acceleration at or near stations may affect local air quality as the fuel use and emission hotspots were inversely related to segment average train speed.

TABLE ES-2. Relative Percentage Differences in Notch Average Fuel Use Rate, CO_2 Emission Rate and BATS NO_x Control Efficiency due to BATS Installation on Locomotive NC 1859 Running on ULSD

Throttle Notch Position	Relative Percentage Difference with Respect to Baseline (%)		BATS NO_x Control Efficiency (%)
	Fuel Use	CO_2	
Low-Idle	-0.9	-1.1	92
High-Idle	-0.8	-1.1	53
1	1.6	1.7	50
2	0.1	0.1	75
3	0.7	1.4	93
4	0.5	1.5	96
5	0.4	0.8	93
6	1.2	1.3	81
7	0.1	0.3	90
8	0.4	0.5	88

Fuels

Locomotive FUER for biodiesel blends B10, B20 and B40 were compared to ULSD. B20 was found to be the most suitable fuel as B20 had the lowest cycle average NO_x and PM emission rates on the Average Piedmont cycle. B40 had the lowest fuel use rate. However, B20 also had a lower fuel use rate compared to ULSD. Thus, B20 is a suitable choice that leads to lower FUER. Cycle average FUER were estimated for each biodiesel blend and compared to ULSD. Cycle average FUER are given in Table ES-3. Cycle average CO_2 emission rates had similar trends as fuel use rates. Cycle average CO and HC emission rates were lower for B20 and B40. Cycle average NO_x emission rates were 4 percent lower for B20 compared to ULSD. B10 and B40 had higher NO_x emission rates. Cycle average PM emission rates were also lowest for B20. B40 also had lower cycle average PM emission rates compared to ULSD. B10 had comparable cycle average PM emission rates.

Combined Effect of Technology, Operation, and Fuels

Trip total fuel use and emissions were estimated for a locomotive running on ULSD without BATS for two selected trips with highest and lowest trip total fuel use. Trip total fuel use and emissions were also estimated for high and low fuel use trips for a locomotive operated on B20 without BATS; operated on ULSD with BATS; and operated on B20 with BATS. The trip total fuel use and emissions for each case are given in Table ES-4. The number of hotspots for each case is given in Table ES-5.

The mass of fuel consumed per trip decreased by 27 percent from 713 kgs to 518 kgs, due to better operational practices and switching from ULSD to B20. About 93 percent of this decrease was due to operational practices. The number of fuel use hotspots decreased by 55 percent. Better operational practice comprised 92 percent of the reduction in fuel use hotspots. Thus, most of the reduction in trip total fuel use and number of fuel use hotspots was due to better operational practices. Because fuel use increases slightly as a result of BATS, the BATS did not contribute to a decrease in fuel use rates or reduction in fuel use hotspots.

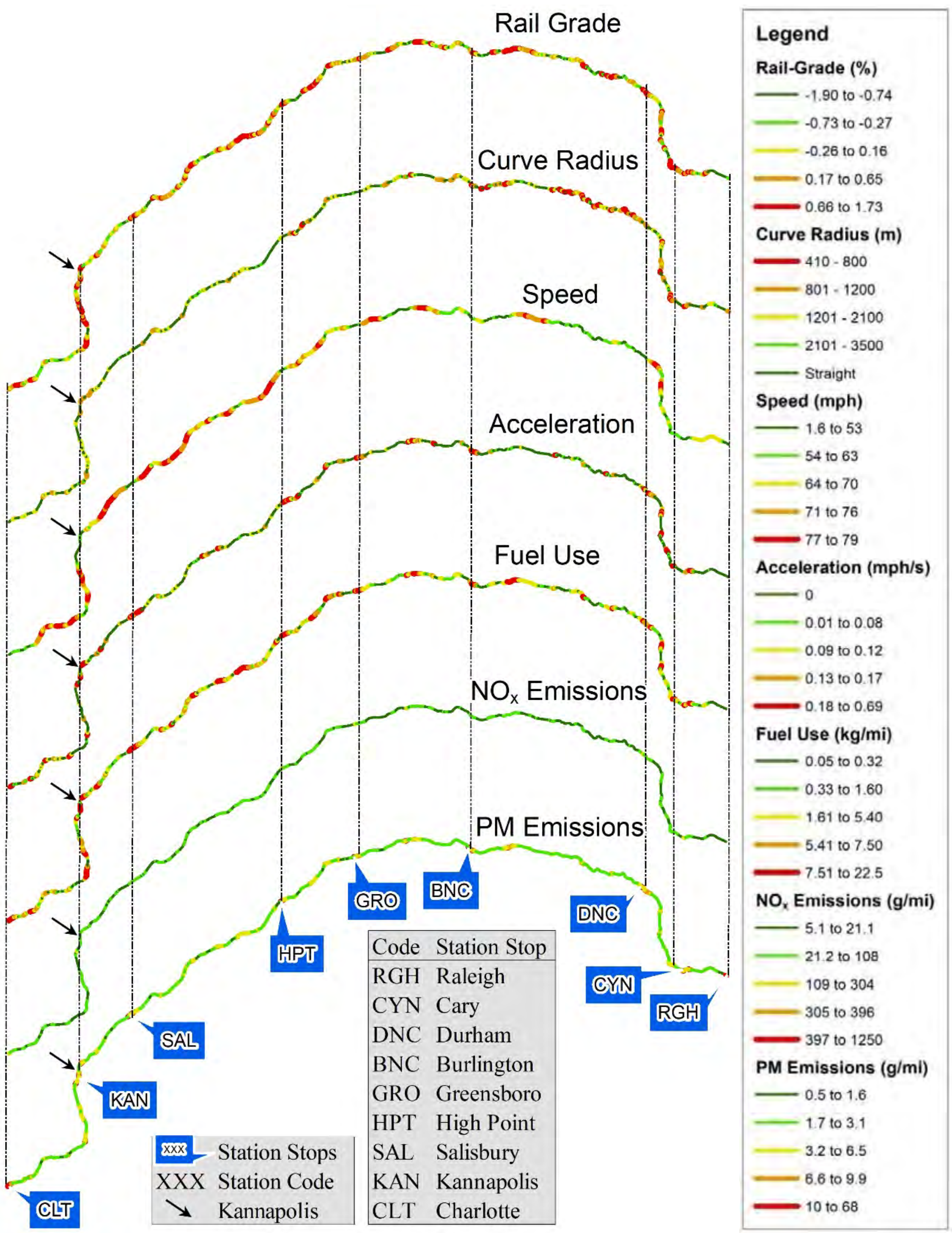

FIGURE ES-1. Estimated train activity, track geometry, fuel use and emissions for the observed trip with highest fuel use for locomotive NC 1859 running on ULSD. Train consist included one locomotive and three cars. Each variable is divided into 5 ranges with cutoff points indicating 20 percent frequency ranges based on the trip with highest fuel use. Red indicates the segments with top 20 percent frequency range and green represents the bottom 20 percent frequency range.

TABLE ES-3. Cycle Average Fuel Use and Emission Rates for an Average Locomotive Running on ULSD, B10, B20 and B40.

Quantity	Cycle	Unit	Fuel			
			ULSD	B10	B20	B40
Fuel Use	EPA Line-haul	g/bhp-hr	92.7	93.2	89.5	86.7
	Average Piedmont		109	109	105	103
CO_2	EPA Line-haul	g/bhp-hr	287	290	259	268
	Average Piedmont		339	340	307	319
CO	EPA Line-haul	g/bhp-hr	0.59	0.64	0.38	0.34
	Average Piedmont		0.73	0.80	0.47	0.42
HC[a]	EPA Line-haul	g/bhp-hr	1.3	0.7	0.6	0.6
	Average Piedmont		1.4	0.7	0.6	0.6
NO_x[a]	EPA Line-haul	g/bhp-hr	4.9	5.2	4.7	5.2
	Average Piedmont		5.4	5.8	5.3	5.8
PM[a,b]	EPA Line-haul	g/bhp-hr	0.17	0.18	0.10	0.13
	Average Piedmont		0.21	0.21	0.11	0.16

[a] *HC was measured using non-dispersive infrared (NDIR) of Axion PEMS, which accurately measures some compounds but responds only partially to others. NO_x includes NO and NO_2. Only NO was measured using Axion PEMS. NO_x is always reported as equivalent mass of NO_2. THC and NO_x were estimated from Axion measurements by applying bias correction factors given in Table 4-1. PM was measured using a light scattering technique, which provides useful relative comparisons of particle levels in the exhaust. Results include multiplicative correction factor of 5 to approximate total PM.*

[b] *The PM detection method used here is not a Federal Reference Method. However, cycle average PM emission rates are useful to quantify the effect of technology, operation, and fuels on locomotive fuel use and emission rates.*

TABLE ES-4. Trip Total Fuel Use and Emissions for Selected Trips with Highest and Lowest Fuel Use for Combined Effects of Technology, Operation, and Fuels on Diesel Locomotives

Techno-logy	Operation	Fuel	Fuel Use (kg)	NO_x (kg)	PM (kg)	CO (kg)	HC (kg)
None	Highest Fuel Use	ULSD	713	38.9	1.12	2.3	2.5
	Lowest Fuel Use		531	33.8	0.98	1.2	2.2
None	Highest Fuel Use	B20	694	38.5	0.66	1.5	1.3
	Lowest Fuel Use		518	33.4	0.60	0.8	1.2
BATS	Highest Fuel Use	ULSD	720	4.9	1.12	2.3	2.5
	Lowest Fuel Use		536	4.4	0.98	1.2	2.2
BATS	Highest Fuel Use	B20	715	4.9	0.66	1.5	1.3
	Lowest Fuel Use		532	4.4	0.60	0.8	1.2

TABLE ES-5. Fuel Use and Emission Hotspots for Individual and Combined Effects of Technology, Operation, and Fuels on Diesel Locomotives

Techno-logy	Operation	Fuel	Number of Hotspots				
			Fuel Use	NO_x	PM	CO	HC
None	Highest Fuel Use	ULSD	139	135	137	137	135
	Lowest Fuel Use		71	104	110	61	96
None	Highest Fuel Use	B20	83	128	29	57	65
	Lowest Fuel Use		63	100	21	27	49
BATS	Highest Fuel Use	ULSD	165	0	137	137	135
	Lowest Fuel Use		115	0	110	61	96
BATS	Highest Fuel Use	B20	138	0	29	57	65
	Lowest Fuel Use		73	0	21	27	49

The combination of BATS, better operation and switching fuel to B20 resulted in 89 percent reduction in trip total NO_x emissions from 39 kgs to 4 kgs. 86 percent of this reduction was due to BATS. Operational practice and switching fuel to B20 led to 13 percent and 1 percent of the reduction, respectively. BATS was estimated to eliminate all NO_x emission hotspots on the route. Improved operational practices reduced 23 percent of the NO_x emission hotspots. Switching fuels to B20 only reduced 5 percent of the NO_x hotspots. Thus, most of the estimated trip total NO_x emissions and NO_x emission hotspots are attributed to the BATS.

PM emissions were estimated to decrease by 46 percent due to better operation and switching to B20. Fuel switching comprised 79 percent of the reduction in PM emissions. PM emission hotspots were estimated to be reduced by 79 percent due to fuel switching. Thus, most of the estimated reduction in trip total PM emissions and PM emission hotspots were associated with fuel switching. CO and HC emissions were low for the baseline case. However, switching fuels and better operation are estimated to decrease CO and HC trip total emissions and the number of emission hotspots.

Conclusions

The PEMS-based measurement method was found to be precise and accurate compared to a certification measurement method for fuel use rate and emission rates of CO_2 and NO_x. The PEMS-based CO and HC exhaust concentrations were typically below detection limits, consistent with low CO and HC concentrations measured with the certification method. The PEMS-based PM emission rates were highly correlated with PM emission rates measured by the certification method. Thus, the PEMS-based measurements are deemed to be valid.

A BATS is estimated to reduce the trip total NO_x emissions by 87 percent and eliminate all NO_x emission hotspots on the route. A BATS does not significantly affect fuel use and PM emissions. Better locomotive operation can lead to reduction in fuel use, CO, HC, NO_x and PM emissions and reduction in the number of CO, HC, NO_x and PM hotspots. Switching fuels to B20 leads to a 40 percent reduction in PM emissions. B20 has a statistically insignificant effect on fuel use and NO_x emissions. Combining technology, operation, and fuels is estimated to decrease the trip total fuel use, NO_x and PM emissions by 25 percent, 89 percent, and 47 percent, respectively. Consequently, the number of hotspots could be reduced by 47 percent, 100 percent, and 85 percent for fuel use, NO_x and PM, respectively.

Recommendations

The combined effect of technology, operation, and fuels was evaluated based on additive effects of each. Measurements for the combined effects can be performed in the future to verify the current estimates. A theoretical second-by-second speed trajectory can be estimated based on 1-Hz locomotive power demand that leads to reduced fuel use and emissions while adhering to the train schedule.

The most effective way to reduce fuel consumption is to adapt efficient locomotive operation. This involves fewer notch changes and avoiding rapid accelerations and decelerations. For reducing NO_x emissions, the use of BATS is highly recommended. For reducing CO, HC and PM emissions, switching to B20 biodiesel is effective. Thus, a combination of changes in technology, operation and fuels is highly recommended to reduce fuel consumption and emissions of CO, HC, NO_x and PM.

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Chapter 1. Introduction

Passenger rail transport is typically more energy efficient than other transport modes (*1*). Therefore, the emission intensity for some pollutants, such as carbon dioxide (CO_2), carbon monoxide (CO) and hydrocarbons (HC), is typically lower for passenger rail transport than for other modes. However, for diesel-powered trains, the per passenger mile emission rates of nitrogen oxides (NO_x) and particulate matter (PM) can be higher (*2*). In 2016, passenger rail transport accounted for 2.1 percent of U.S. transport petroleum use, and 2.4 percent of U.S. total transport energy use (*1*). Passenger rail transport contributed 2.6 percent to U.S. total greenhouse gas emissions from transportation sector in U.S. (*1*). Even though the energy consumption for passenger rail is a small portion of national transport energy consumption, the magnitude of energy consumption is large, at 95.9 trillion BTU (*1*).

NO_x is a precursor to ozone (O_3) and secondary PM formation. Nitric oxide (NO) and nitrogen dioxide (NO_2) constitutes NO_x. NO_2 and O_3 are both criteria pollutants regulated by the U.S. Environmental Protection Agency (EPA) under the National Ambient Air Quality Standards (NAAQS) because of their impact on human health. Inhalation of ground level ozone can cause health problems such as damage to lung tissue, reduction of lung function, and sensitization of the lungs to other irritants. Another criteria pollutant emitted in significant amounts by diesel engines is primary PM. Inhalation of PM can cause cardiovascular disease and premature mortality in humans (*3*, *4*). Thus, measures that reduce fuel use and emissions can have substantial human health benefits.

Diesel locomotives used for passenger rail service typically have two engines: Prime Mover Engine (PME) and Head End Power (HEP) engine (*5*–*7*). These engines are typically operated on ultra-low sulfur diesel (ULSD). The PME is used to generate direct current electricity for traction motors. The PME has a throttle control with eight positions, a high idle, and a low idle position. Each of the throttle positions is called a Notch (*5*–*7*). The locomotive is slowed using mechanical braking or dynamic braking. In dynamic braking, the traction motors act as generators and electricity is dissipated as heat through an electric resistance grid. PME emissions are regulated under locomotive emission standards. The U.S. Environmental Protection Agency (EPA) has adopted more stringent Tier 4 emission standards in 2015 to reduce NO_x and PM emissions for PMEs (*8*). Tier 4 standards are based on leveraging advanced exhaust after treatment technologies used for highway diesel vehicles (*8*, *9*). All newly-built and remanufactured locomotives after 2015 are required to comply with Tier 4 standards.

The HEP engine is used to generate alternating current electricity for hotel services in the passenger cars, such as lighting and space conditioning (*6*, *7*, *10*). The load on the HEP engine is dependent on the number of passenger cars. The HEP engine is considered a non-road engine and is regulated under non-road engine standards. Thus, different emission standards apply for the PME and the HEP engine.

Emission standards for the PME are based on measuring steady-state notch average emission factors that are time weighted based on a standard duty cycle. A duty cycle is the fraction of time spent at each throttle notch position. Emission factors are defined as mass of emissions per unit of activity. Activity for a locomotive can be estimated in terms of time, distance traveled, fuel consumed or engine power output. Emission factors for regulatory purposes are estimated in terms of engine power output (bhp-hr) and the duty cycle. In the U.S., PME emission standards are based on the EPA line-haul duty cycle for long-haul locomotives (*11*, *12*). Thus, compliance with the emission standards depends on the notch average emission factors and duty cycle.

Notch average emission factors can be reduced by adapting technology such as exhaust after-treatment systems or variation in fuel injector timing, or by switching fuels. Emission control technologies developed in the last decade for highway trucks are available for adoption for locomotives. Such technologies include selective catalytic reduction (SCR), diesel oxidation catalysts (DOCs), and diesel particulate filters (DPFs). SCR reduces exhaust NO_x emissions (*13*). DOC and DPF reduce exhaust emissions of PM. A DOC oxidizes CO, HC, and the soluble organic fraction (SOF) of PM. DOCs reduce PM emissions by 20-40 percent, CO emissions by 10-60 percent, and HC emissions by 40-75 percent (*14*–*16*). DPFs are aftertreatment devices that can trap PM. DPFs are known to reduce over 90 percent of PM emissions for heavy duty highway trucks (*17*–*19*).

Different fuels have different energy intensities and chemical composition. Thus, switching fuels may affect the fuel use and emission rates (FUER) of a locomotive. Real world locomotive operation often differs from the regulatory duty cycle due to differences in route, train consist, and driver behavior. Notch average emission factors typically increase with notch position because the engine generates more power output at higher notches resulting in an increase in fuel use rate (*2*, *20*–*22*). Thus, a higher fraction of time spent at high notch positions would lead to higher emissions compared to the regulatory cycle. Fuel use for such trips would also be higher. Thus, technology, operation, and fuels affect locomotive FUER.

The North Carolina Department of Transportation (NCDOT) owns eight diesel locomotives for Amtrak-operated passenger service between Raleigh, NC and Charlotte, NC. The PMEs of NCDOT locomotives are old, lack emission controls and produce high emissions of gaseous pollutants and PM (*21*, *22*). The NCDOT seeks to quantify the emissions of these locomotives and to identify and evaluate options for emissions reductions to meet increasingly stringent emission standards.

1.1 Prior Work by NCSU

In 2008, NCSU first began to use a Portable Emission Measurement System (PEMS) to measure NCDOT locomotive emissions during static load tests in the rail yard (*21*). Rail yard measurements on the now out-of-service GP40 locomotive NC 1792 were conducted pre- and post-rebuild to quantify the effect of variation in injector timing on locomotive FUER. For example, notch average engine output-based fuel rate decreased by 4 percent on an average for all notch positions. Engine output-based NO_x emission rate decreased by 40 percent on an average for all notch positions.

PEMS measurements in the rail yard were subsequently compared to PEMS measurements using an engine dynamometer as the basis for conducting engine load tests (*21*). This work was done at the American Motive Power, Inc. engine dynamometer in Dansville, NY during post-rebuild tests of three PMEs. Measurements were conducted on 3,000-hp prime movers, including an EMD 16-645 for a GP40 and two EMD 12-710s for F59PHs. Fuel use and PEMS-based cycle average emission rates of NO, CO, HC, and PM were compared between dynamometer and rail yard (RY) static load tests and with data from previous literature. Cycle average fuel use and NO_x emission rates after engine rebuild were lower for the GP40 prime mover, and the fuel use and NO_x emission rates for the F59PH rebuilt engines were lower than those of the rebuilt GP40 engine. PEMS were found to provide useful data for comparative assessment of locomotive emissions (*21*, *23*).

Measurements with engine dynamometers or during rail yard static load tests are typically conducted at steady state for each PME throttle notch setting. However, this method may not represent real-world locomotive activity and, therefore, may not lead to representative estimates of emissions. A method for in-use measurement of passenger locomotives, using a PEMS, was developed by NCSU beginning in 2008 to estimate cycle average emission rates. In the years since, measurements of the PMEs for over 100 one-way trips on the Piedmont rail-route between Raleigh, NC and Charlotte, NC were conducted on six NCDOT-owned locomotives NC 1755, NC 1797, NC 1810, NC 1859, NC 1869 and NC 1893 (*2*, *20–22*, *24*, *25*). Three replicates of rail yard measurements of PMEs were also conducted on each of the locomotives. Real-world duty cycles differed from those used for regulatory analyses, leading to statistically significant lower cycle average NO_x and HC emission rates compared to the regulatory cycle average NO_x and HC emission rates. Compared to RY measurements, notch average NO_x emission rates measured over-the-rail (OTR) at the highest two notch settings were, on average, 19 percent lower for four locomotives. At the highest notch, OTR notch average CO_2 emission rates were, on average, 12 percent lower than RY rates for five locomotives. Thus, for a more accurate representation of real-world notch average emission rates, OTR measurements are preferred (*22*).

In other work, highway vehicle emissions avoided by diesel passenger rail service were quantified based on real world data (*26*). Avoided highway emissions are attributed to reduction in the number of personal automobile trips for passenger rail riders. Per passenger-kilometer locomotive emissions were quantified based on PEMS measured exhaust concentrations, actual ridership data and real-world duty-cycles estimated from 68 one-way trips conducted with six Tier 0+ and Tier 1+ locomotives between Raleigh, NC and Charlotte, NC. Average one-way passenger ridership was 18.6 percent on the Piedmont train during the study period. Light-duty gasoline vehicle (LDGV) emission factors were estimated using the U.S. EPA's Motor Vehicle Emissions Simulator (MOVES) assuming one passenger per LDGV. Moving a passenger from an LDGV to a Piedmont train led to a net reduction in CO_2 and CO emissions by 44 percent and 94 percent, respectively. However, NO_x, HC, and PM emission factors were 4 to 11 times higher than for the LDGV, respectively. Delays for either the train or highway vehicles did not substantially affect the emission factors. Increased ridership, lower emitting locomotives, or combinations of both could lead to lower NO_x, HC and PM emissions for train versus private automobile travel.

NCSU conducted a multi-year study of the effect of biodiesel fuel on emissions of selected NCDOT locomotives with sponsorship from the Federal Railroad Administration (FRA), and in collaboration with NCDOT (*20*, *25*). Using PEMS, cycle average NO_x, HC, CO, PM and CO_2 emission rates were measured for three locomotives operating on ULSD and soy-based B10, B20, and B40 biodiesel blends. Measurements were conducted in the RY and OTR during passenger service. Compared to ULSD, B20 biodiesel had statistically significant cycle average emission rate reductions in the RY of 58 percent for CO, 45 percent for PM, and 6 percent CO_2 and OTR of 59 percent for HC, 50 percent for CO, 26 percent for PM, and 5 percent for CO_2. The average differences in cycle average NO_x emission rates for both the RY and OTR, and HC in the RY, were not statistically significant. The OTR findings typically agreed qualitatively with the RY findings; however, OTR provides a better basis for estimating the real-world impact of fuel switching. The results indicate substantial potential to reduce in-use locomotive emissions for existing older locomotives, with the exception of NO_x.

PEMS-based FUER were estimated for the HEP engines of NCDOT owned locomotives NC 1755, NC 1797, NC 1810, NC 1859, NC 1869 and NC 1893 operated on ULSD and B20 based on RY measurements (*10*). An external load box was used to simulate a wide range of loads on the HEP engine. Simulated loads include 50kW, 125 kW, 250 kW, 375 kW and 500 kW. Measured emission rates were compared with the EPA emission standards for non-road engines. Mass per time-based FUER increased with increasing load for each engine and fuel. Cycle average PM emission rates for B20 were 23 percent lower than for ULSD. Cycle average CO emission rates and HC emission rates for B20 were 3 percent and 6 percent lower than for ULSD. However, these differences were not statistically significant. Cycle average NO_x emissions rates for B20 were 3 percent higher than for ULSD, but the difference was not statistically significant. Cycle average CO and HC emission rates were 90 percent and 30 percent lower than the level of EPA nonroad Tier 2 standards for all locomotives for both fuels, respectively. Cycle average NO_x emission rates were higher than the level of Tier 2 standards for NC 1797 and NC 1810 on ULSD, and for NC 1869 on B20. Cycle average PM emission rates were comparable to the level of the Tier 2 standards for only the HEP engine of NC 1859 operated on B20. For all other locomotive-fuel combinations, cycle average PM emission rates were higher than the level of Tier 2 standards.

The prior studies have demonstrated PEMS to be a useful instrument for quantifying locomotive FUER for both RY and OTR tests, and demonstrated differences between RY and OTR tests and, thus, the need for OTR tests (*2*, *10*, *10*, *20–23*, *25*, *26*).

1.2 Objectives

Field measurements of locomotive FUER are needed to assess the effect of technology, operation, and fuels, and study the interactions amongst them. The objective of this report is to quantify the effect of technology, operation, and fuels on locomotive FUER.

The effect of emission control technology is assessed here based on measurements of an SCR system retrofitted to one of the NCDOT locomotives. The effect of variability in operations on FUER is assessed by comparing inter-run variability based on OTR measurements. The effect of substituting biofuels for ULSD is quantified by taking into account results from the FRA-funded study on measurement of FUER based on different fuels.

1.3 Overview of the Report

Chapter 2 provides background regarding locomotive emission standards and the NCDOT locomotive fleet, including specifications for the PME and HEP engines of these locomotives.

Chapter 3 describes the methods used for measurements of locomotive fuel use and emission rates using portable emission measurements systems. Chapter 3 describes the instruments used, the procedures for rail yard measurements, the procedures for over-the-rail measurements, and the procedures for data analysis, including time alignment of data from multiple instruments, quality assurance procedures, and quantification of fuel use and emission rates based on measured data.

Chapter 4 provides the results of the baseline rail yard measurements made on locomotive NC 1859 prior to retrofit of an SCR-based Blended After-Treatment System (BATS). The results include engine activity data, exhaust concentrations of gaseous and particle pollutants, and fuel use and emission rates for each PME throttle notch position. Three replicates of the rail yard tests were conducted. Fuel use and emission rates were estimated for each replicate and for the average of the three replicates. Cycle average rates for fuel use and emission were also quantified.

Chapter 5 provides results for baseline over-the-rail measurements made on locomotive NC 1859 prior to the BATS retrofit. Two sets of measurements were made. Each set included multiple one-way trips. The first set was based on deployment of NC 1859 in a tandem shared-load configuration with another locomotive. The second set was based on the use of NC 1859 as the only locomotive that provided the full tractive power requirement for the train. Measurements results are provided for each set of measurements, for each run and for each throttle notch position in each run. Notch average and cycle average fuel use and emission rates were quantified for both train configurations. Single and tandem locomotive operations are compared with regard to their effect on fuel use and emissions per passenger car.

Chapter 6 details the methods used to quantify the effect of the retrofitted SCR-based BATS system on locomotive fuel use and emissions taking into account how the SCR system affects the mass balance of exhaust gas flow and composition. The methods implemented to sample exhaust emissions from the exhaust channels of the SCR outlet are explained. Two methods for quantifying fuel use and emission rates are explained and developed. One method is based on gravimetric measurement of the total fuel use by both the PME and the HEP engines. The other method is based on estimating engine air flow for the PME using measured engine activity variables. Results from field measurements of the BATS retrofitted to NC 1859 are given and compared based on the two methods for quantifying fuel use and emission rates.

Chapter 7 quantifies the effect of variability in locomotive operations on cycle average fuel use and emission rates. Factors that affect locomotive power demand are identified and described to provide insight regarding how and why variability in operator choices regarding engine load lead to variation in fuel use and emission rates. Locomotive power demand depends on factors such as speed, acceleration, rail grade, and horizontal curvature. Methods for quantifying grade and curvature are discussed. Locomotive power demand is quantified as a function of speed, acceleration, grade, and horizontal curvature. Location-specific hotspots for fuel use and emissions are quantified based on spatial mapping of measurement 1 Hz rates. The factors that lead to locations of high fuel use and emissions rates are discussed taking into account known sources of locomotive power demand, such as speed, acceleration, grade, and curvature. Based on comparison of multiple trips with different spatial distributions and averages for fuel use and emission rates, operational factors that could lead to reduction in fuel use and emission rates are identified.

Chapter 8 quantifies the effect of switching from ULSD to biodiesel fuel with regard to energy use and air pollutant emissions of passenger rail locomotives. The data upon which these estimates are based is from a prior study by NCSU funded by the FRA. The data are interpreted with regard to the role of fuel properties. The change in notch average rates for fuel use, CO_2 emissions, CO emissions, HC emissions, NO_x emissions, and PM emissions are estimated for substituting B10, B20, and B40 for ULSD. Changes in cycle average rates for these substitutions are also estimated.

Chapters 6, 7, and 8 quantify the effects of technology, operation, and fuel choice individually, respectively. Chapter 9 quantifies the effect of combining technology, operation, and fuels choice on the fuel use and emissions rates of diesel passenger locomotives. In this chapter, pair-wise combinations of effects are considered, including technology and operation, fuels and operation, and technology and fuels. Furthermore, the joint effect of all three approaches is also quantified.

Chapter 10 provides conclusions regarding the implications of changes in technology, operation, and fuel with respect to reductions in fuel use and emission rates.

Appendices provide additional detail regarding the results of measurements. Appendix A provides detailed results of baseline rail yard measurements of NC 1859 on ULSD. Appendix B provides details of baseline OTR measurements of NC 1859 on ULSD. Detailed results from rail yard measurements of NC 1859 with the retrofitted BATS are given, based on ULSD, in Appendix C. A parametric study to determine the optimal location in the BATS exhaust channels to use as a representative sample of exhaust concentrations is detailed in Appendix D. Detailed analyses for the effect of fuels is given in Appendix E. A list of abbreviations and acronyms, and their definitions, is given in Appendix F.

Chapter 2. Technical Background

This chapter consists of a description of the emission standards applicable to locomotives and specifications of NCDOT locomotives.

2.1 Locomotive Emission Standards

The PME provides traction to the wheels whereas the HEP engine provides hotel services. PME are regulated under locomotive emission standards. The HEP engine is considered a non-road engine. Thus, different standards apply for the PME and the HEP engine. The standards applicable to the PME and the HEP engine are described below.

2.1.1 *Prime Mover Engine*

The U.S. EPA has adopted locomotive engine emissions standards for exhaust emissions of NO_x, PM, CO and HC based on the average amount of time spent by the PME in a specific notch and the associated notch emission factors obtained from Federal Reference Method measurements. Emission factors are estimated for steady state operation of the engine. In steady state operation, a PME is operated at a given notch position continuously for longer periods of time, typically between 5 min to 10 min. Transitions from one notch position to other are excluded from analysis. The standards are based on two U.S. EPA duty cycles: line-haul and switch cycle. Based on data from Amtrak, an average passenger locomotive duty cycle estimated by EPA is similar to the average line-haul duty cycle, with the exception of the amount of time spent in idle (*27*). There has been some change in duty cycle composition over the past 20 years, especially with the addition of dynamic braking (*28*, *29*). Emission standards for the EPA line-haul cycle are given in Table 2-1. The PMEs are required to be compliant with the emission standards corresponding to the year in which the locomotives were rebuilt.

2.1.2 *Head End Power Engine*

The HEP engines are required to be compliant with Nonroad Compression-Ignition Engine Exhaust Emission Standards. The nonroad standards cover mobile nonroad diesel engines of all sizes used in a wide range of construction, agricultural and industrial equipment. The EPA defines nonroad engines as engines installed on: (1) self-propelled equipment; (2) on equipment that is propelled while performing its function; or (3) on equipment that is portable or transportable, as indicated by the presence of wheels, skids, carrying handles, dolly, trailer, or platform [40 CFR 1068.30]. Thus, nonroad engines include all internal combustion engines except motor vehicle (highway) engines, stationary engines (or engines that remain at one location for more than 12 months), engines used solely for competition, or engines used in engines used in otherwise regulated sources such as locomotive and marine vessels. Nonroad engine standards are specified based on engine size in terms of shaft power output. The HEP engines used in NCDOT fleet range from 447 kW to 671 kW power output. Emission standards applicable to nonroad engines for sizes relevant to NCDOT HEP engines are given in Table 2-2.

TABLE 2-1. U.S. EPA Line-Haul Locomotive Emission Standards (*11*)

Year of original manufacture	Tier of standards	Standards (g/bhp-hr)			
		NO_x	PM	HC	CO
1973 - 1992[a]	Tier 0[b]	8.0	0.22	1.00	5.0
1993[a] - 2004	Tier 1[b]	7.4	0.22	0.55	2.2
2005 - 2011	Tier 2[b]	5.5	0.10	0.30	1.5
2012 - 2014	Tier 3[c]	5.5	0.10	0.30	1.5
2015 or later	Tier 4[d]	1.3	0.03	0.14	1.5

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

[b] *Line-haul locomotives subject to the Tier 0 through Tier 2 emission standards must also meet switch standards of the same tier.*

[c] *Tier 3 line-haul locomotives must also meet Tier 2 switch standards.*

[d] *Manufacturers may elect to meet a combined NO_x + HC standard of 1.4 g/bhp-hr instead of the otherwise applicable Tier 4 NO_x and HC standards.*

TABLE 2-2. Nonroad Compression-Ignition Engine Exhaust Emission Standards (*30*)

Rated Power (kW)	Tier	Model Year	NMHC (g/kW-hr)	NMHC + NO_x (g/kW-hr)	NO_x (g/kW-hr)	PM (g/kW-hr)	CO (g/kW-hr)
$225 \leq$ kW < 450	1	1996-2000	1.3	-	9.2	0.54	11.4
	2	2001-2005	-	6.4	-	0.20	3.5
	3	2006-2010	-	4.0	-	0.20	3.5
	4	2011-2013	-	4.0	-	0.02	3.5
		2014+	0.19	-	0.40	0.02	3.5
$560 \leq$ kW < 900	1	2000-2005	1.3	-	9.2	0.54	11.4
	2	2006-2010	-	6.4	-	0.20	3.5
	4	2011-2014	0.40	-	3.5	0.10	3.5
		2015+	0.19	-	3.5	0.04	3.5

2.2 NCDOT Fleet

NCDOT has a fleet of two F59PHIs and six F59PHs series locomotives configured for passenger service. Two of the F59PHs have been recently acquired and rebuilt by NCDOT. The older locomotives are NC 1755 “City of Salisbury”, NC 1797 “City of Asheville”, NC 1810 “City of Greensboro”, NC 1859 “City of High Point”, NC 1869 “City of Durham” and NC 1893 “City of Burlington”. The recently acquired locomotives are NC 1871 “Town of Cary” and NC 1984 “City of Kannapolis.” All of the locomotives have an Electro Motive Diesel (EMD) 12-710 3,000 hp PME. The F59PHIs and the two recently acquired F59PHs have an electronic fuel injection system. The older F59PHs have a mechanically governed fuel injection system. Six of the locomotives, except for the two recently acquired locomotives, have a Caterpillar Advanced Combustion Emissions Reduction Technology (CAT ACERT) C18 900 hp HEP engine. The two recently acquired locomotives have CAT ACERT C-15 600 hp HEP engines.

The detailed specifications of the PMEs of the locomotives in NCDOT fleet are given in Table 2-3. The detailed specifications of the HEP engine of the locomotives in NCDOT fleet are given in Table 2-4.

TABLE 2-3. Prime Mover Engine Specifications

Locomotive type	F59PHI	F59PH	F59PH
Locomotives	NC 1755, NC 1797	NC 1810, NC 1859, NC 1869, NC 1893	NC 1871, NC 1984
Prime Mover Diesel Engine	EMD	EMD	EMD
Model	12N-710G3B-EC	12N-710G3	12N-710G3
Fuel Injection	Electronically governed	Mechanically governed	Electronically governed
Aspiration	Turbocharged	Turbocharged	Turbocharged
Total Displacement	139.6 L (8,520 in^3)	139.6 L (8,520 in^3)	139.6 L (8,520 in^3)
Number of Cylinders	12	12	12
Cylinder Arrangement	45° “V”	45° “V”	45° “V”
Compression Ratio	16:1	16:1	16:1
Displacement per Cylinder	11,635 cm^3 (710 in^3)	11,635 cm^3 (710 in^3)	11,635 cm^3 (710 in^3)
Cylinder Bore	230.19 mm (9.06 in)	230.19 mm (9.06 in)	230.19 mm (9.06 in)
Cylinder Stroke	279.4 mm (11.0 in)	279.4 mm (11.0 in)	279.4 mm (11.0 in)
Operating Principle	2 Stroke Cycle	2 Stroke Cycle	2 Stroke Cycle
Rotation (Facing Flywheel End)	Counterclockwise	Counterclockwise	Counterclockwise
Full Speed	904 RPM	904 RPM	904 RPM
Normal Idle Speed	343 RPM	371 RPM	268 RPM
Low Idle Speed	200 RPM	238 RPM	219 RPM
Rated speed of traction motors	110 mph	83 mph	83 mph
Weight	13,700 kg (30,200 lbs)	13,700 kg (30,200 lbs)	13,700 kg (30,200 lbs)
Rated power	3,000 hp (2,240 kW)	3,000 hp (2,240 kW)	3,000 hp (2,240 kW)
Emission Standard	U.S. EPA Tier 0+	U.S. EPA Tier 0+	U.S. EPA Tier 0+

TABLE 2-4. Head End Power Engine Specifications

Specification	CAT ACERT C-18	CAT ACERT C-15
Locomotives	NC 1755, NC 1797, NC 1810, NC 1859, NC 1869, NC 1893	NC 1871, NC 1984
Rated power	900 hp (671 kW)	600 hp (447 kW)
Rated Speed	1800-1900 RPM	1800-2100 RPM
Emission Standards	U.S. EPA Tier 2 Final Nonroad	U.S. EPA Tier 3 Final Nonroad
Engine Configuration	In-Line 6, 4-Stroke-Cycle Diesel	In-Line 6, 4-Stroke-Cycle Diesel
Stroke	183 mm (7.2 in)	171 mm (6.73 in)
Bore	145 mm (5.71 in)	137 mm (5.4 in)
Displacement	18.1 L (1104.5 in^3)	15.2 L (927.6 in^3)
Aspiration	Turbocharged-After cooled	Turbocharged-After cooled
Compression Ratio	16.0:1	17.0:1
Combustion System	Direct Injection	Direct Injection
Length	1438 mm (56.6 in)	1438 mm (56.6 in)
Width	943-1132 mm (37.1-44.6 in)	943-1132 mm (37.1-44.6 in)
Height	1239-1356 mm (48.8-53.4 in)	1239-1356 mm (48.8-53.4 in)
Weight - Net Dry (Basic Operating Engine Without Optional Attachments)	1580-1717 kg (3583-3785 lb)	1542-1666 kg (3395.5-3673 lb)

Chapter 3. Measurement Methods

This section includes the description of instruments and methods used to conduct RY and OTR tests. The methods include measurement of engine-out exhaust gas and PM concentrations and engine activity parameters such as engine RPM, IAT and MAP. The data collected from multiple instruments and sensors are time aligned and screened for errors.

The baseline tests include the measurement of engine-out exhaust from PMEs and HEP engines. Baseline measurements for PMEs include RY and OTR measurements. For HEP engines, only RY measurements were conducted since HEP engines typically operate at steady state load during OTR. Methods to estimate FUER from the measured exhaust concentrations are described.

3.1 Instruments

This section includes a description of the PEMS used by NCSU: Axion PEMS and SEMTECH-DS PEMS. The Axion PEMS is more portable and is used for OTR measurements. The larger, heavier SEMTECH is used along with the Axion fir RY measurements. This section also includes a description of the EF&EE LEMS used here for benchmarking the Axion PEMS. PME activity data were recorded by a locomotive activity recorder. HEP Engine activity data were recorded by a Caterpillar Electronic Technician (CAT-ET) Electronic Control Unit (ECU) data logger.

3.1.1 *GlobalMRV Axion PEMS*

Engine exhaust was continuously sampled and measured using a GlobalMRV Axion PEMS. The Axion is comprised of two parallel five-gas analyzers, a PM measurement system and an on-board computer. The two parallel gas analyzers simultaneously measure the volume percentage of CO_2, CO, HC, NO, and oxygen (O_2) in the engine exhaust. The PM measurement capability includes a laser light scattering detector and a sample conditioning system. The Axion PEMS uses a Non-Dispersive Infrared (NDIR) to measure CO_2, CO and HC, and electrochemical cells to measure NO and O_2. The Axion requires two exhaust sample lines: one each for gas and PM analyzers.

The precision of the Axion is ± 0.3 %, ± 0.02 %, ± 13 ppm, and ± 25 ppm for CO_2, CO, HC and NO, respectively. The detection limit of the Axion PEMS is 0.1 %, 0.008 %, 13 ppm and 1 ppm for CO_2, CO, HC and NO, respectively. Comparison of the PEMS with a dynamometer laboratory shows that the Axion system has good precision and accuracy. For example, the prior version of the Axion was evaluated in the Environmental Technology Verification (ETV) program of the U.S. EPA. Emissions of several vehicles were measured simultaneously on a laboratory grade dynamometer facility and with the PEMS (*31*). The coefficients of determination (R^2) for the comparison exceeded 0.86 for all pollutants, indicating good precision. The slopes of the parity plots for CO, CO_2 and NO ranged from 0.92 to 1.05, indicating good accuracy.

The Axion PEMS has an electrochemical sensor for NO only. Thus, Axion PEMS does not measure total NO_x, which also includes nitrogen dioxide (NO_2). Typically, uncontrolled diesel exhaust comprises 95 percent NO and 5 percent NO_2; thus, Axion measured NO_x might be biased low by approximately 5 percent for diesel exhaust (*32*). This bias is small. Therefore, the measured NO is a useful indicator of total NO_x. NDIR is well known to respond only partially to the total loading of hydrocarbon species in the exhaust, because NDIR responds well to alkanes but is less responsive for other aromatics (*33*–*35*). Thus, HC may not be representative of Total Hydrocarbons (THC) (*36*–*38*). The HC measurement is useful for relative comparisons, such as between notch positions for the same engine. The laser light scattering-based PM measurement is also typically biased low by a factor of 5 as shown by Durbin *et. al*., 2007 (*39*). Typically, scattering detects particles greater than 100 nm in diameter. The amount of light scattered is different for elemental carbon versus organic carbon particles and varies by particle shape (*39*). The laser light scattering measurement is useful for relative comparisons.

The two gas analyzers (referred to as “benches”), work simultaneously. Periodically, one bench is taken offline for zeroing to prevent the instrumental drift. Zeroing is defined as calibrating the analyzer at the lower end of the analyzer’s range. During zeroing, the gas analyzer intakes ambient air instead of engine exhaust and switches back to exhaust when finished. Each gas analyzer takes about 55 seconds for zeroing.

A sensor array can be connected to the Axion PEMS and installed on the engine. The sensor array includes sensors to record engine activity parameters such as engine revolutions per minute (RPM), the intake air temperature (IAT), and the manifold air pressure (MAP) (also referred to as the “airbox pressure”). A light-sensor measures engine RPM, a thermocouple measures the temperature in the engine intake air manifold, and a pressure sensor measures pressure in the engine intake air manifold. Reflective tape is put on the engine flywheel and a light beam is aimed towards the flywheel. The RPM sensor counts the number of times light is reflected from the flywheel to the sensor and gives engine RPM. A sensor array box receives signals from these sensors and routes them to the PEMS. The PEMS also has a GPS receiver that records the position and speed data. Engine activity data are used to estimate FUER from the measured exhaust gas and PM concentrations as described later in Section 3.6. The components of the Axion PEMS are shown in Figure 3-1.

3.1.2 *SEMTECH-DS PEMS*

The SEMTECH-DS PEMS is manufactured by Sensors Inc. The SEMTECH-DS uses NDIR to measure CO_2, CO, and HC, non-dispersive ultraviolet (NDUV) to measure NO and NO_2, an electrochemical sensor to measure O_2, and Heated Flame Ionization Detection (HFID) to measure THC. These methods provide CFR-40 1065 Subpart J compliant measurements for CO_2, CO, NO, NO_2 and THC. The SEMTECH-DS requires a single exhaust sample line to the gas analyzers. A heated sample line at a temperature of 191 °C is used to sample exhaust gas to prevent the condensation of heavy hydrocarbon particles in the exhaust sample. The SEMTECH-DS also uses a weather probe and ambient pressure sensor to record ambient temperature, relative humidity and ambient pressure.

CO_2 is measured within a range of 0 % to 20 % at a resolution of 0.01 % and an accuracy of ± 0.1 %. CO is measured within a range of 0 % to 8 % at a resolution of 10 ppm and an accuracy of ± 50 ppm, when span calibrated at 1,200 ppm to 1,500 ppm and zero calibrated prior to a test. The CO analyzer has an accuracy of ± 200 ppm when span calibrated in the range of 2,000 ppm to 80,000 ppm. HC is measured within a range of 0 ppmC to 4,000 ppmC (propane) at a resolution of 4 ppm and an accuracy of ± 1 ppm.

FIGURE 3-1. The GlobalMRV Axion PEMS and components: (a) GPS receiver; (b) Meteorology sensor; (c) Intake Air Temperature Sensor; (d) Exhaust sample lines; (e) Axion PEMS; (f) Engine sensor array; (g) Zero air and exhaust-out lines; (h) Manifold Absolute Pressure sensor; and (i) Engine RPM sensor

THC is measured within the range of 0 ppmC to 40,000 ppmC using HFID. At a user selectable range of 0 ppmC to 100 ppmC of THC, the HFID has accuracy of ± 5 ppmC and resolution of 0.1 ppmC. The fuel needed to ignite the FID consists of a 40/60 mole % mixture of hydrogen and helium.

NO is measured within a range of 0 ppm to 2,500 ppm, at a resolution of 1 ppm and an accuracy of ± 15 ppm. NO_2 is measured within a range of 0 ppm to 500 ppm, at a resolution of 1 ppm and an accuracy of ± 10 ppm. Prior to entering the NDUV analyzer, the exhaust sample is dried to remove heavy hydrocarbons which may contaminate the optical sensors. An ambient air temperature coalescing filter and a thermoelectric coupler are used for this purpose. During drying, less than 5% NO_2 is lost, which is within the acceptable limits for NO_2 to NO converters in certification equipment. The NDUV analyzer compares well with laboratory chemiluminescent analyzers (*40*).

The oxygen sensor records oxygen within a range of 0 % to 25 % at a resolution of 0.1 % and an accuracy of ± 1 %. The electrochemical sensor produces a signal proportional to the partial pressure of oxygen in the exhaust sample.

Ambient temperature is recorded within a range of -39 °C to 60 °C at an accuracy of ± 0.2°. Relative humidity is recorded within a range of 0.8 % to 100% at an accuracy of ± 2%. The ambient pressure is recorded between 15 kPa and 115 kPa.

3.1.3 *Locomotive Emission Measurement System*

The LEMS was used by EF&EE to conduct a compliance test on the locomotive NC 1859 at the rail yard after the locomotive was retrofitted with BATS. The LEMS is based on a proportional partial-flow constant volume sampling from the exhaust pipe (*41*, *42*). Pollutant concentration measurements in the LEMS follow methods specified by the U.S. EPA (US 40 CFR 86, and 40 CFR 1065) and ISO standard 8178. CO_2 and CO are measured by NDIR analysis of the dehumidified dilute exhaust sample, NO_x is measured by chemiluminescent analysis of the dilute exhaust sample, PM is measured gravimetrically using filter-based measurements, and THC is measured using HFID. The LEMS also performs gravimetric fuel use measurements. The engine is operated using fuel from an external fuel tank. The tank is weighed periodically to determine the amount of fuel consumed between successive weighing. Then LEMS was used as a federal equivalent method to benchmark Axion PEMS measurements.

3.1.4 *Locomotive Activity Recorder*

The NCDOT locomotives have a computer system that records locomotive activity data such as locomotive speed and solenoid valve settings. Real-time engine RPM and horsepower output data are displayed in the locomotive cab. These data are noted manually. At idle, the on-board readout does not display a value for engine output. Therefore, the engine load at idle is estimated at 10 hp based on measurements of the EMD12-710 prime mover engine of NC 1859 on an engine dynamometer (*21*).

The locomotive notch position is required to obtain notch specific average FUER. However, the notch position is not recorded by the locomotive activity recorder. The notch position is known from the railyard test since RY tests follow a specified test plan. However, locomotive operation for OTR tests depends on the driver. The notch position for OTR tests is inferred from the solenoid valve settings (Solenoid valves A, B, C, and D), Generator, and Dynamic Braking that are recorded each second. The values for each setting are typically either 0 or 1. The combination of these values can be used to identify the current notch position of the locomotive. The solenoid valve, generator and dynamic breaking configuration settings for each notch position are given in Table 3-1.

3.1.5 *CAT-ET Electronic Control Unit*

A CAT-ET ECU is a scan tool that records 1-Hz engine fuel use rate, engine RPM, MAP, IAT and boost pressure. The scan tool was installed on the HEP engine of the locomotive to record data.

TABLE 3-1. Data Recorded by Locomotive Computer System

Notch	Solenoid Valve A	Solenoid Valve B	Solenoid Valve C	Solenoid Valve D	Generator	Dynamic Braking
Dynamic Brake	0	0	0	0	0	1
Idle	0	0	0	0	1	0
1	0	0	0	0	1	0
2	1	0	0	0	1	0
3	0	0	1	0	1	0
4	1	0	1	0	1	0
5	0	1	1	1	1	0
6	1	1	1	1	1	0
7	0	1	1	0	1	0
8	1	1	1	0	1	0

3.2 Railyard Measurements

This section describes the measurements conducted at the rail yard. Baseline exhaust gas and PM concentration measurements were conducted for the PME and HEP engine. Axion and SEMTECH-DS PEMS were used for the measurements. RY measurements were conducted at the NCDOT Capital Yard Maintenance Facility in Raleigh, NC. NCDOT staff and RailPlan staff provided logistical support and operated the locomotives during rail yard tests. The installation of the PEMS, engine sensor array and the exhaust sample lines are described in this section.

3.2.1 *Prime Mover Engine Exhaust*

Measurements of the PME exhaust include installation of the PEMS and the engine sensor array and operating the locomotive according to a pre-defined test-schedule.

Installation

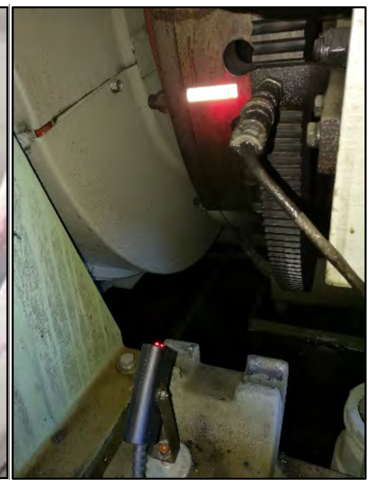
The Axion PEMS was operated on 120 VAC shore power using a 12 VDC transformer. Two exhaust sample lines, one each for gases and PM, were fitted to the PME exhaust duct and routed to the Axion PEMS. Engine exhaust was continuously sampled and vented from the PEMS to the atmosphere via exhaust-out tubes. A sample line was used to periodically "zero" the gas analyzers using ambient air to prevent the instrument drift. Prior to each set of measurements, each of the PEMS were calibrated with a California Bureau of Automotive Repair (BAR) certified calibration gas (BAR-97 Low). Each Axion PEMS gas analyzer was re-calibrated using ambient air to "zero" values every 10 minutes on a staggered schedule, so that typically at least one gas analyzer was measuring while the other was "zeroing." The SEMTECH-DS PEMS was used to measure NO_2 and THC. SEMTECH-DS requires one exhaust sample line.

The installation of the Axion PEMS and SEMTECH-DS PEMS for rail yard data collection is illustrated in Figure 3-2. The PEMS were placed adjacent to the locomotive, as shown in Figure 3-2 (a). Exhaust gases and PM were continuously sampled from the PME exhaust duct, as shown in Figure 3-2 (b). Pressure and temperature sensors were installed on a modified airbox access port as shown in Figure 3-2 (c). The engine RPM sensor was placed near the flywheel, as shown in Figure 3-2 (d). Engine power output (in hp) was recorded manually from the in-cab display, shown in Figure 3-2 (e).

(a) Axion and SEMTECH-DS PEMS

(b) Exhaust sampling port

(c) Manifold absolute pressure and temperature sensor



(d) Engine RPM sensor

(e) Locomotive in-cab display

FIGURE 3-2. Installation of Axion and SEMTECH-DS PEMS for measuring Prime Mover Engine exhaust for Rail Yard tests: (a) Axion and SEMTECH-DS PEMS placed by the side of the locomotive; (b) exhaust sampling lines from the prime mover engine exhaust to the PEMS; (c) manifold absolute pressure and temperature sensor; (d) engine RPM sensor; and (e) locomotive in-cab display.

Test Schedule
During the static RY tests, the prime mover engine was tested under load. The electrical power generated by the prime mover engine was sent to the electrical resistor grid located at the top of the locomotive, where the electrical power was dissipated as heat. The resistor grid is also known as dynamic braking grid. After the installation of all instruments, the PME was operated at idle for 45 minutes to warmup the engine. During the same time, both the PEMS were also running and warming up. Engine and PEMS warmup ensures consistent test results.

The test of the prime mover engine followed a prescribed sequence and timing of throttle notch settings, as given in Table 3-2, including idle and Notches one through eight. The schedule allowed sufficient time to enable steady state operation of the engine while avoiding overheating of the dynamic braking grid, particularly at notch settings six through eight. The test schedule included three repetitive measurements called replicates. For the first replicate, the PME was operated at idle for 45 minutes to allow the engine to warmup. After warmup the PME was operated at Notches 8 through 1 and idle in descending order for 5 minutes at each notch. Notch 8, Notch 7 and Notch 6 were followed by 3 minutes at idle to avoid overheating of the dynamic braking grid. For the next replicates, the warmup was skipped as the locomotive was already warmed up.

TABLE 3-2. Railyard Test Schedule for Prime Mover Engine.

Notch Position	Time (min)
Idle for Warm-up	45
Notch 8	5
Idle for Cooling	3
Notch 7	5
Idle for Cooling	3
Notch 6	5
Idle for Cooling	3
Notch 5	5
Notch 4	5
Notch 3	5
Notch 2	5
Notch 1	5
Idle	5

3.2.2 *Head End Power Engine exhaust*
Measurements for the HEP Engine of locomotive NC 1859 were conducted in a prior study (*10*). Measurements included installation of the gaseous and PM sampling lines on the HEP exhaust outlet. The HEP engine provided fuel use data using a CAT-ET scan tool. The HEP engine is connected to a load box and run at several predefined loads. Additional details are given in the prior study (*10*).

3.3 Over-the-Rail Measurements
This section describes the measurements conducted during regular passenger service. The locomotives were provided by NCDOT and operated by Amtrak for passenger service between Raleigh, NC and Charlotte, NC. RY and OTR tests are similar in terms of instrumentation, quality

assurance, and data analysis procedures, except that the OTR measurements are made on-board the locomotive for actual trips instead of a predefined test schedule. The operation of PME is not as per a test schedule and is determined by several factors discussed in Chapter 1. The HEP engine operates at approximately steady state. Thus, OTR measurements for the HEP engine are not required.

The typical train consist of the Piedmont passenger rail service includes one locomotive, two passenger cars and one baggage/café car. Increased ridership demand (especially on holidays) affects the train consist. NCDOT may use additional passenger cars and an additional locomotive to accommodate increased ridership demand. Sometimes, track maintenance may prevent the train from turning around for its return trip. Thus, during such events, the train may be operated with two locomotives on either end of the train "double-headed."

Exhaust gas and PM measurements were conducted for the PME of locomotive NC 1859. OTR measurements were conducted using the Axion PEMS only because the PEMS have to be placed inside the locomotive cab. The large size of the SEMTECH-DS PEMS prohibits its deployment on-board. Other places such as the generator room are not viable because of high temperatures and vibrations due to engine activity. The use of hydrogen-helium fuels for the SEMTECH-DS is also considered hazardous. Therefore, NCDOT did not allow use of the SEMTECH-DS PEMS for OTR measurements. OTR measurements have only been conducted for the PME. No OTR measurements were conducted for the HEP engine because the HEP engine operates at approximately steady state. The installation of the PEMS, engine sensor array and the exhaust sample lines are described in this section.

OTR measurements on the PME of NC 1859 were conducted during November 2015 and during April 2016 before the BATS was installed. No OTR measurements could be conducted after BATS installation as the locomotive was taken out of service. OTR Measurements in November 2015 were conducted on a consist that included two locomotives, four passenger cars and one baggage/café car. Both the locomotives were at the in front of the passenger cars. The two locomotives were operated in tandem and each shared 50 percent of the total load. OTR measurements in April 2016 were conducted with a typical train consist of one locomotive, two passenger cars and one baggage/café car.

3.3.1 *Installation*

The Axion PEMS and the engine sensor array were installed on-board the locomotive. Additionally, 10 GPS-receivers fitted with barometric altimeters were installed on the locomotive to record locomotive activity and position data. The PEMS was powered from electricity available from the HEP engine-generator. The placement of the Axion PEMS inside the locomotive cab is shown in Figure 3-3. Engine sensor array installation was same as for the RY tests. Exhaust sample lines were routed to the PEMS.

3.3.2 *Test Schedule*

The OTR test procedure is observational rather than controlled. Thus, there is not a predetermined test schedule as was the case for rail yard tests (e.g., Table 3-2). Instead, measurements were made for one-way trips between Raleigh, NC and Charlotte, NC, and vice versa, on the Amtrak-operated Piedmont train service, as depicted in Figure 3-4. The schedule of stops in both directions is given in Table 3-3. For OTR measurements, the locomotive was operated normally on the North Carolina Amtrak Piedmont rail service by Amtrak engineers. The twice-daily Piedmont service covers a one-way distance of 280 kilometers in a scheduled 3 hours and 10 minutes. The goal of data collection was to obtain data for at least 6 one-way OTR measurements on each locomotive.

FIGURE 3-3. Installation of Axion PEMS inside the locomotive cab

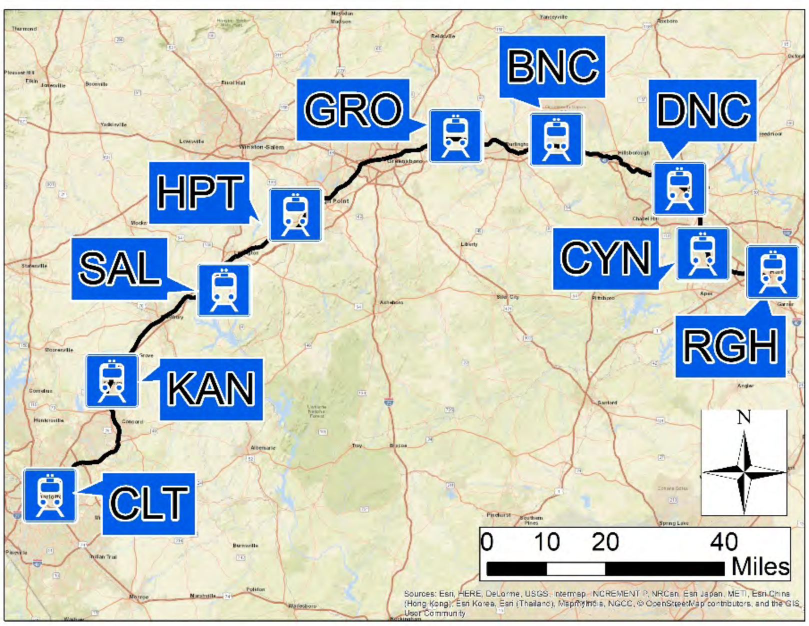


FIGURE 3-4. Route map of the North Carolina AMTRAK Piedmont passenger rail service between Raleigh, NC and Charlotte, NC.

TABLE 3-3. North Carolina AMTRAK Piedmont Passenger Rail Service Timetable for (a) southbound trains from Raleigh to Charlotte; and (b) northbound trains from Charlotte to Raleigh.

(a) Southbound Trains

Station	Train 73	Train 75
Raleigh (RGH)	06:45	11:45
Cary (CYN)	06:57	11:57
Durham (DNC)	07:17	12:17
Burlington (BNC)	07:53	12:53
Greensboro (GRO)	08:18	13:18
High Point (HPT)	08:34	13:34
Salisbury (SAL)	09:08	14:08
Kannapolis (KAN)	09:24	14:24
Charlotte (CLT)	(arrival) 09:55	(arrival) 14:55

(b) Northbound Trains

Station	Train 74	Train 76
Charlotte (CLT)	12:00	17:15
Kannapolis (KAN)	12:25	17:40
Salisbury (SAL)	12:41	17:56
High Point (HPT)	13:14	18:29
Greensboro (GRO)	13:34	18:49
Burlington (BNC)	13:55	19:10
Durham (DNC)	14:33	19:48
Cary (CYN)	14:53	20:08
Raleigh (RGH)	(arrival) 15:11	(arrival) 20:26

Timetable reflects the timetable during the study period. Current timetable may be different. Times are departure times, unless indicated.

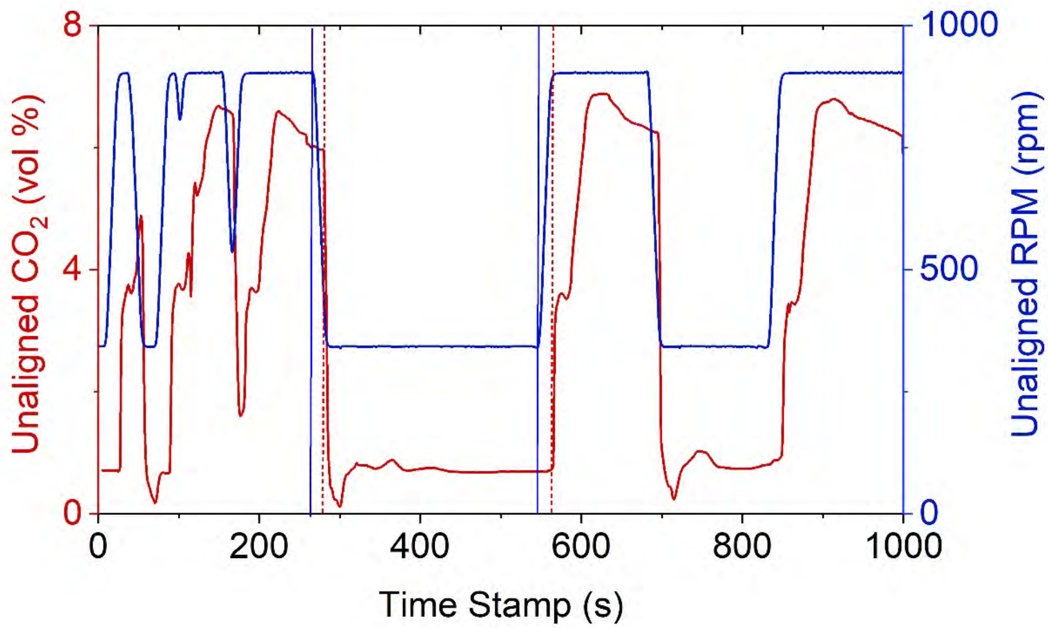
3.4 Time Alignment

Each instrument may have slightly different clock times and some instruments or sensors may have different response times for a measurement. Thus, the recorded time in each instrument may not correspond to the actual time of the measurement. Hence, it is necessary to align the data from multiple sources such that each row of data corresponds to the same time. Time alignment between two measurement sources involves identification of a reference measurement from each source which are known to be correlated. The reference data were aligned such that peaks and troughs in one dataset aligned with the peaks and troughs in the other dataset. For example, a peak in engine RPM typically corresponds to a peak in CO_2 and NO concentrations. Reference data from one dataset is chosen as primary reference and the reference data from the other dataset is chosen as secondary reference. Secondary reference data are aligned with respect to primary reference data. In this study, engine RPM was chosen as primary reference as engine RPM is an indicator of engine activity.

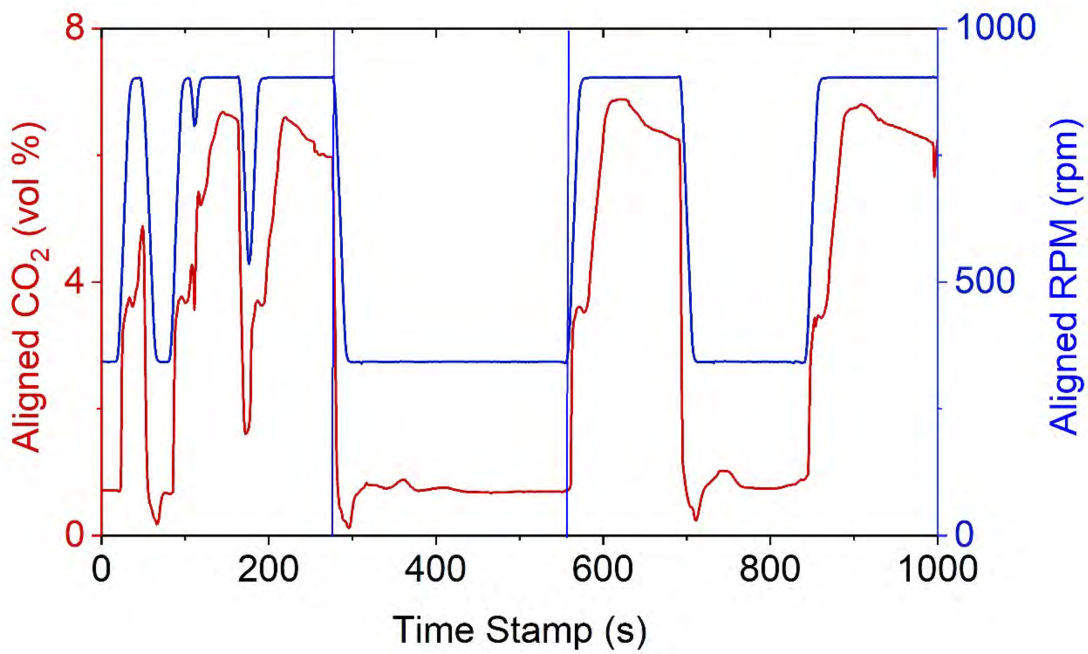
The gaseous and PM exhaust concentrations measured with the PEMS were aligned to the engine activity data measured with the PEMS using CO_2 concentration as secondary reference data. An example of time series plots of unaligned CO_2 concentrations and engine RPM, and CO_2 concentrations aligned to engine RPM, are shown in Figure 3-5 (a) and 3-5 (b), respectively. In Figure 3-5 (a), the dashed red lines indicate the start of a sudden rise or fall in the engine RPM. The corresponding start of rise or fall in the CO_2 concentration is indicated by the dashed blue lines. The difference between the two lines is the difference in the recorded timestamps of the two measurements. Hence, keeping the engine RPM as primary reference data, CO_2 concentrations were shifted by a time equal to the difference of the times for the start of a rise or fall, such that the dashed lines fell exactly on top of each other, as shown in Figure 3-5 (b). Exhaust gas and PM measurements from the same dataset were also shifted by the same time period.

The next step was aligning engine activity data with the locomotive activity recorder data. Engine RPM was again chosen as a primary reference data and locomotive speed recorded by the activity recorder was chosen as the secondary reference data. Example of time series plots of unaligned locomotive speed and engine RPM, and locomotive speed aligned to engine RPM, are shown in Figure 3-6 (a) and 3-6 (b), respectively. These two datasets are typically aligned based on comparing locomotive speed and RPM at station stops. At such a stop, speed is zero and RPM is low. As the train leaves a station, both speed and RPM increase simultaneously.

The time aligned locomotive speed was used as primary reference to align the GPS data using locomotive speed measured with GPS receiver (referred to as ‘GPS speed’) as secondary reference data. For this particular case, the data are aligned to obtain maximum correlation between the two reference data as they both measure the same thing. Example time series plots of unaligned locomotive speed and GPS speed, and GPS speed aligned to locomotive speed, are shown in Figure 3-7 (a) and 3-7 (b), respectively.

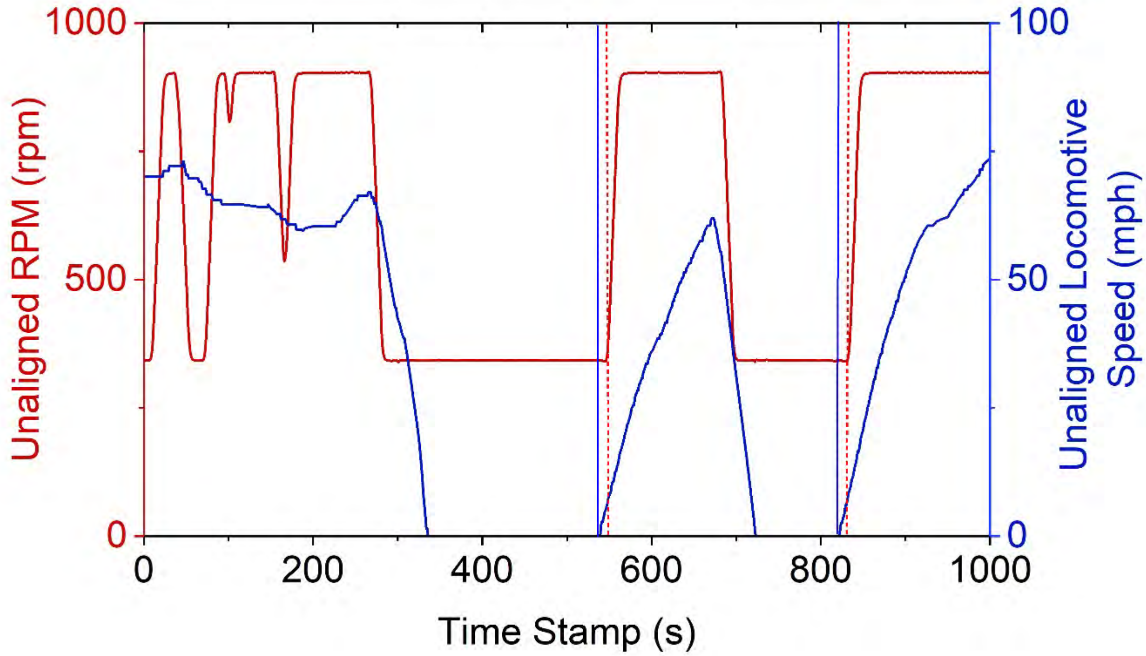


(a) Unaligned CO_2 concentrations and engine RPM

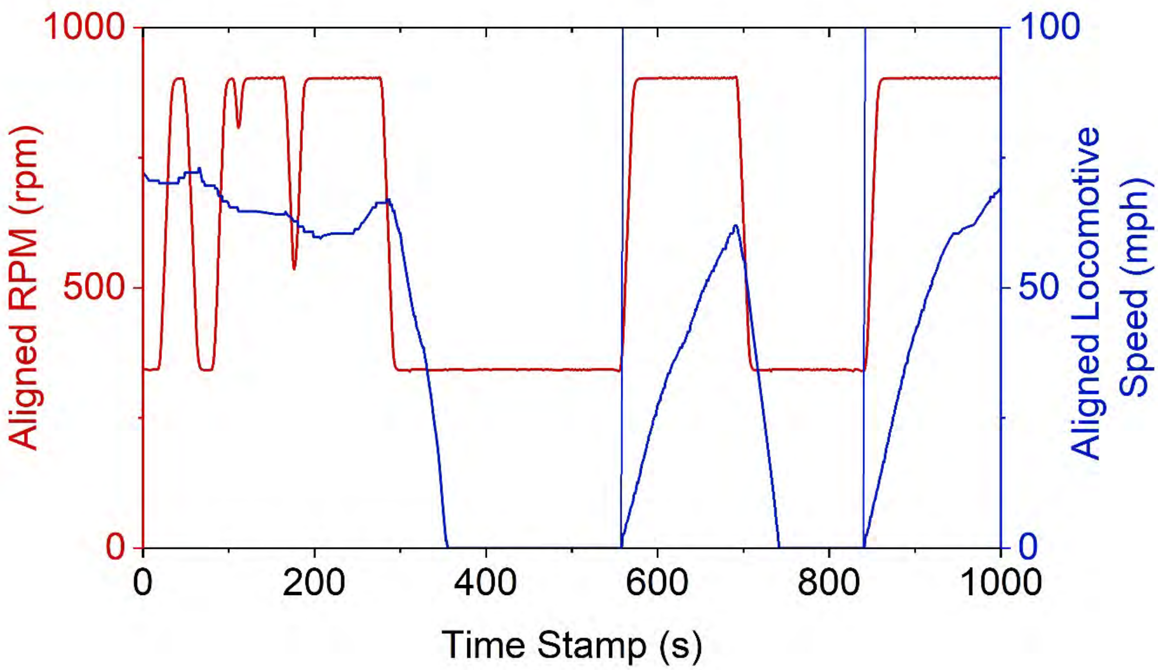


(b) CO_2 concentrations aligned to engine RPM

FIGURE 3-5. Time series plot of CO_2 concentration and engine RPM measured with PEMS for: (a) unaligned CO_2 concentrations and engine RPM; and (b) CO_2 concentrations aligned to engine RPM. Blue lines represent an event in the primary dataset. Red dashed lines represent the same event in the secondary dataset. Datasets were aligned such that these two lines lie on top of each other.

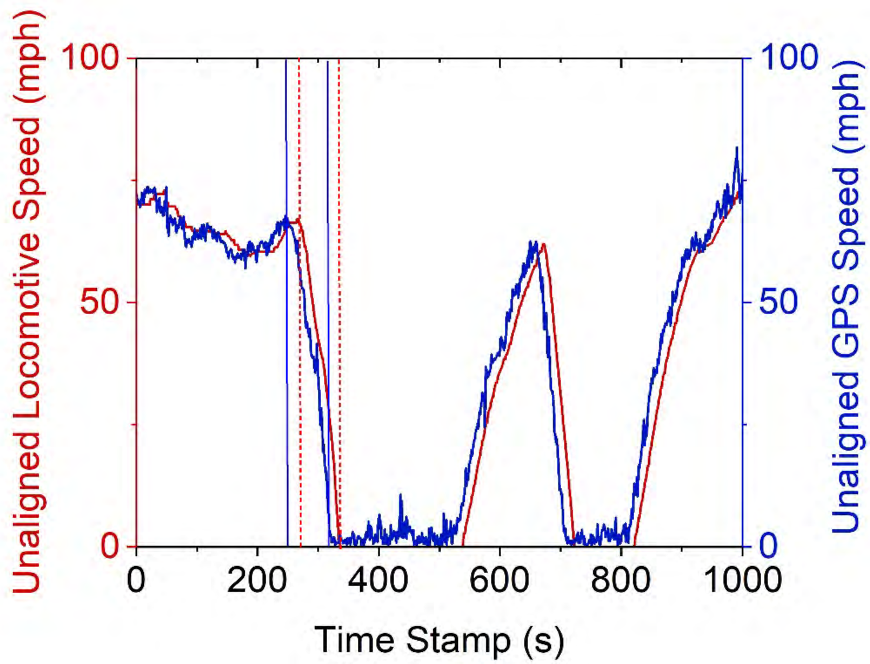


(a) unaligned locomotive speed and engine RPM

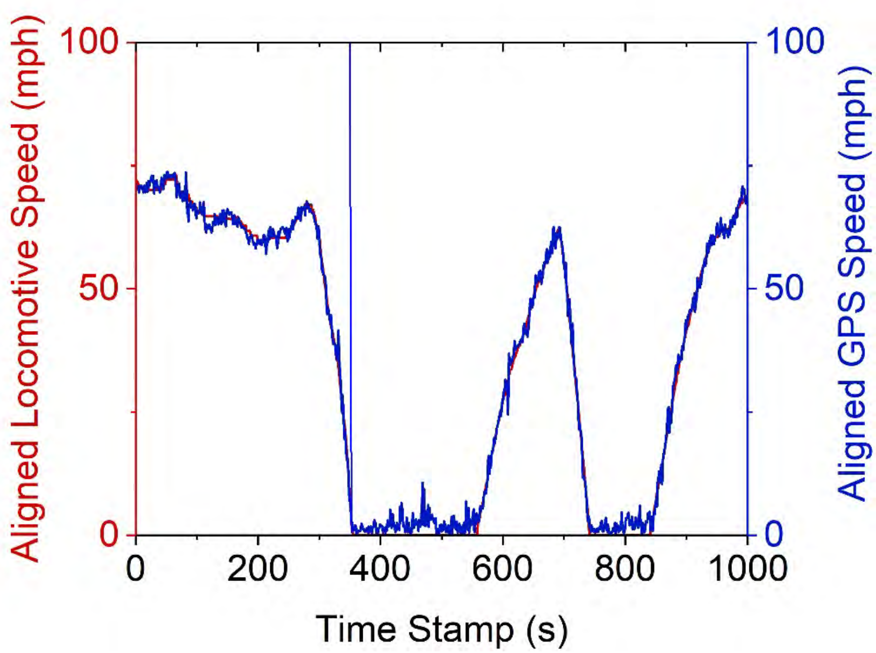


(b) locomotive speed aligned to engine RPM

FIGURE 3-6. Example time plot of locomotive speed measured with locomotive activity recorder and engine RPM measured with PEMS to illustrate: (a) unaligned locomotive speed and engine RPM; and (b) locomotive speed aligned to engine RPM. Blue lines represent an event in the primary dataset. Red dashed lines represent the same event in the secondary dataset. Datasets were aligned such that these two lines lie on top of each other.



(a) Unaligned GPS speed and locomotive speed



(b) GPS speed aligned to locomotive speed

FIGURE 3-7. Example time plot of locomotive speed measured with locomotive activity recorder and GPS speed measured with GPS receiver to illustrate: (a) unaligned locomotive and GPS speed; and (b) GPS speed aligned to locomotive speed. Blue lines represent an event in the primary dataset. Red dashed lines represent the same event in the secondary dataset. Datasets were aligned such that these two lines lie on top of each other.

3.5 Quality Assurance

The time-aligned dataset was screened for errors. The erroneous data were either corrected or rejected from the data analysis. Typical errors in the data include: (1) errors in engine sensor array; and (2) errors in the gas analyzer.

Errors in the engine sensor data can be identified as deviating from credible ranges of RPM, IAT and MAP. The engine RPM of the locomotives tested varies between 190 RPM at idle to 950 RPM at Notch 8. The IAT typically varies between 10 °C and 125 °C. The MAP typically varies between 90 kPa and 250 kPa. Thus, any data outside these ranges were excluded from further analysis.

Errors in gas analyzer data can be identified by comparing the measurements of both the benches of an Axion PEMS when both of them are operating simultaneously. If the relative error between the measurements is within a Maximum Allowable Difference (MAD), an average of the two values was taken. However, if the relative error exceeds the MAD, then further assessment of data quality was required. The MAD for CO_2, CO, HC, NO and O_2 are 0.6 %, 0.04 %, 28 ppm, 50 ppm and 0.5 %, respectively. Any discrepancy in measurements might be due to any of the following: (1) a leakage in the sample exhaust line leading to a bench; (2) overheating of a bench; or (3) problems with the sampling pump of a bench, leading to inadequate flow. In such a case, only the data from the bench working properly was used. The data from the erroneous bench was rejected. Negative values of concentrations are physically implausible and typically arise when the concentration is reported to be negative for a value lower than zero by more than the detection limit of the instrument. Such values tend to occur from time to time for the HC concentration and are excluded. Negative concentrations that are lower than zero by less than the detection limit of the instrument are assumed to be zero.

Additional details on quality assurance are provided elsewhere (*2*, *21*, *43*).

3.6 Fuel Use and Emission Rates

Notch average fuel use and emission rates of CO_2, CO, HC, NO_x and PM are typically expressed as mass per time based or mass per engine power output based. Typically, notch average emission rates are estimated for steady state engine operation since regulatory cycles are also based on steady state engine operation. Thus, transitions from one notch position to the other, often called transients, are excluded from analysis. Two criteria were used to define steady state engine operation: (1) absolute change in engine speed between consecutive seconds was $\leq$ 10 rpm; and (2) engine speed was within ± 20 rpm of the expected notch average engine speed based on previous dynamometer measurements of the same model engine. Notch average emission rates are more accurate for OTR tests while taking transients into account. However, the error in cycle average emission rates compared to using RY tests and steady-state notch average rates is within ± 10 percent (*22*). This error is tolerable for relative comparison studies such as quantifying effect of fuels, operation and technology on FUER by comparing them with baseline FUER.

Mass per time-based emission rates of gases are estimated as a product of dry molar exhaust flow rate and the measured volumetric exhaust concentration. Engine power output-based emission rates are estimated by dividing mass per time-based emission rates by the engine power output. Thus, dry molar exhaust flow rate is a key parameter in estimating the emission rates. Dry molar exhaust flow rate can be estimated in two ways: (1) engine fuel use method; and (2) engine activity method.

The engine fuel use method is based on direct measurement or data logging of fuel flow rate to estimate dry molar exhaust flow rate. Engine activity method is based on estimation of mass air flow through the engine and the air to fuel ratio. Mass air flow is estimated using the "speed-density method" based on measurement of engine activity parameters and a previously developed estimate of engine volumetric efficiency (*21*). The air to fuel ratio is inferred based on the volume percent of carbon species in the exhaust, including CO_2, CO, and HC, because all of the carbon in the exhaust comes only from the fuel.

3.6.1 *Engine Fuel Use Method*

The Engine Fuel Use Method is applicable where the fuel use rate is available along with the measured exhaust concentrations. This is typically the case for the HEP engine, for which fuel use rate can be logged from the engine ECU using a scan tool. The method can also be used for the PME if an external fuel tank is used and weighed periodically, as in the case of measurement with the LEMS. If the fuel use of the HEP engine cannot be logged, HEP engine load can be used to estimate fuel use based on the linear relationship with the engine load estimated in prior study (*10*). Assuming all the carbon in the exhaust is coming from the carbon content of fuel, the molar exhaust flow rate is estimated using a carbon balance as:

$$M_{e,t,dry} = \frac{m_{f,t}}{MW_f \times (y_{CO_2,\mathrm{t},dry} + y_{CO,t,dry} + m \times y_{HC,\mathrm{t},dry})} \quad (1)$$

Where,

$M_{e,t,dry}$	=	molar exhaust flow rate (gmol/s) at time *t* on a dry basis
$y_{s,t,dry}$	=	mole fraction (gmol/gmol of dry exhaust) of pollutant species *s* at time *t* on a dry basis
x,z	=	elemental composition of fuel CH_xO_z where x is gmol of hydrogen per gmol of carbon in the fuel, and y is the gmol of oxygen per gmol of carbon in the fuel
$m_{f,t}$	=	mass fuel use rate (g/sec) by the engine at time *t*

For each second, mass emission rates (g/sec) of gaseous pollutants are estimated based upon the pollutant mole fraction on a dry basis, dry exhaust molar flow rate, and molecular weight of the gaseous pollutant:

$$m_{s,t} = y_{s,\mathrm{t},dry} \times M_{e,\mathrm{t,dry}} \times MW_s \quad (2)$$

Where,

$m_{s,t}$	=	mass emission rate (g/sec) of pollutant species *s* at time *t*
MW_s	=	equivalent molecular weight (g/gmol) of pollutant species *s*

The PM mass emission rate ($m_{PM,t,dry}$) is estimated as:

$$m_{PM,t,dry} = C_{PM,t,dry} \times M_{e,t,dry} \times \left(\frac{R\,T}{P_B}\right) \quad (3)$$

Where,

$m_{PM,t,dry}$	=	PM mass emission rate (g/sec) at time *t* on a dry basis
$C_{PM,t,dry}$	=	measured PM concentration (mg/m^3) in the exhaust at time *t* on a dry basis
T	=	standard temperature (298 K)

The engine power output-based emission rates are obtained from the mass per time based emission rates as:

$$m'_{s,t,P} = m_{s,t} \times 3600/P_t \quad (4)$$

Where,

$m'_{s,t,P}$	=	engine output-based mass emission rate (g/bhp-hr) of the pollutant species *s* at time *t*
P_t	=	engine power output (in HP) at time *t*

3.6.2 *Engine Activity Method*

The engine activity method is applicable for estimation of FUER when engine activity parameters and exhaust concentrations can be measured or estimated. The engine activity method is used for the PME except for the special case in which fuel use rate is measured gravimetrically. However, gravimetric fuel use measurement is not possible on a moving train. The engine activity parameters required for this method include engine RPM, IAT, MAP and engine volumetric efficiency ($\eta_{ev,t}$). The exhaust measurements include concentrations of CO_2, CO, HC, NO and PM. The engine volumetric efficiency of the PME of the NCDOT locomotives is known from prior dynamometer measurements on the same locomotive (*21*).

Volumetric efficiency is the ratio of the actual volume of air that flows through the engine cylinders versus the maximum volume possible based on physical cylinder displacement. Volumetric efficiency accounts for factors that affect air flow such as engine design and operation. Volumetric efficiency was found to be well correlated with product of MAP and RPM during prior dynamometer measurements on similar EMD 12-710 PMEs (*21*). Thus, volumetric efficiency of a PME can be estimated based on measured RPM and MAP.

The fuel use and emission rates of CO_2, CO, HC, NO_x and PM from the engine exhaust are calculated from engine activity data and exhaust concentrations, following a series of steps. First, the intake air molar flow rate for a PME ($M_{a,t}$) is calculated from the engine activity data using the “speed-density” method. Speed-density is a method of estimating airflow into an engine based on the ideal gas law (*44*):

$$M_{a,t} = \frac{\left(P_{M,t} - \frac{P_B}{ER}\right) \times EV \times \left(\frac{ES_t}{30 \times EC}\right) \times \eta_{ev,t}}{R \times \left(T_{int,t} + 273.15\right)} \quad (5)$$

Where,

$M_{a,t}$	=	intake molar air flow rate (gmol/s) at time *t*
EC	=	engine strokes per cycle (1 for two-stroke engines and 2 for four-stroke engines)
ER	=	engine compression ratio
ES_t	=	engine speed (RPM) at time *t*
EV	=	engine displacement (L)
P_B	=	barometric pressure (101 kPa)
$P_{M,t}$	=	engine manifold absolute pressure (kPa) at time *t*
$T_{int,t}$	=	intake air temperature (°C) at time *t*
$\eta_{ev,t}$	=	engine volumetric efficiency of the engine at time *t*
R	=	universal gas constant (8.314 J mol^{-1} K^{-1})

Exhaust molar flow rate on a dry basis ($M_{e,\mathrm{t,dry}}$) is estimated based on $M_{a,t}$ and air to fuel ratio (AFR) inferred from exhaust gas composition (*43*):

$$M_{e,t,dry} = \frac{2 \times 0.21 \times M_{a,t}}{\left(2+\frac{x}{2}-z\right) y_{CO_2,t,dry} + \left(1+\frac{x}{2}-z\right) y_{CO,t,dry} + 2y_{O_2,t,dry} + y_{NO,t,dry} + 0.5\times(3x-8-6z)\, y_{HC,t,dry}} \quad (6)$$

Fuel use rate is estimated as:

$$m_{f,t} = M_{e,\mathrm{t},dry} \times MW_f \times (y_{CO_2,t,dry} + y_{CO,\mathrm{t},dry} + m \times y_{HC,\mathrm{t},dry}) \quad (7)$$

Mass per time based gaseous and PM emission rates are estimated using Equation (2) and Equation (3), respectively. The engine power output-based emission rates are estimated using Equation (4).

3.7 Cycle Average Emission Rates (CAER)

Notch average engine power output-based emission rates can be weighted to any locomotive duty cycle to obtain cycle average emission rates. Locomotive duty cycle is the fraction of total time spent at each notch position.

Cycle average emission rates of CO_2, CO, HC, NO and PM were estimated for the EPA line-haul duty cycle and for an average Piedmont duty cycle. Steady-state notch average FUER were used for RY and OTR measurements. The average Piedmont duty cycle was estimated by Graver and Frey, 2015 based on 48 one-way trips conducted between Raleigh, NC and Charlotte, NC (*22*). Duty cycle was estimated based on all seconds of measured data between the start and end of each one-way trip even though notch average FUER were estimated based on steady state data only. The EPA passenger duty cycle and average Piedmont duty cycle are given in Table 3-4.

Dynamic braking was unavailable for the rail yard tests conducted without an external dynamic braking grid. The dynamic braking grid was only used for the BATS testing. Thus, where dynamic braking was unavailable, the time spent in dynamic braking grid was allocated to idle.

TABLE 3-4. EPA Line-Haul Duty Cycle and Average Piedmont Duty Cycle

Notch	Percent Time in each notch	
	EPA Line-Haul	Piedmont Average
Idle	38.0	28.4
Dynamic Brake	12.5	11.1
1	6.5	3.8
2	6.5	4.8
3	5.2	3.7
4	4.4	4.0
5	3.8	2.2
6	3.9	2.5
7	3.0	0.9
8	16.2	38.6

Note: The Average Piedmont duty cycle was estimated by Graver and Frey, 2015 based on 48 one-way trips conducted between Raleigh, NC and Charlotte, NC.

Chapter 4. Results of Baseline Rail Yard Measurements

The baseline PME exhaust measurements on locomotive NC 1859 were conducted on November 18, 2015. The locomotive was operated on ULSD. The test was conducted at the rail yard. Three replicates of the rail yard test procedure were conducted. An Axion PEMS was used to measure CO_2, CO, HC, NO and PM. THC and NO_x were measured using a SEMTECH-DS PEMS. Notch average THC/HC and NO_x/NO ratios were estimated. These ratios were used to bias correct Axion measured HC and NO for RY measurements. Approximately 3 hours of data were collected during RY measurements. Typically, less than one percent of total data collected were excluded after quality assurance screening.

Key measured parameters such as notch average engine RPM, IAT and MAP are discussed here. Notch average measured concentrations and engine-output based notch average FUER are shown here. Detailed results of each replicate such as notch average fuel use based, mass per time based FUER, inter-replicate variability are given in Appendix A.

Notch average measured values of the engine activity parameters are shown in Figure 4-1. Engine rpm varied from 239 RPM at low idle to 903 RPM at Notch 8, increasing monotonically with notch position. This engine operates with a high idle RPM, which was consistently at 371 RPM for each of the three replicates of the tests. For each notch position, the standard deviation of inter-replicate variability in RPM was less than 0.3 RPM. Thus, the engine RPM was highly repeatable across the three replicates.

IAT varied among the notch positions, with the IAT being slightly higher for high engine load than for low engine load. However, the average difference in temperature for Notch 8 versus idle was only 15 $^{\circ}$C. The standard deviation of inter-notch variation in temperature was less than 1 $^{\circ}$C for most notches, with a maximum value of 1.36 $^{\circ}$C for high idling. Thus, the results for IAT were highly repeatable.

MAP averaged 98 kPa for idle and 223 kPa for Notch 8. The standard deviation of inter-replicate variability in MAP for a given notch was less than 0.24 kPa for all notches except Notch 8, which had standard deviation of 3.18 kPa.

The coefficient of variation (CV), which is the standard deviation divided by the mean, did not exceed 0.02 for RPM, MAP, and IAT. Thus, the engine performance was quite consistent from one replicate to another. The finding of a high degree of replicability in engine performance is typical for all locomotive PMEs.

Notch average concentrations are shown in Figure 4-2. CO_2 varied from 0.62 vol % at low idle to 6.31 vol % at Notch 8, increasing monotonically with notch position. The standard deviation varied between 0.01 and 0.28, but, was lower than 0.10 for all notches, except Notch 4 and Notch 8. The CV was lower than 0.05 for all notch positions. Thus, CO_2 shows very little inter-replicate variability.

CO and HC exhaust concentrations were mostly below the detection limit of the Axion PEMS. Therefore, the measured concentrations and estimated notch average emission rates were not statistically significantly different than zero.

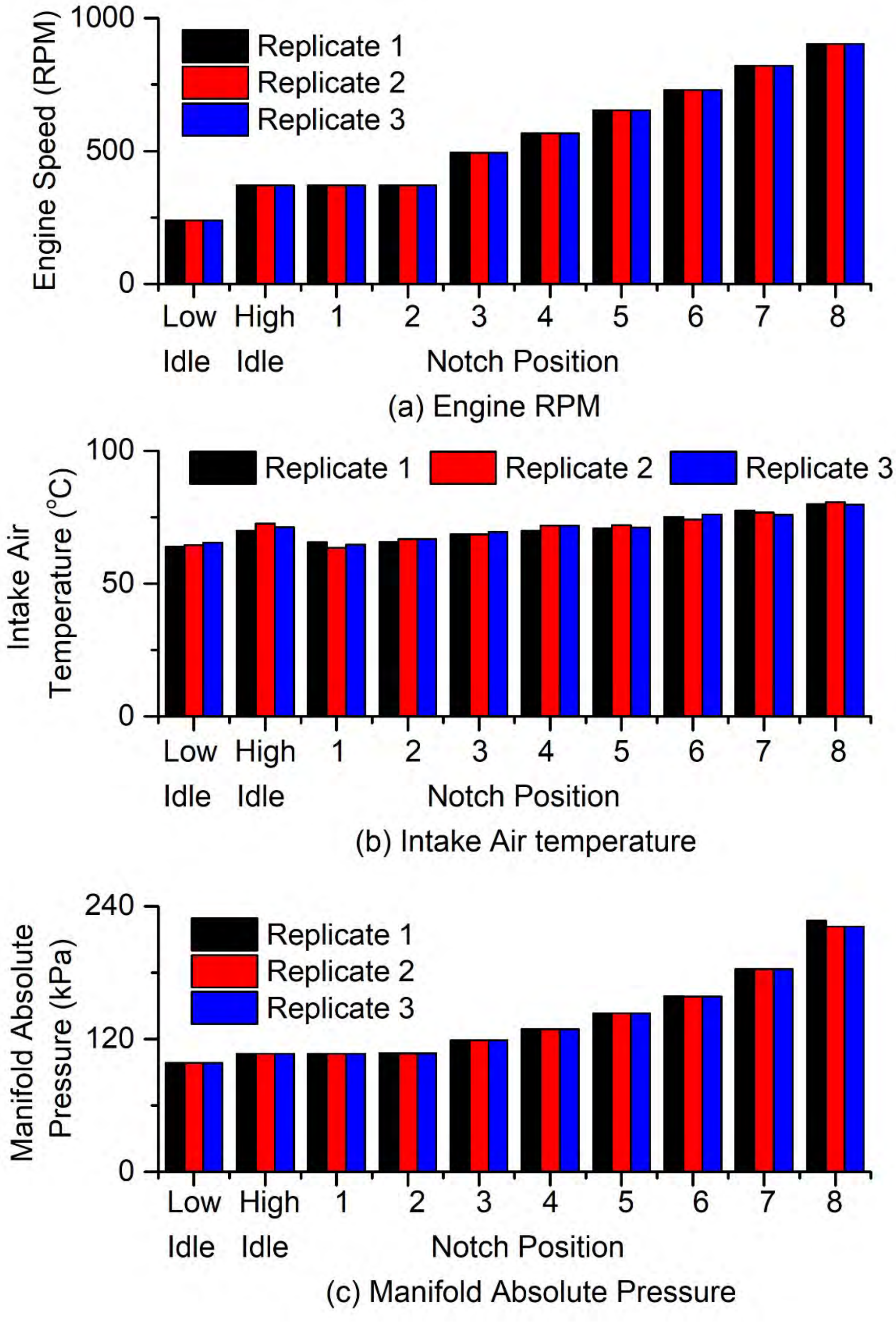


FIGURE 4-1. Measured Engine Activity Parameters during November 18, 2015 Rail Yard Measurements on the Prime Mover Engine of NC 1859 Operated on ULSD: (a) Engine RPM; (b) Intake Air Temperature; and (c) Manifold Absolute Pressure.

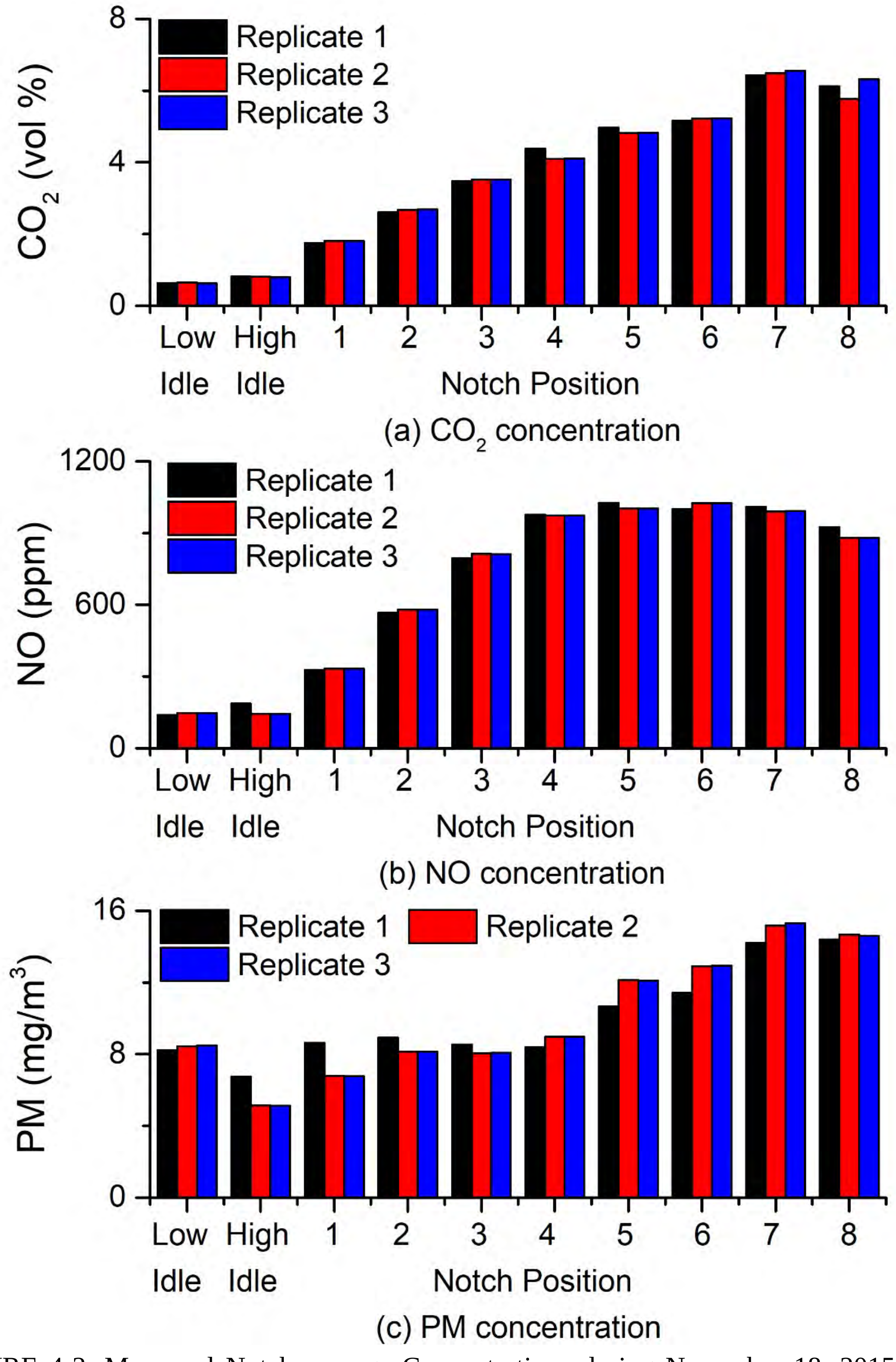


FIGURE 4-2. Measured Notch average Concentrations during November 18, 2015 Rail Yard Measurements on the Prime Mover Engine of NC 1859 Operated on ULSD: (a) CO_2 Concentration; (b) NO concentration; and (c) PM Concentration.

Measured NO concentration varied between 138 ppm at idle and 1027 ppm at Notch 5. NO concentration typically increased monotonically until Notch 4, became approximately constant and decreased after Notch 6. The results were highly repeatable as the CV was less than 0.04 for all notches.

Measured PM concentration varied between 5.1 mg/m^3 at high idle and 15.2 mg/m^3 at Notch 7. A monotonic increase in PM concentration was observed from high idle to Notch 7. Low idle has higher PM concentration than high idle. PM concentration at Notch 8 was also lower than at Notch 7. The measurements were all highly repeatable with CV less than 0.5.

Notch average emission rates were estimated from measured concentrations using Engine Activity Method described in Section 3.6.2. Bias correction factors for THC and NO_x were estimated based on measurements with SEMTECH-DS. SEMTECH-DS based THC and NO_x measurements are shown in Appendix A. The bias correction factors for each notch position are given in Table 4-1. Bias correction factors were applied to Axion PEMS measured HC and NO concentrations to estimate THC and NO_x.

Bias correction factor for NO was 1.01 for low and high idle notches and 1.03 for Notch 1 and Notch 2. For Notch 3 through Notch 8, the NO was correction factor was 1.04. Increasing NO_x/NO ratio means that the fraction of NO_2 is increasing with increasing notch position. At the highest NO_x/NO ratio of 1.04, about 96 percent of the total NO_x is comprised of NO. Bias correction factor for HC varied between 2.73 and 5.03.

Notch average engine output based FUER are shown in Table 4-2. For PM, HC, CO, NO and CO_2, the highest engine output-based emission rate was at idle, while Notch 4 through Notch 6 typically had the minimum notch average emission rates for all pollutants except for NO, whose notch average emission rates continuously decreased with increase in notch position.

TABLE 4-1. Notch average Bias Correction Factors for Axion PEMS measured HC and NO to estimate THC and NO_x.

Throttle Notch position	NO_x/NO Ratio				THC/HC Ratio			
	Rep 1	Rep 2	Rep 3	Avg	Rep 1	Rep 2	Rep 3	Avg
Low Idle	1.04	1.00	1.00	1.01	4.44	4.64	4.45	4.51
High Idle	1.02	1.01	1.01	1.01	5.12	4.51	4.84	4.82
1	1.06	1.01	1.02	1.03	3.92	4.42	5.98	4.77
2	1.05	1.03	1.03	1.03	3.99	3.58	4.90	4.16
3	1.05	1.04	1.04	1.04	3.34	3.16	3.98	3.49
4	1.04	1.04	1.04	1.04	3.62	3.08	3.16	3.29
5	1.04	1.04	1.04	1.04	3.10	2.80	2.82	2.91
6	1.04	1.04	1.04	1.04	2.83	2.56	2.80	2.73
7	1.04	1.03	1.04	1.04	5.42	5.45	5.34	5.40
8	1.04	1.05	1.04	1.04	5.01	5.26	4.83	5.03

TABLE 4-2. Engine Output-Based Notch Average Fuel Use and Emission Rates from Rail Yard Measurement of the Prime Mover Engine of NC 1859 running on Ultra-Low Sulfur Diesel measured using Axion PEMS on 11/18/2015: (a) Fuel Use Rates; (b) CO_2 Emission Rates; (c) CO Emission Rates; (d) HC Emission Rates; (e) NO_x Emission Rates; and (f) PM Emission Rates.

(a) Engine Output Based Notch Average Fuel Use Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based Fuel Use Rate (g/bhp-hr)					
		11/18/2015 Replicate 1	11/18/2015 Replicate 2	11/18/2015 Replicate 3	Average	Standard Deviation	CV[d]
Idle	9	1200	1220	1190	1200	13.5	0.01
DB[a]	9	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]
1	190	198	207	206	204	5.23	0.03
2	350	161	166	166	164	2.91	0.02
3	675	146	149	148	147	1.18	0.01
4	1000	145	136	136	139	5.28	0.04
5	1300	151	147	147	148	2.38	0.02
6	1600	148	147	146	147	0.88	0.01
7	2200	161	162	163	162	0.80	0.00
8	2700	155	147	154	152	4.79	0.03

(b) Engine Output Based Notch Average CO_2 Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based CO_2 Emission Rate (g/bhp-hr)					
		11/18/2015 Replicate 1	11/18/2015 Replicate 2	11/18/2015 Replicate 3	Average	Standard Deviation	CV[d]
Idle	9	3760	3800	3710	3760	42.3	0.01
DB[a]	9	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]
1	190	618	647	644	637	16.2	0.03
2	350	502	518	517	512	8.94	0.02
3	675	457	465	462	461	3.77	0.01
4	1000	454	426	425	435	16.4	0.04
5	1300	472	460.	459	464	7.43	0.02
6	1600	461	460.	456	459	2.72	0.01
7	2200	503	506	508	506	2.52	0.00
8	2700	486	458	482	475	15.0	0.03

Table 4-2. Continued on next page.

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(c) Engine Output Based Notch Average CO Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based CO Emission Rate (g/bhp-hr)					
		11/18/2015 Replicate 1	11/18/2015 Replicate 2	11/18/2015 Replicate 3	Average	Standard Deviation	CV[d]
Idle	9	0.68	1.17	1.16	1.01	0.28	0.27
DB[a]	9	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]
1	190	*0.07*	*0.000*	*0.003*	*0.02*	*0.04*	*1.62*
2	350	*0.003*	*0.02*	*0.02*	*0.01*	*0.01*	*0.66*
3	675	*0.000*	*0.000*	*0.000*	*0.000*	*0.00*	–[c]
4	1000	*0.001*	*0.001*	*0.001*	*0.001*	*0.00*	*0.01*
5	1300	*0.000*	*0.000*	*0.000*	*0.000*	*0.00*	–[c]
6	1600	*0.000*	*0.000*	*0.000*	*0.000*	*0.00*	–[c]
7	2200	*0.44*	*0.43*	*0.43*	*0.44*	*0.01*	*0.01*
8	2700	*0.29*	*0.33*	*0.32*	*0.31*	*0.02*	*0.07*

(d) Engine Output Based Notch Average HC Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based HC Emission Rate (g/bhp-hr)					
		11/18/2015 Replicate 1	11/18/2015 Replicate 2	11/18/2015 Replicate 3	Average	Standard Deviation	CV[d]
Idle	9	9.82	13.7	13.7	12.4	2.24	0.18
DB[a]	9	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]
1	190	*1.16*	*1.62*	*1.59*	*1.46*	*0.26*	*0.18*
2	350	*0.72*	*1.13*	*1.13*	*0.99*	*0.23*	*0.24*
3	675	*0.44*	*0.24*	*0.25*	*0.31*	*0.11*	*0.36*
4	1000	*0.32*	*0.11*	*0.12*	*0.19*	*0.12*	*0.62*
5	1300	*0.27*	*0.19*	*0.19*	*0.21*	*0.05*	*0.21*
6	1600	*0.23*	*0.06*	*0.06*	*0.12*	*0.10*	*0.79*
7	2200	*0.21*	*0.21*	*0.21*	*0.21*	*0.00*	*0.00*
8	2700	*0.11*	*0.22*	*0.21*	*0.18*	*0.06*	*0.33*

Table 4-2. Continued on next page.

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(e) Engine Output Based Notch Average NO_x Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based NO_x Emission Rate (g/bhp-hr)					
		11/18/2015 Replicate 1	11/18/2015 Replicate 2	11/18/2015 Replicate 3	Average	Standard Deviation	CV[d]
Idle	9	92.2	89.3	88.7	90.1	1.89	0.02
DB[a]	9	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]
1	190	12.8	13.2	13.1	13.0	0.22	0.02
2	350	12.0	12.3	12.3	12.2	0.18	0.02
3	675	11.5	11.8	11.7	11.7	0.15	0.01
4	1000	11.1	11.1	11.1	11.1	0.03	0.00
5	1300	10.8	10.5	10.5	10.6	0.13	0.01
6	1600	9.8	9.9	9.8	9.8	0.06	0.01
7	2200	8.6	8.5	8.4	8.5	0.12	0.01
8	2700	8.0	7.7	7.4	7.7	0.33	0.04

(f) Engine Output Based Notch Average PM Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based PM Emission Rate (g/bhp-hr)					
		11/18/2015 Replicate 1	11/18/2015 Replicate 2	11/18/2015 Replicate 3	Average	Standard Deviation	CV[d]
Idle	9	12.3	11.9	11.8	12.0	0.25	0.02
DB[a]	9	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]
1	190	0.8	0.6	0.6	0.7	0.10	0.14
2	350	0.4	0.4	0.4	0.4	0.02	0.05
3	675	0.3	0.3	0.3	0.3	0.01	0.03
4	1000	0.2	0.2	0.2	0.2	0.01	0.04
5	1300	0.2	0.3	0.3	0.3	0.02	0.07
6	1600	0.2	0.3	0.3	0.3	0.02	0.06
7	2200	0.3	0.3	0.3	0.3	0.01	0.04
8	2700	0.3	0.3	0.3	0.3	0.01	0.02

[a] *DB = Dynamic Brake*
[b] *n/a = Measurement not conducted*
[c] *No data for this throttle notch position*
[d] *CV = Coefficient of Variation (CV = Standard deviation divided by the mean)*
Values shown in italics correspond to notch average pollutant concentrations that were below the gas analyzer detection limit.
HC was measured using non-dispersive infrared (NDIR) of Axion PEMS, which accurately measures some compounds but responds only partially to others. NO_x includes NO and NO_2. Only NO was measured using Axion PEMS. NO_x is always reported as equivalent mass of NO_2. THC and NO_x were estimated from Axion measurements by applying bias correction factors given in Table 4-1. PM was measured using a light scattering technique, which provides useful relative comparisons of particle levels in the exhaust. Results include multiplicative correction factor of 5 to approximate total PM.

Engine output-based fuel use rate was highest at idle with an average value of 1200 g/bhp-hr. Fuel use rate decreased to an average of 204 g/bhp-hr at Notch 1. Fuel use rate showed very little variation for Notch 2 through Notch 8 with values ranging between 139 g/bhp-hr and 164 g/bhp-hr. Measurements for all the notches were repeatable with inter-replicate CV less than 0.04 for all notch positions. Notch average CO_2 emission rates showed similar trends as fuel use rates. Notch average CO_2 emission rate was 3760 g/bhp-hr at idle and 637 g/bhp-hr at Notch 1. For Notch 2 through Notch 8, CO_2 emission rate varied between 435 g/bhp-hr and 512 g/bhp-hr. Notch average CO_2 emission rates were highly repeatable with CV less than 0.04 for all notch positions.

CO and HC measurements were below the detection limit of Axion PEMS except at idle. Engine output-based notch average NO_x emission rates decreased with increasing notch position. Notch average NO_x emission rates were 90.1 g/bhp-hr at idle and 7.72 g/bhp-hr at Notch 8. Notch average NO_x emission rates were repeatable with inter-replicate CV of less than 0.04 for all notch positions. Notch average PM emission rates decreased until Notch 2 and thereafter became approximately constant with increasing notch position. PM measurements were also repeatable with a CV of less than 0.14 for all notch positions.

The estimated notch average engine output based FUER were weighted to an average Piedmont duty cycle and the EPA line-haul duty cycle. Cycle average rates for these two cycles are given in Table 4-3. The EPA line-haul cycle typically had higher FUER, except for CO emissions. Cycle average emission rates were compared to the locomotive exhaust emission standards given in Table 2-1. The measured cycle average NO_x emission rate was higher than the level of the Tier 0+ standard for each of the three replicates. Cycle average CO emission rates were lower than the level of the Tier 4+ standards. Cycle average HC emission rates were lower than the level of the Tier 3+ standards. The estimated cycle average PM emission rate was higher than the level of the Tier 0+ standard. The PM detection method used here is not a Federal Reference Method. However, cycle average PM emission rates are useful to quantify the effect of technology, operation, and fuels on locomotive FUER.

TABLE 4-3. Cycle Average Emission Rates for the Prime Mover Engine of NC 1859 operated on Ultra-Low Sulfur Diesel Based for the Rail Yard Measurements conducted on 11/18/2015.

Property	Cycle	Cycle Average Emission Rates (g/bhp-hr)					
		Replicate 1	Replicate 2	Replicate 3	Average	Standard Deviation	CV[a]
Fuel	EPA Line-Haul	162	156	161	160	3.06	0.02
	Average Piedmont	158	150	157	155	4.00	0.03
CO_2	EPA Line-Haul	506	488	502	499	9.62	0.02
	Average Piedmont	494	470	490	484	12.8	0.03
CO	EPA Line-Haul	0.2	0.2	0.2	0.2	0.01	0.06
	Average Piedmont	0.3	0.3	0.3	0.3	0.02	0.07
HC[c]	EPA Line-Haul	0.3	0.4	0.3	0.3	0.04	0.12
	Average Piedmont	0.2	0.3	0.3	0.2	0.05	0.22
NO_x[c]	EPA Line-Haul	9.6	9.4	9.1	9.4	0.23	0.02
	Average Piedmont	8.7	8.4	8.1	8.4	0.29	0.03
PM[c]	EPA Line-Haul	0.41	0.42	0.41	0.41	0.00	0.01
	Average Piedmont	0.36	0.37	0.35	0.36	0.01	0.02

[a] *CV = Coefficient of Variation (CV = Standard deviation divided by the mean)*

[b] *n/a = Measurement not conducted*

[c] *HC was measured using non-dispersive infrared (NDIR) of Axion PEMS, which accurately measures some compounds but responds only partially to others. NO_x includes NO and NO_2. Only NO was measured using Axion PEMS. NO_x is always reported as equivalent mass of NO_2. THC and NO_x were estimated from Axion measurements by applying bias correction factors given in Table 4-1. PM was measured using a light scattering technique, which provides useful relative comparisons of particle levels in the exhaust. Results include multiplicative correction factor of 5 to approximate total PM.*

Chapter 5. Results of Baseline Over-the-Rail Measurements

Baseline OTR PME exhaust concentration measurements on locomotive NC 1859 were conducted during November 2015 and April 2016. The 2015 measurement was with NC 1859 operated in tandem with another similar locomotive, with each locomotive providing 50 percent load. The train consist included two locomotives (same weight and horsepower output), four passenger cars and one baggage/café car. The two locomotives were coupled together. The 2016 measurement was with a single locomotive and typical Piedmont train consist of two passenger cars and one baggage/café car. The locomotive was operated on ULSD. The Axion PEMS was used to measure CO_2, CO, HC, NO and PM. Six one-way trips between Raleigh and Charlotte were conducted for each train consist.

5.1 Tandem Locomotive Operation

Approximately 3 h 20 m of data were collected during each one-way trip. Six one-way trips were conducted. During one of the 2015 trips, NC 1859 was idling during the entire trip and the other locomotive provided the complete load. Thus, measurements from that trip were excluded from further analysis. Therefore, a total of 15 h of useful data were collected. Typically, less than one percent of total data collected were excluded after quality assurance screening.

OTR measured values of RPM, IAT, and MAP for each notch position were similar to those measured in the RY test. Therefore, differences, if any, in cycle average emission rates between RY and OTR measurements are not attributed to these engine parameters. Furthermore, OTR measured notch average values of RPM, IAT, and MAP were repeatable, with inter-trip CV typically less than 0.05. When a notch is switched to a different position, the engine parameters and FUER change over a period of 30 seconds to 50 seconds during a transition from steady state operation in each notch setting. In some cases, change in notch positions occurred more frequently than the transition time required to achieve steady state. Thus, no steady state data was obtained for such notch positions for that transition. PME output was similar between RY and OTR measurements for idle through Notch 6. Engine output at Notches 7 and 8 were 300 hp higher for OTR versus RY measurements, because of the way the engine is programmed for load testing by the engine manufacturer. Detailed results of each replicate such as notch average mass of pollutant emitted per volume of fuel consumed, mass per time based FUER, inter-trip variability are given in Appendix B.

Notch average concentrations are shown in Figure 5-1. Notch average CO_2 exhaust concentrations varied from 0.71 vol % at low idle to 6.80 vol % at Notch 8, increasing monotonically with notch position. The standard deviation varied between 0.02 vol % and 0.58 vol %, but, was lower than 0.20 vol %, except for Notches 6 through 8. The CV was lower than 0.09 for all notch positions. Thus, CO_2 had low inter-trip variability.

CO and HC exhaust concentrations were mostly below the detection limit of the Axion PEMS. Therefore, the measured concentrations and estimated notch average emission rates were not statistically significantly different than zero. Measured notch average NO concentration varied between 160 ppm at idle and 1066 ppm at Notch 7. NO concentration typically increased monotonically from idle to Notch 4, became approximately constant and decreased for notches higher than 6. The results were repeatable as indicated by inter-trip CV of less than 0.20 for all notches.

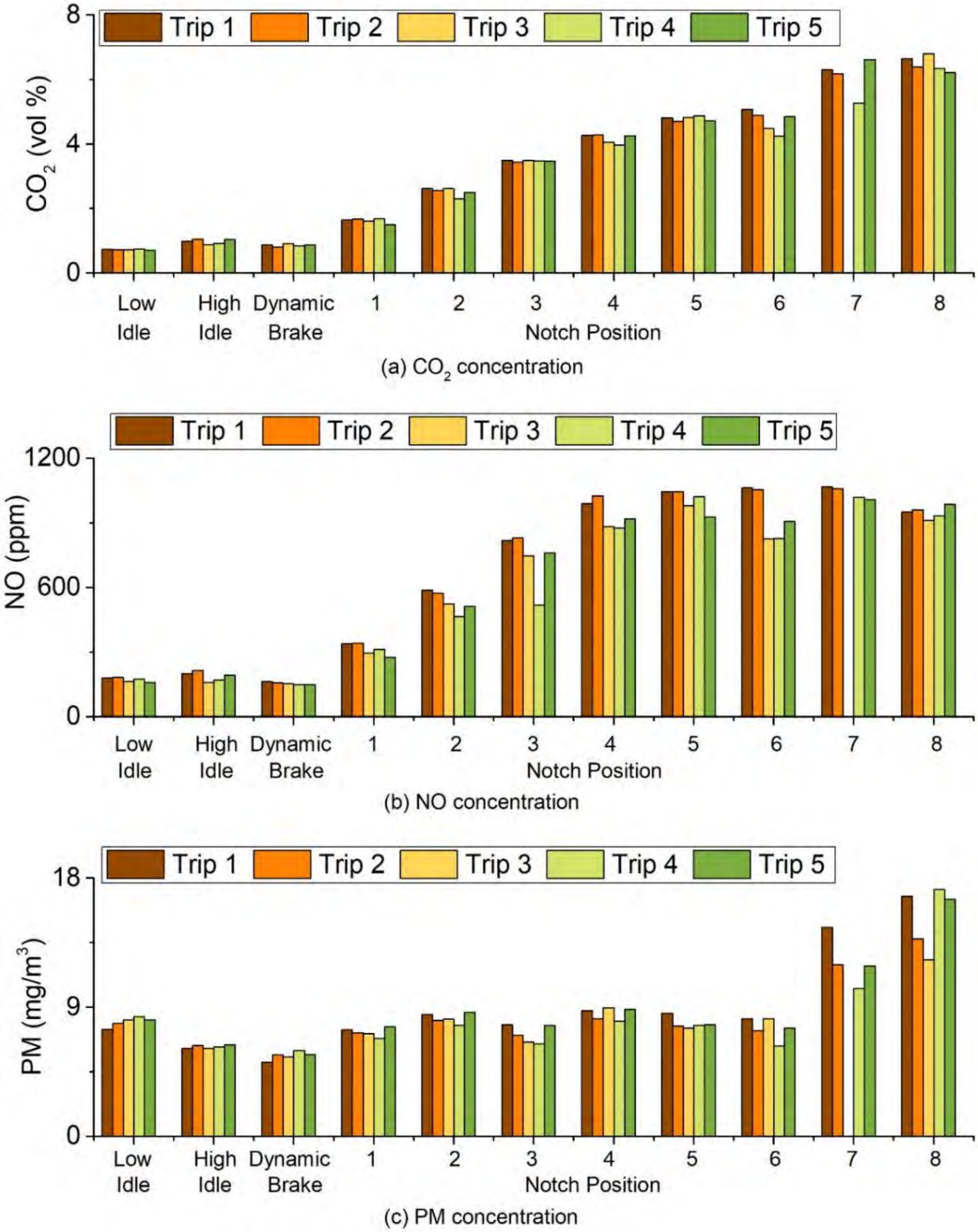

FIGURE 5-1. Measured Notch average Concentrations during Over-the-Rail Measurements on the Prime Mover Engine of NC 1859 Operated on ULSD and connected in Tandem with another locomotive: (a) CO_2 Concentration; (b) NO concentration; and (c) PM Concentration.

Measured notch average PM concentration varied between 5.2 mg/m^3 for dynamic brake to 16.7 mg/m^3 at Notch 8. PM concentrations were approximately similar for dynamic braking through Notch 6. Thereafter, a monotonic increase was observed. The measurements were repeatable as indicated by inter-replicate CV of 0.23 or less.

Duty cycles for the five one-way trips and total trip duration are given in Table 5-1. Trip duration ranged between 3h 13m and 3h 34 m with an average duration of 3h 25m. The locomotive typically spent 37.8 percent to 46.1 percent of time at idle with an average of 41.5 percent. The time spent at Notch 8 varied between 14.8 percent and 38.1 percent, with an average of 27.1 percent. Typically, idle and Notch 8 accounted for more than 70 percent of the trip duration. Intermediate notch positions were typically used to transition between these two notches. Typically, trips that complete on time, and the fastest trips had the lowest fraction of time spent at idle and the highest fraction of time at Notch 8. Delays and slow train movement led to extended time at idle and other low notch positions. Thus, the fraction of time at Notch 8 were lower for longer duration trips.

Overall, the fraction of time spent at idle was higher than the fraction of time spent at idle in the Average Piedmont cycle given in Table 3-4. Conversely, the fraction of time at Notch 8 was lower than for the Average Piedmont cycle. The use of two locomotives in tandem to pull four passenger cars and one baggage/café car resulted in a lower ratio of cars to locomotives compared to the typical train consist on the Piedmont route. Thus, the locomotive was typically operated at lower notch positions.

TABLE 5-1. Duty Cycle for the 5 One-Way Trips Conducted on Locomotive NC 1859 Operated in Tandem with another Locomotive on ULSD

Over-the-Rail Tandem Locomotive Operation Test								
Throttle Notch Position	Percent time in each notch (%)							
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Idle	43.1	46.1	37.8	39.9	40.4	41.5	3.2	0.1
DB[a]	6.5	4.8	19.1	19.6	14.8	13.0	7.0	0.5
1	8.8	8.7	1.4	2.3	2.7	4.8	3.6	0.8
2	6.2	4.8	1.1	0.9	2.6	3.1	2.3	0.7
3	1.6	3.3	0.8	0.7	2.3	1.7	1.1	0.6
4	4.0	7.7	0.6	0.8	5.6	3.7	3.1	0.8
5	2.7	2.5	0.8	0.8	2.6	1.9	1.0	0.5
6	4.9	6.4	0.4	0.3	2.2	2.8	2.7	1.0
7	0.8	0.9	0.0	0.0	0.3	0.4	0.4	1.1
8	21.5	14.8	38.1	34.7	26.5	27.1	9.5	0.3
Trip Duration	3h 34m	3h 31m	3h 13m	3h 22m	3h 25m	3h 25m		

[a] *DB = Dynamic Brake*
[b] *CV = Coefficient of Variation (CV = Standard deviation divided by the mean)*
Train consist included of two locomotives, one baggage/café car and four passenger cars.

Cycle average emission rates were estimated for NC 1859 based on the EPA line-haul duty cycle. Notch average engine output based FUER are given in Table 5-2. For PM, HC, CO, NO and CO_2, the highest engine output-based emission rate was at idle, while Notch 4 through Notch 6 typically had the lowest notch average emission rates for all pollutants except for NO, whose emission rates continuously decreased with increase in notch position.

Engine output-based fuel use rate was highest for dynamic braking with an average value of 2090 g/bhp-hr. Fuel use rate was also high at idle with an average value of 1390 g/bhp-hr. Fuel use rate decreased to an average of 178 g/bhp-hr at Notch 1. Fuel use rate showed very little variation for Notch 2 through Notch 8 with values ranging between 135 g/bhp-hr and 149 g/bhp-hr. Measurements for all the notches were repeatable with inter-trip CV of less than 0.07 for all notch positions. Notch average CO_2 emission rates showed similar trends as fuel use rates. CO_2 emission rate was 6520 g/bhp-hr for dynamic braking, 4320 g/bhp-hr at Idle, and 556 g/bhp-hr at Notch 1. For Notch 2 through Notch 8, CO_2 emission rate was between 418 g/bhp-hr and 466 g/bhp-hr. Notch average CO_2 emission rates were repeatable with inter-trip CV of less than 0.04 for all notch positions.

CO and HC measurements were below the detection limit of Axion PEMS except in idle. Engine output-based notch average NO_x emission rates decreased with increasing notch position. Notch average NO_x emission rates were 105 g/bhp-hr at idle, 129 g/bhp-hr for dynamic braking, and 6.7 g/bhp-hr at Notch 8. For notches 1 through 8, NO_x emission rate varied between 9.1 g/bhp-hr and 11.8 g/bhp-hr. Notch average NO_x emission rates were repeatable with inter-trip CV of less than 0.19 for all notch positions. Notch average PM emission rates decreased from 11.5 g/bhp-hr at idle to 0.4 g/bhp-hr at Notch 2. Notch average PM emission rates were 12.0 g/bhp-hr for dynamic braking. For notches 3 and higher notch average PM emission rates were approximately constant. Notch average PM emission rates were also repeatable with inter-trip CV of less than 0.25 for all notch positions.

Compared to the RY measurements on the same locomotive operated as a single locomotive, notch average engine power output was 300 hp higher than the corresponding RY measurements at Notch 7 and Notch 8. This is because of the way the locomotive is programmed to operate for RY static load operation versus real world operation. Engine output-based notch average fuel use and CO_2 emission rates were higher for OTR tests compared with the RY tests at idle. For Notch 1 through Notch 8, fuel use and CO_2 emission rates were lower than the corresponding rates for RY tests. Notch average NO_x and PM emission rates also showed similar trends for RY versus OTR tests as notch average fuel use and CO_2 emission rates.

TABLE 5-2. Engine Output-Based Notch Average Fuel-Use and Emission Rates from Over-The-Rail Measurements of the PME of NC 1859 operating in tandem with another locomotive and running on Ultra-Low Sulfur Diesel conducted between Nov 25-27, 2015: (a) Fuel Use Rates; (b) CO_2 Emission Rates; (c) CO Emission Rates; (d) HC Emission Rates; (e) NO_x Emission Rates; and (f) PM Emission Rates.

(a) Engine Output Based Notch Average Fuel Use Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based Fuel Use Rate (g/bhp-hr)							
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Average	Std Dev	CV[d]
Idle	9	1410	1430	1350	1390	1370	1390	31.9	0.02
DB[a]	9	2220	1920	2280	1970	2080	2090	155	0.07
1	190	183	186	175	186	161	178	10.5	0.06
2	350	156	152	155	137	145	149	7.92	0.05
3	675	145	142	143	136	139	141	3.60	0.03
4	1000	139	140	133	128	134	135	4.91	0.04
5	1300	145	142	144	146	137	143	3.49	0.02
6	1600	145	142	127	121	134	134	9.99	0.07
7	2500	159	158	–[c]	145	156	155	6.31	0.04
8	3000	165	160	125	128	130	142	19.2	0.14

(b) Engine Output Based Notch Average CO_2 Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based CO_2 Emission Rate (g/bhp-hr)							
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Average	Std Dev	CV[d]
Idle	9	4390	4460	4200	4330	4250	4320	103	0.02
DB[a]	9	6910	5970	7100	6140	6480	6520	482	0.07
1	190	571	580	548	582	502	556	33.2	0.06
2	350	488	475	485	429	453	466	24.7	0.05
3	675	454	444	447	425	435	441	11.3	0.03
4	1000	435	438	414	400	420	421	15.4	0.04
5	1300	453	444	451	455	429	446	10.8	0.02
6	1600	454	444	397	379	418	418	31.2	0.07
7	2500	498	492	–[c]	454	489	483	19.6	0.04
8	3000	516	500	391	399	405	442	60.2	0.14

Table 5-2. Continued on next page.

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(c) Engine Output Based Notch Average CO Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based CO Emission Rate (g/bhp-hr)							
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Average	Std Dev	CV[d]
Idle	9	2.52	4.22	5.49	5.33	5.25	4.56	1.25	0.27
DB[a]	9	6.37	8.78	7.38	8.59	4.27	7.08	1.85	0.26
1	190	0.23	0.31	0.37	0.16	0.38	0.29	0.09	0.32
2	350	0.12	0.09	0.10	0.14	0.12	0.11	0.02	0.18
3	675	0.03	0.06	0.01	0.06	0.07	0.05	0.03	0.54
4	1000	0.06	0.16	0.22	0.11	0.07	0.12	0.06	0.53
5	1300	0.04	0.05	0.08	0.38	0.07	0.12	0.14	1.17
6	1600	0.10	0.19	0.12	0.10	0.08	0.12	0.04	0.34
7	2500	*0.42*	*0.59*	–[c]	*0.36*	*0.24*	0.40	0.15	0.36
8	3000	*0.60*	*0.47*	*0.42*	*0.38*	*0.50*	0.47	0.08	0.18

(d) Engine Output Based Notch Average HC Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based HC Emission Rate (g/bhp-hr)[e]							
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Average	Std Dev	CV[d]
Idle	9	15.7	18.3	22.1	13.9	26.8	19.4	5.2	0.3
DB[a]	9	35.2	21.0	40.0	26.9	34.0	31.4	7.5	0.2
1	190	1.0	1.2	1.0	0.7	1.3	1.0	0.2	0.2
2	350	0.5	0.6	0.7	0.4	*0.4*	0.5	0.1	0.2
3	675	0.3	0.4	0.1	0.4	0.4	0.3	0.1	0.4
4	1000	0.2	0.4	1.0	0.2	0.3	0.4	0.3	0.7
5	1300	0.2	0.3	0.2	0.2	0.2	0.2	0.1	0.2
6	1600	0.3	0.4	0.9	0.2	0.2	0.4	0.3	0.8
7	2500	0.2	0.7	–[c]	0.1	0.1	0.3	0.3	1.0
8	3000	0.2	0.2	0.2	0.1	0.2	0.2	0.0	0.2

Table 5-2. Continued on next page.

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(e) Engine Output Based Notch Average NO_x Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based NO_x Emission Rate (g/bhp-hr) [e]							
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Average	Std Dev	CV[d]
Idle	9	112	115	97.2	104	98.5	105	7.95	0.08
DB[a]	9	142	127	131	120	123	129	8.57	0.06
1	190	12.9	13.1	11.1	11.9	10.2	11.8	1.24	0.1
2	350	12.0	11.8	10.7	9.5	10.2	10.8	1.05	0.1
3	675	11.7	11.8	10.5	6.9	10.5	10.3	1.95	0.19
4	1000	11.1	11.5	9.9	9.7	10	10.5	0.81	0.08
5	1300	10.9	10.9	10.1	10.5	9.2	10.3	0.66	0.06
6	1600	10.5	10.5	8	8.1	8.6	9.1	1.24	0.14
7	2500	9.2	9.2	–[c]	9.6	8.1	9.1	0.64	0.07
8	3000	8.1	8.2	5.7	6	5.7	6.7	1.29	0.19

(f) Engine Output Based Notch Average PM Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based PM Emission Rate (g/bhp-hr) [e]							
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Average	Std Dev	CV[d]
Idle	9	11.0	11.5	11.7	11.9	11.5	11.5	0.4	0.0
DB[a]	9	11.6	11.9	12.2	12.3	12.0	12.0	0.3	0.0
1	190	0.7	0.7	0.7	0.7	0.7	0.7	0.0	0.0
2	350	0.4	0.4	0.4	0.4	0.4	0.4	0.0	0.0
3	675	0.3	0.3	0.2	0.2	0.3	0.3	0.0	0.1
4	1000	0.3	0.2	0.3	0.2	0.2	0.2	0.0	0.1
5	1300	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.1
6	1600	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.1
7	2500	0.3	0.3	–[c]	0.2	0.2	0.3	0.0	0.2
8	3000	0.4	0.3	0.2	0.2	0.2	0.3	0.1	0.3

[a] *DB = Dynamic Brake*
[b] *n/a = Measurement not conducted*
[c] *No steady state data for this throttle notch position*
[d] *CV = Coefficient of Variation (CV = Standard deviation divided by the mean)*
Values shown in italics correspond to notch average pollutant concentrations that were below the gas analyzer detection limit.
[e] *HC was measured using non-dispersive infrared (NDIR) of Axion PEMS, which accurately measures some compounds but responds only partially to others. NO_x includes NO and NO_2. Only NO was measured using Axion PEMS. NO_x is always reported as equivalent mass of NO_2. THC and NO_x were estimated from Axion measurements by applying bias correction factors given in Table 4-1. PM was measured using a light scattering technique, which provides useful relative comparisons of particle levels in the exhaust. Results include multiplicative correction factor of 5 to approximate total PM.*
Train consist included of two locomotives, one baggage/café car and four passenger cars.

The estimated notch average engine output based FUER were weighted to an average Piedmont duty cycle (see Table 3-4) and the EPA line-haul duty cycle (see Table 3-4) to estimate CAER. The CAERs for both duty cycles are given in Table 5-3. The EPA line-haul cycle typically had higher FUER, except for CO emissions. Cycle average emission rates were compared to the locomotive exhaust emission standards given in Table 2-1. The measured cycle average NO_x emission rates were higher than the level of the Tier 0+ standards for two trips. For the remaining three trips, cycle average NO_x emission rates were between the level of Tier 1+ and Tier 0+ standards on the EPA line-haul cycle and between the level of Tier 3+ and Tier 1+ standards for the average Piedmont cycle. Cycle average CO emission rates were lower than the level of the Tier 4+ standards. Cycle average HC emission rates were lower than the level of the Tier 3+ standards. The estimated cycle average PM emission rate was higher than the level of the Tier 0+ standard. However, the PM detection method used here is not a Federal Reference Method.

Cycle average fuel use rate for OTR tests were on an average 10 g/bhp-hr lower than RY tests for both the EPA line-haul cycle and the average Piedmont cycle. CO_2 and NO_x cycle average emission rates were also lower for OTR measurements by 30 g/bhp-hr and 0.1 g/bhp-hr for both duty cycles, respectively. Cycle average PM emission rates were comparable to the cycle average PM emission rates estimated in RY tests.

TABLE 5-3. Cycle Average Emission Rates Emission Rates from Over-The-Rail Measurements of the PME of NC 1859 Operating in Tandem with Another Locomotive and Running on Ultra-Low Sulfur Diesel Conducted Between November 25 and November 27, 2015.

Property	Unit	Cycle	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Avg	Std Dev	CV[a]
Fuel	g/bhp-hr	EPA Line-Haul	169	165	134	141	143	150	16	0.10
		Average Piedmont	167	162	129	133	135	145	18	0.12
CO_2	g/bhp-hr	EPA Line-Haul	527	514	419	440	447	469	48	0.10
		Average Piedmont	521	506	404	416	423	454	55	0.12
CO	g/bhp-hr	EPA Line-Haul	0.4	0.4	0.3	0.4	0.4	0.4	0.0	0.10
		Average Piedmont	0.5	0.4	0.4	0.4	0.5	0.4	0.1	0.15
HC[b]	g/bhp-hr	EPA Line-Haul	0.4	0.4	0.5	0.3	0.4	0.4	0.1	0.18
		Average Piedmont	0.3	0.3	0.3	0.2	0.3	0.3	0.0	0.17
NO_x[b]	g/bhp-hr	EPA Line-Haul	9.9	10.1	7.5	8.0	7.8	8.6	1.3	0.15
		Average Piedmont	8.9	9.0	6.5	6.8	6.6	7.5	1.3	0.17
PM[b]	g/bhp-hr	EPA Line-Haul	0.4	0.4	0.3	0.3	0.3	0.3	0.0	0.14
		Average Piedmont	0.4	0.3	0.2	0.3	0.3	0.3	0.1	0.20

[a] *CV = Coefficient of Variation (CV = Standard deviation divided by the mean)*

[b] *HC was measured using non-dispersive infrared (NDIR) of Axion PEMS, which accurately measures some compounds but responds only partially to others. NO_x includes NO and NO_2. Only NO was measured using Axion PEMS. NO_x is always reported as equivalent mass of NO_2. THC and NO_x were estimated from Axion measurements by applying bias correction factors given in Table 4-1. PM was measured using a light scattering technique, which provides useful relative comparisons of particle levels in the exhaust. Results include multiplicative correction factor of 5 to approximate total PM.*

Train consist included of two locomotives, one baggage/café car and four passenger cars.

5.2 Single Locomotive Operation

Approximately 16 hours of data were collected during OTR measurements. Typically, less than one percent of total data collected were excluded after quality assurance screening. For each one-way run, notch average engine output-based notch average emission rates were estimated for idle, dynamic brake, and the eight notch positions.

OTR measured values of RPM, IAT, and MAP for each notch position were similar to those measured in the RY. Therefore, differences, if any, in cycle average emission rates between RY and OTR measurements are not attributed to these engine parameters. Furthermore, OTR measured notch average values of RPM, IAT, and MAP were repeatable, with inter-trip CV typically less than 0.05. PME output was similar between RY and OTR measurements for idle through Notch 6. Engine output at Notches 7 and 8 were 300 hp higher for OTR versus RY measurements, because of the way the engine is programmed for load testing by the engine manufacturer.

Duty cycles for the 6 one-way trips are given in Table 5-4. Trip duration ranged between 3h 14m and 3h 34m, with an average trip duration of 3h 27m. The locomotive typically spent 34.8 percent to 47.2 percent of total time at idle with an average of 38.8 percent. The fraction of time spent at Notch 8 varied between 25.4 percent and 45.5 percent, with an average of 37.9 percent. Typically, idle and Notch 8 account for more than 70 percent time of the trip duration. Intermediate notch positions are mostly used to transition between the two notches. Typically, trips that complete on time and the fastest trips have the lowest fraction of time spent at idle and the highest time at Notch 8. Delays and slow train movement lead to extended time at idle and low notch positions. Thus, the fraction of time at Notch 8 reduces. Overall, the time spent at idle and Notch 8 was comparable to the Average Piedmont Duty cycle on similar train consists.

TABLE 5-4. Duty Cycle for the 5 One-Way Trips Conducted on Locomotive NC 1859 Operated as Single Locomotive on ULSD

Over-the Rail Single Locomotive Operation Test									
Throttle Notch Position	Percent time in each notch (%)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Avg	Std Dev	CV[b]
Idle	37.0	47.2	34.8	36.5	40.1	37.3	38.8	4.4	0.1
DB[a]	8.9	5.3	10.3	12.1	10.6	12.6	10.0	2.6	0.3
1	2.5	5.2	3.2	2.9	1.7	2.7	3.0	1.2	0.4
2	1.3	3.8	2.5	2.5	3.7	3.4	2.9	0.9	0.3
3	1.7	2.8	2.1	2.0	3.3	1.1	2.2	0.8	0.4
4	0.9	3.8	1.0	1.1	4.5	1.2	2.1	1.6	0.8
5	1.4	2.3	1.1	0.9	3.1	0.8	1.6	0.9	0.6
6	0.6	3.2	0.5	0.3	1.4	1.2	1.2	1.1	0.9
7	0.2	0.9	0.4	0.1	0.4	0.1	0.3	0.3	0.9
8	45.5	25.4	43.9	41.6	31.3	39.8	37.9	7.9	0.2
Trip Duration	3h 25m	3h 34m	3h 14m	3h 24m	3h 31m	3h 33m	3h 27m		

[a] *DB = Dynamic Brake*

[b] *CV = Coefficient of Variation (CV = Standard deviation divided by the mean)*

Engine output-based notch average FUER for single locomotive operation are given in Table 5-5. Fuel use rate was 1500 g/bhp-hr, 2210 g/bhp-hr and 196 g/bhp-hr for idle, dynamic brake and Notch 1, respectively. For notches 2 and higher, fuel use rate varied between 142 g/bhp-hr and 163 g/bhp-hr. Fuel use rate estimates were repeatable with an inter-trip CV of less than 0.17 for all notch positions. Notch average CO_2 emission rates also showed similar trends with highest emission rate for dynamic braking, and then decreasing emission rate from idle to Notch 1, and approximately constant for notches 2 and higher. Notch average CO_2 emission rates were repeatable with an inter-trip CV of less than 0.17 for all notch positions.

Notch average CO and HC concentrations were below the detection limit of the Axion PEMS. Notch average NO_x emission rates were 114 g/bhp-hr at idle, 144 g/bhp-hr for dynamic braking, and 8.3 g/bhp-hr at Notch 8. For notches 1 through 7, notch average NO_x emission rate varied between 8.7 g/bhp-hr and 12.7 g/bhp-hr. Notch average NO_x emission rates were repeatable with inter-trip CV of less than 0.17 for all notch positions. Notch average PM emission rates decreased from 13.2 g/bhp-hr at idle to 0.5 g/bhp-hr at Notch 2. Notch average PM emission rates were 13.9 g/bhp-hr for dynamic braking. For notches 3 and higher notch average PM emission rates were approximately constant. Notch average PM measurements were also repeatable with inter-trip CV of less than 0.13 for all notch positions.

Compared to the tandem locomotive operation, engine output-based fuel use rate for single locomotive operation was 100 g/bhp-hr higher for idle and dynamic braking. For Notch 2 through Notch 8, fuel use rate was higher by about 10 g/bhp-hr to 15 g/bhp-hr. Notch average CO_2 emission rates were also higher for single locomotive operation compared with tandem locomotive operation for all notch positions. Notch average NO_x and PM emission rates were also systematically higher for single locomotive operation compared with tandem locomotive operation for all notch positions.

TABLE 5-5. Engine Output-Based Notch Average Fuel-Use and Emission Rates from Over-The-Rail Measurements of the PME of NC 1859 Operated as Single Locomotive running on Ultra-Low Sulfur Diesel conducted between April 6 and April 20, 2016: (a) Fuel Use Rates; (b) CO_2 Emission Rates; (c) CO Emission Rates; (d) HC Emission Rates; (e) NO_x Emission Rates; and (f) PM Emission Rates.

(a) Engine Output Based Notch Average Fuel Use Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based Fuel Use Rate (g/bhp-hr)								
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Avg	Std Dev	CV[d]
Idle	9	1990	1530	1210	1400	1440	1450	1500	262	0.17
DB[a]	9	2250	2210	2100	2130	2090	2490	2210	150	0.06
1	190	185	205	194	201	176	217	196	14.4	0.07
2	350	127	162	159	148	149	172	153	15.4	0.10
3	675	159	154	151	148	142	141	149	6.94	0.05
4	1000	145	148	129	138	140.	148	142	7.44	0.05
5	1300	152	152	144	155	142	157	150	6.11	0.04
6	1600	147	150	142	151	149	147	148	3.31	0.02
7	2500	173	167	–[c]	–[c]	147	–[c]	162	13.7	0.08
8	3000	167	164	159	164	162	161	163	2.66	0.02

(b) Engine Output Based Notch Average CO_2 Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based CO_2 Emission Rate (g/bhp-hr)								
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Avg	Std Dev	CV[d]
Idle	9	6200	4780	3750	4360	4480	4510	4680	819	0.17
DB[a]	9	7000	6860	6530	6570	6520	7730	6870	466	0.0677
1	190	579	639	605	629	550	675	613	44.6	0.07
2	350	397	506	498	462	465	537	478	48.1	0.10
3	675	496	480	473	462	443	439	465	21.7	0.05
4	1000	454	463	403	433	437	464	442	23.2	0.05
5	1300	475	475	451	485	443	491	470	19.1	0.04
6	1600	459	467	443	473	466	459	461	10.4	0.02
7	2500	539	521	–[c]	–[c]	459	–[c]	477	68.3	0.14
8	3000	521	513	498	514	506	503	509	8.30	0.02

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(c) Engine Output Based Notch Average CO Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based CO Emission Rate (g/bhp-hr)								
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Avg	Std Dev	CV[d]
Idle	9	*4.32*	*3.99*	*5.75*	*5.18*	*5.99*	*6.10*	5.2	0.9	0.2
DB[a]	9	*7.70*	*9.82*	*6.30*	*8.22*	*7.54*	*9.34*	8.2	1.3	0.2
1	190	*0.34*	*0.32*	*0.41*	*0.22*	*0.29*	*0.33*	0.3	0.1	0.2
2	350	*0.07*	*0.12*	*0.11*	*0.14*	*0.03*	*0.19*	0.1	0.1	0.5
3	675	*0.06*	*0.07*	*0.02*	*0.05*	*0.04*	*0.09*	0.1	0.0	0.4
4	1000	*0.11*	*0.15*	*0.23*	*0.15*	*0.17*	*0.07*	0.1	0.1	0.4
5	1300	*0.05*	*0.05*	*0.09*	*0.11*	*0.15*	*0.07*	0.1	0.0	0.4
6	1600	*0.12*	*0.21*	*0.22*	*0.10*	*0.09*	*0.11*	0.1	0.1	0.4
7	2500	*0.73*	*0.43*	–[c]	–[c]	*0.44*	–[c]	0.5	0.2	0.3
8	3000	*0.66*	*0.77*	*0.34*	*0.45*	*0.64*	*0.55*	0.6	0.2	0.3

(d) Engine Output Based Notch Average HC Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based HC Emission Rate (g/bhp-hr)[c]								
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Avg	Std Dev	CV[d]
Idle	9	*29*	*23*	*25*	*36*	*22*	*39*	29	7	0.2
DB[a]	9	*43*	*42*	*32*	*51*	*36*	*69*	45	13	0.3
1	190	*1.3*	*2.9*	*1.7*	*1.8*	*1.5*	*3.8*	2.2	1.0	0.5
2	350	*0.6*	*0.9*	*1.2*	*1.0*	*0.8*	*0.9*	0.9	0.2	0.2
3	675	*0.4*	*0.7*	*0.4*	*0.5*	*0.4*	*0.9*	0.6	0.2	0.4
4	1000	*0.7*	*0.5*	*0.3*	*0.3*	*0.3*	*0.6*	0.5	0.2	0.4
5	1300	*0.5*	*0.4*	*0.6*	*0.3*	*0.3*	*0.5*	0.4	0.1	0.3
6	1600	*0.5*	*0.3*	*0.4*	*0.3*	*0.3*	*0.4*	0.4	0.1	0.2
7	2500	*2.1*	*0.1*	–[c]	–[c]	*0.4*	–[c]	0.8	0.9	1.1
8	3000	*0.4*	*0.4*	*0.2*	*0.3*	*0.2*	*0.4*	0.3	0.1	0.3

Table 5-5. Continued on next page.

Table 5-5. Continued from previous page.

(e) Engine Output Based Notch Average NO_x Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based NO_x Emission Rate (g/bhp-hr) [c]								
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Avg	Std Dev	CV[d]
Idle	9	145	123	92.3	109	101	113	114	18	0.16
DB[a]	9	141	151	141	139	132	158	144	9	0.07
1	190	11.4	14.0	12.9	13.3	10.5	14.4	12.7	1.5	0.12
2	350	8.2	12.6	11.0	10.9	9.1	12.7	10.8	1.8	0.17
3	675	12.3	12.6	11.9	12.1	9.8	11.0	11.6	1.0	0.09
4	1000	10.7	12.2	10.0	11.0	9.8	12.0	10.9	1.0	0.09
5	1300	11.0	11.7	10.7	11.6	9.5	11.2	10.9	0.8	0.07
6	1600	10.1	10.9	9.5	11.4	9.3	10.2	10.2	0.8	0.08
7	2500	10.4	9.6	–[c]	–[c]	7.6	–[c]	8.7	1.5	0.17
8	3000	8.4	9.0	8.3	8.7	7.4	8.2	8.3	0.6	0.07

(f) Engine Output Based Notch Average PM Emission Rate

Throttle Notch Position	Engine Output (hp)	Engine Output Based PM Emission Rate (g/bhp-hr) [c]								
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Avg	Std Dev	CV[d]
Idle	9	13.3	12.5	13.1	13.0	13.8	13.6	13.2	0.5	0.03
DB[a]	9	12.3	13.2	14.2	14.1	15.1	14.7	13.9	1.1	0.08
1	190	0.7	0.8	0.8	0.9	0.8	0.9	0.8	0.1	0.06
2	350	0.4	0.5	0.5	0.5	0.5	0.6	0.5	0.1	0.09
3	675	0.3	0.3	0.3	0.3	0.3	0.4	0.3	0.0	0.09
4	1000	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.0	0.13
5	1300	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.0	0.12
6	1600	0.2	0.2	0.2	0.3	0.3	0.3	0.2	0.0	0.11
7	2500	0.3	0.3	–[c]	–[c]	0.2	–[c]	0.3	0.0	0.10
8	3000	0.3	0.3	0.3	0.3	0.4	0.4	0.3	0.1	0.17

[a] *DB = Dynamic Brake*
[b] *n/a = Measurement not conducted*
[c] *No steady state data for this throttle notch position*
[d] *CV = Coefficient of Variation (CV = Standard deviation divided by the mean)*
[e] *Values shown in italics correspond to notch average pollutant concentrations that were below the gas analyzer detection limit.*
[f] *HC was measured using non-dispersive infrared (NDIR) of Axion PEMS, which accurately measures some compounds but responds only partially to others. NO_x includes NO and NO_2. Only NO was measured using Axion PEMS. NO_x is always reported as equivalent mass of NO_2. THC and NO_x were estimated from Axion measurements by applying bias correction factors given in Table 4-1. PM was measured using a light scattering technique, which provides useful relative comparisons of particle levels in the exhaust. Results include multiplicative correction factor of 5 to approximate total PM.*
Train consist included of one locomotive, one baggage/café car and two passenger cars.

The estimated notch average engine output based FUER were weighted to an average Piedmont duty cycle and the EPA line-haul duty cycle to estimate CAER. The CAER for both duty cycles are given in Table 5-6. The EPA line-haul cycle typically had higher FUER, except for CO emissions. Cycle average emission rates were compared to the locomotive exhaust emission standards given in Table 2-1. The measured cycle average NO_x emission rate was higher than the level of the Tier 0+ standard for each of the six trips. Cycle average CO emission rates were lower than the level of the Tier 4+ standards. Cycle average HC emission rates were lower than the level of the Tier 3+ standards. The estimated cycle average PM emission rate is higher than the level of the Tier 0+ standard. However, the PM detection method used here is not a Federal Reference Method.

TABLE 5-6. Cycle Average Emission Rates from Over-The-Rail Measurements of the PME of NC 1859 Operated as Single Locomotive running on Ultra-Low Sulfur Diesel conducted between April 6 and April 20, 2016.

Property	Duty Cycle	Cycle Average Emission Rates (g/bhp-hr)								
		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Avg	Std Dev	CV[d]
Fuel	EPA Line-Haul	175	172	156	162	166	162	165	7.0	0.04
	Average Piedmont	170	167	159	164	164	162	164	4.0	0.02
CO_2	EPA Line-Haul	547	536	505	507	518	505	520	18	0.03
	Average Piedmont	531	523	502	512	512	506	514	10	0.02
CO	EPA Line-Haul	0.4	0.4	0.3	0.4	0.4	0.4	0.0	0.1	0.4
	Average Piedmont	0.5	0.4	0.4	0.4	0.5	0.4	0.1	0.1	0.5
HC[c]	EPA Line-Haul	0.7	0.6	0.5	0.6	0.4	0.7	0.6	0.1	0.2
	Average Piedmont	0.5	0.5	0.3	0.4	0.2	0.5	0.4	0.1	0.2
NO_x[c]	EPA Line-Haul	10.2	10.8	9.6	9.9	8.7	9.6	9.8	0.6	0.07
	Average Piedmont	9.1	9.7	8.8	9.2	7.9	8.8	8.9	0.5	0.07
PM[c]	EPA Line-Haul	0.3	0.3	0.3	0.3	0.4	0.4	0.3	0.04	0.10
	Average Piedmont	0.2	0.3	0.3	0.3	0.3	0.4	0.3	0.05	0.14

[a] *CV = Coefficient of Variation (CV = Standard deviation divided by the mean)*
[b] *n/a = Measurement not conducted*
[c] *HC is measured using non-dispersive infrared (NDIR) of Axion PEMS, which accurately measures some compounds but responds only partially to others. NO_x includes NO and NO_2. Only NO was measured using Axion PEMS. NO_x is always reported as equivalent mass of NO_2. THC and NO_x were estimated from Axion measurements by applying bias correction factors given in Table 4-1. PM is measured using a light scattering technique, which provides useful relative comparisons of particle levels in the exhaust. Results include multiplicative correction factor of 5 to approximate total PM.*
Train consist included of two locomotives, one baggage/café car and two passenger cars.

5.3 Single versus Tandem Locomotive Operation

Trip total fuel use and emissions of NO_x and PM are compared for the two locomotive operations. Notch average engine parameters were found to be similar for single and tandem operation of locomotives. Thus, the mass air flow and engine volumetric efficiency were also similar. The key differences between single and tandem locomotive operation include: notch average FUER, observed duty cycle and the train consist. The trip-total fuel use, NO_x emissions and PM emissions are given in Table 5-7. Trip total fuel use and emissions were estimated as sum of all 1-Hz mass per time-based FUER for each trip.

Trip average fuel use of NC 1859 was estimated to be 649 kg when operated alone compared to 523 kg for a tandem operation on an average. Trip total NO_x emissions from NC 1859 were 34.7 kg and 24.4 kg for single and tandem operation, respectively. Trip total PM emissions from NC 1859 were 1381 g and 982 g for single and tandem operation, respectively. As discussed in Section 5.2, single locomotive operation had higher notch average FUER compared to tandem locomotive operation for all notch positions. Single locomotive operation had a higher fraction of time spent at Notch 8 compared to tandem locomotive operation. Conversely, the fraction of time at idle for single locomotive operation was lower than tandem operation. Notch 8 has the highest mass per time-based FUER and idle has the lowest. Thus, for same duration trips, trip total fuel use and emissions were higher for trips with higher fraction of time spent at Notch 8.

Trip total fuel use and emissions per locomotive were higher for single locomotive operation. However, actual trip total fuel use and emissions for tandem locomotive operation would be double of that estimated in Table 5-7 due to use of two similar locomotives. To enable a consistent basis for comparison and to account for train consist, trip total fuel use and emissions are compared on per passenger car basis. For simplifying calculations, a baggage/café car is assumed as a passenger car as they have same weight and dimensions. Per passenger car trip total fuel use and emissions are given in Table 5-8.

TABLE 5-7. Comparison of Trip Total Estimates per Locomotive for Locomotive NC 1859 operated as Single and in Tandem with another Locomotive.

Trip Total Estimates		Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Average
Fuel Use (kg)	Single	762	532	661	679	585	677	649
	Tandem	475	388	669	585	500	n/a[a]	523
NO_x Emissions (kg)	Single	39.6	31.7	35.6	37.1	28.7	35.8	34.7
	Tandem	27.1	24.3	25.1	24.0	21.2	n/a[a]	24.4
PM Emissions (g)	Single	1322	1088	1379	1276	1471	1751	1381
	Tandem	1148	864	1012	979	906	n/a[a]	982

[a] *measurement not conducted for selected trip*

TABLE 5-8. Trip Total Fuel Use and Emissions per Passenger Car for Single and Tandem Locomotive Operations

Trip Total			Number of Passenger Cars[a]	Trip Total per Passenger Cars[a]
Fuel Use (kg)	Single	649	3	216
	Tandem[b]	1047	5	209
NO_x Emissions (kg)	Single	34.7	3	11.6
	Tandem[b]	48.7	5	9.7
PM Emissions (g)	Single	1381	3	460
	Tandem[b]	1964	5	393

[a] *Number of passenger cars include the baggage/café car as these cars are similar to passenger cars in terms of dimensions and weight.*

[b] *Trip total fuel use and emissions for tandem operation are double of that as given in Table 5-7 as those in Table 5-7 were estimated for a single locomotive.*

Both single and tandem operation resulted in similar fuel use per passenger car. However, NO_x and PM emissions per passenger car were lower by 17.2 percent and 14.5 percent for tandem operation, respectively. However, the fuel use and emissions per passenger car could have been even lower if only one locomotive was used to pull 5 passenger cars. The effect of such a train consist has not been measured yet. Several train systems use just one locomotive with a consist of 4 to 8 passenger cars. For example, Metra Burlington Northern Santa Fe (BNSF) uses a similar diesel locomotive (3100 hp) to pull 6 bi-level passenger cars (*45*). Maryland Area Regional Commuter (MARC) Penn line uses one 3100 hp diesel locomotive to pull 5 bi-level cars (*45*). Bi-level cars are heavier than single level cars used on the Piedmont route. Thus, the same locomotive could be able to pull more than 6 single level cars. Hence, unless absolutely necessary, a consist of two locomotives to pull 5 passenger cars should be avoided.

Chapter 6. Emission Control Technology

This chapter is based on reduction in notch average NO_x emission rates using technology. The technology comprises an SCR-based BATS. Methods to estimate BATS NO_x control efficiency are demonstrated. The locomotive NC 1859 was retrofitted with BATS and a 'zero hour' compliance test was conducted. The measurements were conducted at the NCDOT rail yard facility in Raleigh, NC. Exhaust gas and PM concentration measurements were conducted by NCSU using the Axion PEMS. Simultaneously, EF&EE conducted the compliance testing using LEMS. These measurements were conducted for the treated exhaust from the PME and HEP Engine. Additionally, an external fuel tank was used by EF&EE to supply fuel to the PME and HEP engine. Axion PEMS was benchmarked to LEMS.

6.1 Selective Catalytic Reduction

SCR uses a catalyst and a chemical reactant to convert nitrogen oxides to molecular nitrogen and oxygen. The reactant in the SCR is an aqueous solution of 32.5 percent urea by weight, also known as DEF (*46*). Once released into the exhaust gas upstream of the SCR catalyst, DEF decomposes into ammonia (NH_3) that converts nitrogen oxides into nitrogen, water and carbon dioxide (*47*).

Excessive ammonia may lead to ammonia slip. Ammonia slip refers to emissions of unreacted ammonia from the catalyst exit as a result of incomplete reaction between NO_x and the reagent or the use of excessive reagent. The permitted ammonia slip levels in the U.S. are typically 2 ppm to 10 ppm. Ammonia slip at these levels does not pose significant health hazards (*48*). Ammonia slip is generally avoided or minimized by the precise injection of urea based on the NO_x concentration in the exhaust (*47*). Ammonia slip in the BATS is controlled by injection of urea based on the exhaust NO_x concentration measured with a sensor.

The NO_x control process has two steps. In the first step, urea is injected into the exhaust gas upstream of the SCR catalyst and decomposes to produce ammonia (*49*):

$$CO(NH_2)_2 \rightarrow NH_3 + HNCO \text{ (Thermolysis)} \quad (8)$$
$$HNCO + H_2O \rightarrow NH_3 + CO_2 \text{ (Hydrolysis)} \quad (9)$$

In the second step, ammonia reduces NO and NO_2 to nitrogen (N_2) in the presence of the SCR catalyst (*50*):

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \quad (10)$$
$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O \quad (11)$$
$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O \quad (12)$$

Amongst the reactions within the SCR catalyst, Reaction (10) is the dominant reaction under typical operating conditions. This is because typically the vast majority (over 90 percent) of engine-out NO_x emissions are NO. The NO_x reduction reactions (Reaction 10 and Reaction 11) are effective only within a particular temperature range. The optimum temperature range depends on the type of catalyst used and the exhaust gas composition, and typically varies from 250 °C to 427 °C (*49*).

SCR can reduce NO_x emissions by 70 percent for inlet NO_x concentrations as low as 20 ppm. Higher control efficiencies are possible for higher inlet NO_x concentrations. However, the reaction rate does not increase significantly above inlet NO_x concentrations of 150 ppm (*49*).

6.2 Blended Exhaust After-Treatment System

BATS is an SCR-based emission control system that takes in combined (blended) exhaust from the PME and HEP engine. BATS is a 'first-of-a-kind' retrofitted emission after treatment system for locomotives. BATS was developed by Rail Propulsion Systems, EF&EE, and Clean Train Propulsion. The BATS is intended for HEP-equipped EMD passenger locomotives and includes an SCR NO_x control system that uses an aqueous urea solution as a reagent (*48–50*). The BATS takes in combined (blended) exhaust from the PME and HEP engine for treatment. The initial BATS installation was focused on NO_x control, with a particulate filter to be added later for controlling PM emissions. Thus, the focus was on development of a procedure to evaluate BATS effectiveness for NO_x control. A schematic diagram of the BATS is shown in Figure 6-1.

Without the BATS, the PME exhaust and the HEP engine exhaust were directly released to the atmosphere via two separate exhaust ducts. The BATS takes in engine-out exhaust from the PME and the HEP engine and routes it to the SCR. The SCR is integrated into the dynamic braking grid. Urea required for the SCR is stored in a urea tank underneath the locomotive. Urea is injected into the HEP exhaust duct. High exhaust temperature of the HEP engine exhaust results in the decomposition of urea into ammonia. The amount of urea injection into the exhaust is directly proportional to the NO_x concentration in the SCR. The treated exhaust is released to the atmosphere via the BATS exhaust outlet. The BATS exhaust outlet consists of two long channels on the either side of the dynamic braking hatch. A BATS data logger is installed in the locomotive cab. The BATS data logger records the NO_x concentration in the SCR, urea injection rate, throttle notch position, PME load and HEP engine load.

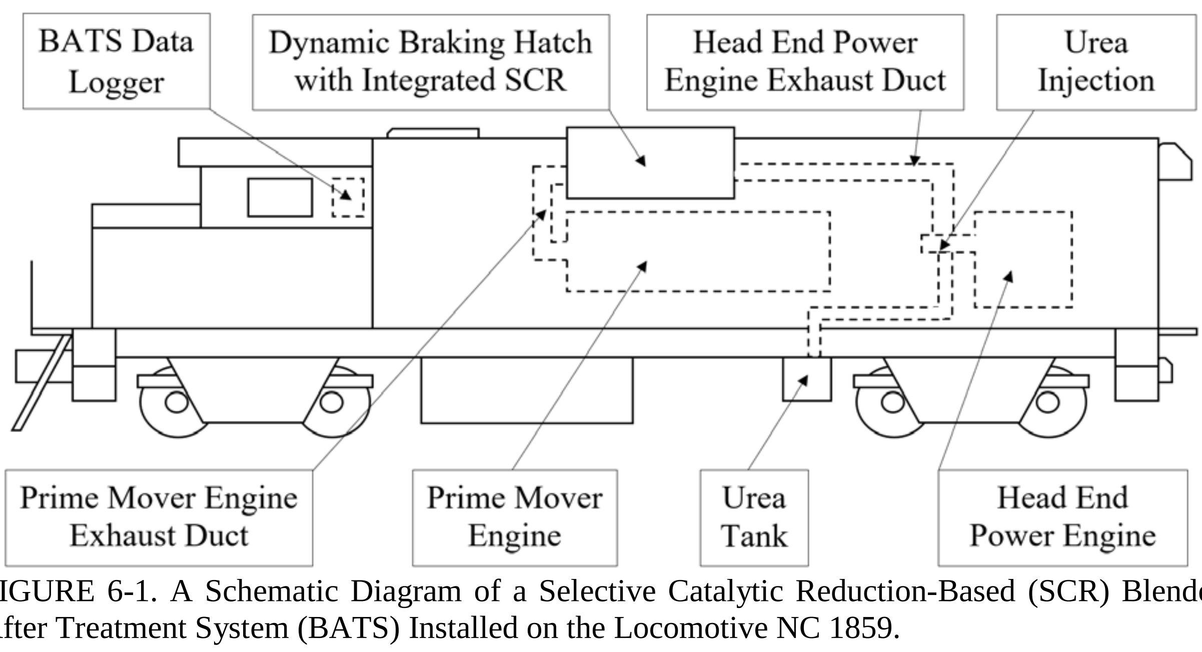

FIGURE 6-1. A Schematic Diagram of a Selective Catalytic Reduction-Based (SCR) Blended After Treatment System (BATS) Installed on the Locomotive NC 1859.

6.3 Experimental Methods

A series of static load railyard measurements were conducted between September 30, 2016 and October 2, 2016 on NC 1859 after installation of the BATS. The measurements included BATS outlet zero-hour certification tests conducted by EF&EE using the LEMS. Concurrently with the LEMS measurements, NCSU conducted BATS exhaust outlet measurements using the Axion PEMS. Baseline measurements of the untreated exhaust from the PME engine were conducted in November 2015 and are discussed in Chapter 4. Baseline measurements for the untreated exhaust from the HEP engine of NC 1859 were previously conducted by NCSU (*10*).

The locomotive was connected to an external dynamic braking (DB) grid. The test schedule included operating the PME at idle for one hour followed by operating at Notch 8 for 10 minutes to warmup the engine. The HEP engine was warmed up simultaneously by running the engine to power six passenger cars and the BATS. After the PME, HEP and BATS warmed up, the PME was operated at notches idle through Notch 7, and dynamic braking for 5 minutes each, and Notch 8 for 10 minutes. During this time, the HEP engine was powering the passenger cars. The external fuel tank was gravimetrically weighed at each notch change. The difference from the previous measurement was used to determine the mass of fuel consumed in each notch position. The test schedule was repeated 4 times. The DEF injection rates in the first three replicates were varied by EF&EE for each notch to determine an optimum DEF injection rate for each notch position. Optimum DEF injection maximizes NO_x control while minimizing the ammonia slip. The final replicate was conducted at the optimum DEF injection rate determined for each notch.

Exhaust gas and PM measurements were done at the two exhaust channels (Section 6.2). A sampling rake, shown in Figure 6-2, was used to collect composite exhaust from both exhaust channels. The composite exhaust from both channels was simultaneously directed to the Axion PEMS and LEMS.

The BATS receives untreated exhaust from the PME and HEP engine, simultaneously. BATS NO_x control efficiency is defined as the ratio of reduction in notch average NO_x emission rates and notch average NO_x emission rates in the untreated exhaust. Thus, assessment of BATS NO_x control efficiency must take into account the uncontrolled NO_x emission rates of both the PME and HEP engine and the controlled NO_x emission rates exiting the BATS. Two methods to estimate NO_x emission rates at the BATS outlet are demonstrated: (1) BATS Engine Activity Method; and (2) BATS Fuel Use Method. These methods are similar in concept to the Engine Activity Method and Fuel Use Method described in Section 3.6 for individual engines. However, the BATS methods differ in that they are applied to the blended exhaust of two engines, rather than to an individual engine. Urea injection into the BATS also affects the molar exhaust flow rate. As discussed in Section 3.6, molar exhaust flow rate is a key parameter to estimate locomotive FUER. Thus, the BATS methods must also account for the change in molar exhaust flow rate due to urea injection.

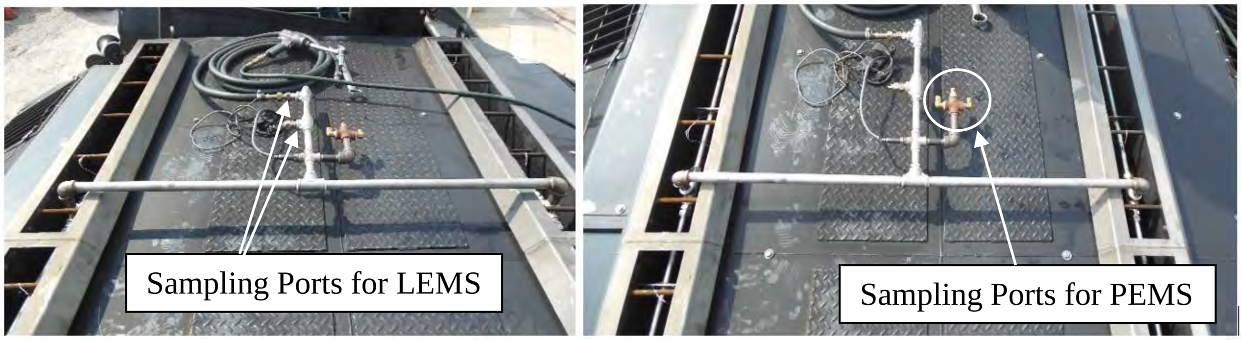

FIGURE 6-2. Installation of sampling rake at the outlets of BATS channels of the locomotive NC 1859.

6.3.1 *BATS Engine Activity Method*

The BATS Engine Activity Method is based on the assumption that the engine loads on the PME and HEP engine are a good indicator of the engine activity and FUER associated with the PME and HEP engine, respectively. Engine activity includes engine RPM, IAT and MAP (See Section 3.1.1). Engine activity and FUER measurements are repeatable with an inter-replicate CV of less than 0.2 for all notch positions (See Chapter 4). Thus, for a PME operating at a given notch position 'n', the engine load, engine activity and PME exhaust concentrations were assumed to be constant based on prior studies on the PME of the same locomotive (*21*, *22*). Similarly, for a HEP engine at load '*l*', the fuel use rate and the HEP exhaust concentrations were assumed to be constant based on the prior studies on the HEP engine of same locomotive (*10*). Thus, engine-out PME and HEP exhaust flow rates and emission rates were quantified based on the measured PME and HEP engine load, respectively.

The total dry exhaust flow rate of the BATS outlet exhaust was estimated based on the mass flow rate of CO_2 in the BATS outlet exhaust. The mass flow rate of CO_2 in the BATS exhaust is the sum of CO_2 mass flow rates from each engine and the mass flow rate of CO_2 from the chemical reaction of urea in the SCR system. The mass flow rate of CO_2 in the BATS exhaust was estimated as the product of the estimated total dry molar exhaust flow rate at time *t* at the BATS outlet, PEMS measured dry mole fraction of CO_2 in the BATS exhaust ($y_{CO_2,dry,BATS,t}$), and molecular weight of CO_2. The total dry molar exhaust flow rate at the BATS outlet was estimated as:

$$M_{e,t,dry,BATS} = \frac{m_{CO_2,dry,p,n,t} + m_{CO_2,dry,h,l,t} + m_{CO_2,urea,t}}{y_{CO_2,t,dry,BATS} \times MW_{CO_2}} \quad (13)$$

Where,

$M_{e,t,dry,BATS}$	=	dry molar exhaust flow rate at time *t* at the BATS outlet (*gmol/s*)
$m_{CO_2,dry,p,n,t}$	=	dry exhaust CO_2 mass flow rate from PME at notch *'n'* at time *t* (*g/s*)
$m_{CO_2,dry,h,l,t}$	=	dry exhaust CO_2 mass flow rate from HEP engine at load *'l'* at time *t* (*g/s*)
$m_{CO_2,urea,t}$	=	mass flow rate of CO_2 due to urea injection (*g/s*)
$y_{CO_2,dry,BATS,t}$	=	CO_2 concentration at time *t* on a dry basis at the BATS outlet (*vol %*)
MW_{CO_2}	=	molecular weight of CO_2 (= 44 g/gmol CO_2)

Based on the key reactions in an SCR system (see Reactions 8 to 12), each mole of urea injected into the BATS decomposes into two moles of NH_3 and one mole of CO_2. To simplify the calculations, all the reactions were assumed to take place instantaneously and stoichiometrically. Thus, the mass flow rate of CO_2 in the BATS exhaust due to urea injection was estimated from the measured DEF volumetric flow rate ($V_{DEF,t}$) in ml/min. The DEF flow rate reported by the BATS data logger was used to estimate the molar flow rate of urea ($M_{urea,t}$) into the SCR as:

$$M_{urea,t} = V_{DEF,t} \left(\frac{ml\ DEF}{min}\right) \times \frac{1}{3785.4}\left(\frac{gal}{ml}\right) \times\ 9.0\left(\frac{lbs\ DEF}{gal\ DEF}\right) \times \frac{32.5}{100} \times \left(\frac{wt.of\ Urea}{wt.of\ DEF}\right) \times \frac{1}{60}\left(\frac{min}{seconds}\right) \times 453.6\left(\frac{g}{lbs}\right) \times \frac{1}{60}\left(\frac{gmol\ urea}{g}\right) \quad (14)$$

Where,

$M_{urea,t}$	=	molar flow rate of urea into the SCR (*gmol/s*)
$V_{DEF,t}$	=	DEF volumetric flow rate into the SCR (*ml/min*)

Based on Reaction (8) and Reaction (9), each mole of urea injected into the SCR resulted in addition of one mole of CO_2 to the BATS exhaust. Thus, the molar flow rate of CO_2 due to urea injection was equal to the molar flow rate of urea. The mass flow rate of CO_2 due to urea injection was estimated as:

$$m_{CO_2,urea,t} = M_{urea,t} \times MW_{CO_2} \quad (15)$$

The dry exhaust flow rate at the BATS outlet was used to estimate the pollutant mass flow rates using Equations (2) and (3) of Section 3.6, based on pollutant concentrations measured at the BATS outlet. The combined fuel use rate for the PME and HEP engine was estimated as:

$$m_{f,p,h,t} = M_{e,\mathrm{t},dry} \times MW_f \times \left\{\left(y_{CO_2,dry,BATS,t} - \frac{M_{urea,t}}{\mathrm{M}_{e,t,dry,BATS}}\right) +\ y_{CO,\mathrm{t},dry} + m \times y_{HC,\mathrm{t},dry}\right\} \quad (16)$$

Where,

$m_{f,p,h,t}$	=	Combined fuel use rate for the PME and HEP engine (*g/s*)

6.3.2 *BATS Fuel Use Method*

As an alternative to the BATS engine activity-based method, in which the exhaust flow rate for individual engines must be known, the BATS outlet emission rate can be estimated based on the total fuel use rate for both engines but without specific knowledge of the exhaust flow rates from individual engines. The total fuel use of both engines could be measured, for example, based on continuous gravimetric weighing of a single fuel tank from which both engines draw fuel and to which both engines return fuel. Such a measurement approach was used in the rail yard measurement of the BATS. The exhaust flow at the BATS outlet was estimated based on fuel flow rate, urea injection rate, a carbon balance, and, indirectly, the air-to-fuel ratio. The carbon in the BATS exhaust was assumed to come from the two engines and from urea injection. Thus, the carbon flow rate in the exhaust, which is comprised of CO_2, CO, and hydrocarbons, must be equal to the total carbon flow rate entering the BATS, which includes CO_2, CO, and HC from PME and HEP engine exhaust that results from fuel combustion and CO_2 from urea injection. Given that the fuel consumption rate was measured, and the urea injection rate was measured, the total carbon flow entering the BATS was known. The carbon flow rate was divided by the measured dry exhaust concentrations of carbon in the exhaust, resulting in an estimate of total dry exhaust flow:

$$M_{e,t,dry,BATS} = \frac{m_{f,p,h,t} + M_{\text{urea,t}} \times MW_f}{MW_f \times (y_{CO_2,t,\text{dry,BATS}} + y_{CO,t,\text{dry,BATS,}} + m \times y_{HC,t,\text{dry},BATS})} \quad (17)$$

Once the dry molar exhaust flow rate was known, the pollutant emissions rates were estimated by multiplying the molar exhaust flow rate with the respective pollutant concentrations as given in Equation (2) and Equation (3).

6.3.3 *Comparison of BATS Methods*

BATS fuel use method is assumed to be more accurate compared to BATS engine activity method, as BATS fuel use method is based on actual fuel use measurement. However, fuel use measurements can be complicated for OTR measurements. Periodic weighing of the tank at each notch change is not feasible as the locomotive operators may change the notch positions frequently based on power demand met by the locomotive. Also, the notch change for OTR measurements does not follow a pre-defined test schedule. Therefore, the notch changes are dynamic. Thus, for OTR measurements, BATS Engine Activity method is the preferred one because the engine activity can be estimated.

6.3.4 *NO_x Control Efficiency*

NO_x control efficiency was determined on the basis of the final replicate with optimum DEF injection rate. The BATS NO_x control efficiency was estimated as the ratio of the mass of NO_x removed by the BATS and the mass of NO_x entering into the BATS:

$$\eta_{NO_x,BATS,n,l} = \left(1 - \frac{m_{NO_x,BATS,n,l}}{m_{NO_x,p,n} + m_{NO_x,h,l}}\right) \times 100 \quad (18)$$

Where,

$\eta_{NO_x,BATS,n,l}$	=	BATS NO_x control efficiency with the PME at notch *'n'* and HEP engine at load *'l'*
$m_{NO_x,BATS,n,l}$	=	NO_x mass emission rate (in g/s) at the BATS outlet with the PME at notch *'n'* and HEP engine at load *'l'*;
$m_{NO_x,p,n}$	=	NO_x mass emission rate (in g/s) from the PME at notch *'n'*
$m_{NO_x,h,l}$	=	NO_x mass emission rate (in g/s) from the HEP engine at load *'l'*

6.3.5 *PEMS Benchmarking*

The Axion PEMS was benchmarked to LEMS. CO_2 and NO_x emissions rates were estimated using BATS fuel use method for Axion PEMS and LEMS measured exhaust concentrations. Parity plots for each emission rates were compared.

6.4 Results and Discussion

This section describes the results of baseline PME and HEP engine exhaust gas and PM concentration measurements. Notch average FUER were estimated using the BATS engine activity and fuel use methods using measurements conducted with Axion PEMS. Notch average fuel use rates estimated using BATS engine activity method were compared to gravimetrically measured notch average fuel use rates to validate the model. CO_2 and NO_x emission rates were also compared to quantify the differences between the two methods. NO_x control efficiency was estimated using the two methods and compared. Axion PEMS measurements were also benchmarked to LEMS. BATS fuel use method was used to estimate CO_2 and NO_x emission rates based on exhaust gas concentration measurements conducted using Axion PEMS and LEMS.

6.4.1 *Baseline measurements*

Baseline measurements for the PME and HEP engine of the locomotive NC 1859 were conducted during rail yard testing on May 25, 2015 and November 18, 2015, respectively. Results of the baseline PME measurements are given in Appendix A. Baseline HEP engine measurements were conducted in a prior study (*10*). The key notch average mass per time based FUER for the PME and HEP engine are given in Table 6-1 and Table 6-2, respectively. The baseline engine-out PME and HEP gaseous exhaust and PM measurements were conducted using an Axion PEMS prior to the installation of the BATS. Both engines were operated on ultra-low sulfur diesel (ULSD). In the baseline measurements, the PME was warmed up and run at idle through Notch 8 for 5 minutes each (See Section 3.2). Dynamic braking could not be measured during the baseline tests. Engine activity was recorded by an engine sensor array. The HEP engine was warmed up and run at several pre-determined engine load levels for 5 minutes each (See Section 3.2). The fuel use rate was logged from the HEP engine control unit using a scan tool (*10*, *22*). The baseline gaseous and PM mass emission rates for the PME and HEP engine were estimated using the engine activity method and fuel use method, respectively (See Section 3.6).

The BATS data logger recorded the PME and HEP engine loads, the throttle notch position of the PME, and the DEF injection rate. The HEP load on the engine varied between 110 kW to 130 kW. Both the PME and HEP engine were operated on ULSD. The Axion PEMS was used to record BATS outlet exhaust concentrations of CO_2, CO, HC, NO and PM, and PME activity parameters: RPM, IAT and MAP. The combined fuel use rate of the PME and HEP engine was measured gravimetrically by EF&EE using an external fuel tank. Notch average fuel use rates were estimated by taking the difference of the mass of the external fuel tank between successive changes in notch position.

Measured PME and HEP engine loads, urea injection rate, and the gaseous and PM exhaust concentrations at the BATS outlet were used to estimate the dry molar exhaust flow rate at the BATS outlet using the BATS engine activity method. The combined fuel use rate of the PME and HEP engine, urea injection rate and the gaseous and PM exhaust concentrations at the BATS outlet were used to estimate the dry molar exhaust flow rate at BATS outlet using the BATS fuel use method.

TABLE 6-1. Baseline fuel use and pollutant emission rates estimated using the 'Engine Activity Method' for the prime mover engine of locomotive NC 1859 running on ULSD during the static load rail yard test conducted on November 18, 2015.

Throttle Notch Position	Engine Output [hp]	Engine Activity			Fuel Use Rate [g/s]	Pollutant Mass Emission Rates				
		RPM [rpm]	IAT [°C]	MAP [kPa]		CO_2 [g/s]	CO [g/s]	HC[a] [g/s]	NO_x[a] [g/s]	PM[a] [g/s]
Idle	9	370	73	108	5.1	14.0	0.74	0.58	0.22	0.004
1	190	370	67	108	11.7	36.1	0.10	0.19	0.50	0.006
2	350	370	69	109	17.7	54.6	0.16	0.32	0.90	0.008
3	675	492	71	120	30.6	94.4	0.27	0.50	1.61	0.010
4	1000	565	72	129	40.9	126	0.41	0.63	2.09	0.014
5	1300	653	72	143	54.7	170	0.23	0.36	2.53	0.018
6	1600	731	74	158	71.8	224	0.30	0.00	3.11	0.026
7	2200	822	76	181	96.9	300	1.34	0.79	3.56	0.040
8	2700	904	78	228	124	383	1.46	1.17	4.06	0.054

[a] *PEMS measurements of NO, HC and PM are based on measured concentrations without bias correction. NO mass emission rates are reported as equivalent NO_x (by using the molecular weight of NO_2).*

TABLE 6-2. Baseline fuel use and pollutant emission rates estimated using the 'Engine Fuel Use Method' for the head end power engine of locomotive NC 1859 running on ULSD during the static load rail yard test conducted on May 25, 2015 (*10*)

Engine Output [kW]	Fuel Use [g/s]	Pollutant Mass Emission Rates				
		CO_2 [g/s]	CO [g/s]	HC[a] [g/s]	NO_x[a] [g/s]	PM[a] [g/s]
12	7.2	22	0.215	0.04	0.25	0.002
21	7.2	22	0.179	0.04	0.27	0.002
25	7.1	22	0.166	0.04	0.28	0.003
35	6.0	18	0.121	0.04	0.20	0.002
58	5.5	17	0.072	0.02	0.18	0.002
125	7.5	24	0.026	0.02	0.25	0.002
247	16.7	53	0.007	0.03	0.41	0.004
366	21.9	69	0.005	0.04	0.57	0.004
488	30.0	94	0.022	0.06	1.00	0.006

[a] *PEMS measurements of NO, HC and PM are based on measured concentrations without bias correction. NO mass emission rates are reported as equivalent NO_x (by using the molecular weight of NO_2).*

6.4.2 *BATS Engine Activity Method*

Notch average combined fuel use rate for the PME and the HEP engine, and the exhaust gas emission rates at the BATS outlet were estimated using the BATS engine activity method and BATS fuel use method. PM concentration measurements were found to be invalid because the sampling configuration used for the PM resulted in too much sample loss. Too many sharp bends between the sampling rake and the Axion PEMS may have resulted in deposition of PM near the bends. Hence, PM emission rates are not reported. The results of the final replicate estimated using the BATS Fuel Use Method were used to evaluate BATS NO_x control efficiency.

Mass per time-based notch average FUER for the final replicate estimated using the BATS engine activity method are given in Table 6-3. The PME engine power output corresponding to each notch position was similar to the baseline measurements. The combined fuel use rate from both the PME and HEP engine varied from 12.3 g/s at idle to 131 g/s at Notch 8. Fuel use rate increased monotonically with increasing notch position.

CO_2 emission rates varied from 36.1 g/s at idle to 409 g/s at Notch 8. CO_2 emission rates increased monotonically with increasing notch position. CO and HC emission rates were based on CO and HC concentrations mostly below the detection limit of the Axion PEMS. NO_x emission rates varied between 0.3 g/s and 1.1 g/s. No particular trend was observed with notch positions. However, NO_x emission rates at Notches 6 through 8 were typically higher than lower notch positions. Overall, cycle average NO_x emission rates were 0.8 g/bhp-hr for the EPA Line-haul and average Piedmont duty cycles which is lower than the level of Tier 4 standards.

TABLE 6-3. Combined PME and HEP Engine Fuel Use Rate and Estimated Emission Rates at BATS Outlet of Locomotive NC 1859 Running on Ultra-Low Sulfur Diesel Estimated using BATS Engine Activity Method.

Notch	Head End Power Engine Load (hp)	Combined Fuel use rate (g/s)	Emission Rates (g/s)			
			CO_2	CO	HC[a]	NO_x[a]
Idle	118	12.3	36.1	0.08	0.49	0.60
DB[b]	127	-[c]	39.3	0.12	0.67	0.31
1	120	19.4	51.1	0.11	0.66	0.62
2	127	25.4	69.9	0.11	0.55	0.57
3	120	38.2	111	0.17	0.92	0.41
4	120	48.5	154	0.17	1.09	0.38
5	126	62.6	204	0.21	1.31	0.56
6	112	79.8	235	0.25	1.39	1.10
7	126	104	282	0.36	1.23	0.69
8	120	132	409	0.84	1.46	0.99

[a] *PEMS measurements of NO and HC are based on measured concentrations without bias correction. NO mass emission rates are reported as equivalent NO_x (by using the molecular weight of NO_2). PM concentration measurements were invalid. Hence, PM emission rates are not reported.*

[b] *DB = Dynamic Brake*

[c] *Results unavailable for dynamic braking as baseline measurements were not conducted for dynamic braking.*

Combined FUERs for the PME and HEP engine were also estimated from the baseline measurements to compare FUERs after BATS installation versus FUER prior to BATS installation. Combined FUERs for a notch position *n* and HEP engine load *l* were estimated from baseline measurements as sum of FUERs corresponding to notch *n* of the PME and load *l* of the HEP engine. FUERs for HEP engine at a given load were interpolated from baseline HEP engine FUER. The combined PME and HEP engine fuel use rate are given in Table 6-4. BATS NO_x control efficiency was estimated as percentage reduction in NO_x emission rate with respect to baseline measurements. Thus, BATS NO_x control efficiency is negative of percentage difference in NO_x emission rate with respect to baseline NO_x emission rate. Relative percentage differences in notch average fuel use rate and CO_2 emission rate due to BATS installation are given in Table 6-5.

TABLE 6-4. Combined PME and HEP Engine Fuel Use Rate of Locomotive NC 1859 Running on Ultra-Low Sulfur Diesel Estimated from the Baseline Measurements.

Throttle Notch Position	PME Fuel Use Rate (g/s)	HEP Engine Load (kW)	HEP Engine Fuel Use Rate (g/s)	Combined PME and HEP Engine Fuel Use Rate (g/s)
Idle	5.1	118	7.3	12.4
1	11.7	120	7.4	19.1
2	17.7	127	7.7	25.4
3	30.6	120	7.4	38.0
4	40.9	120	7.4	48.3
5	54.7	126	7.6	62.3
6	71.8	112	7.1	78.9
7	96.9	126	7.5	104
8	124	120	7.4	131

TABLE 6-5. Relative Percentage Differences in Notch average Fuel Use Rate and CO_2 Emission Rate due to BATS Installation on Locomotive NC 1859 Running on ULSD

Throttle Notch Position	Relative Percentage Difference with Respect to Baseline (%)	
	Fuel Use	CO_2
Idle	-0.9	-1.1
1	1.6	1.7
2	0.1	0.1
3	0.7	1.4
4	0.5	1.5
5	0.4	0.8
6	1.2	1.3
7	0.1	0.3
8	0.4	0.5

Combined fuel use rate estimated from baseline measurements for the given notch position and corresponding to a given HEP load was found to be higher compared to the combined fuel use rate estimated using BATS engine activity method for all notch positions except idle. Similar trends were observed for CO_2 emission rates. Thus, for a given notch position and a given HEP engine load, BATS installation may result in a higher overall fuel use rate. However, the increase in fuel use rate was only between 0.1 percent and 1.6 percent. The slight increase in fuel use rate could be due to backpressure on the engine as a result of exhaust not being released to the atmosphere directly.

6.4.3 *Comparison of BATS Methods*

The baseline notch average fuel use, exhaust concentrations and estimated dry exhaust molar flow rates for the HEP engine are given in Appendix D. The baseline notch average engine activity parameters, exhaust concentrations and estimated dry exhaust molar flow rates for the PME are given in Appendix C. These data were useful in estimating the dry molar exhaust flow rates at the BATS inlet in the 'BATS Engine Activity' method. These data were also used to estimate the baseline pollutant emissions rates from the PME and HEP Engine, respectively.

The notch average engine activity parameters, engine loads, exhaust concentrations, urea injection rate and the fuel use rate for each of the replicates are given in Appendix C. The HEP load was approximately constant at around 110-130 hp during the replicates. CO and HC concentrations were below the detection limit of the Axion PEMS for most of the measurements. The CO_2 concentrations typically increase with increasing notch position except for high idle. The NO concentrations were variable depending upon the urea injection rate. NO concentrations were typically high for mid notches and lower elsewhere.

Notch average molar exhaust flow rates for Axion PEMS measured exhaust concentrations are given in Table 6-6. The molar exhaust flow rates increased monotonically with increasing notch position. The molar exhaust flow rates ranged between 40 gmol/s and 160 gmol/s. The flow rates estimated from both the methods were consistent with each other. The notch average flow rates did not vary much across replicates.

Scatter plots were prepared for each replicate to compare the molar flow rates estimated through both methods. A linear regression was performed between the molar flow rates estimated by two methods to study the relation between them. The intercept was set to 0 and the slope is reported. The scatter plots and results of linear regression are given in Figure 6-3. The slope of the linear fit was very close to 1 with a strong adjusted R^2 value (>0.99) for all the plots, indicating strong agreement between the methods. On a side by side comparison, the molar exhaust flow rates estimated using the fuel use method were consistently higher than the molar exhaust flow rates estimated using the engine loads method, though the difference between them was very less (less than 5 percent).

TABLE 6-6. BATS Outlet Molar Exhaust Flow Rates Estimated using BATS Engine Activity and BATS Fuel Use Methods for Locomotive NC 1859 Running on ULSD

Throttle Notch Position	Notch Average Molar Exhaust Flow Rate at BATS Outlet (gmol/sec)									
	Replicate 1		Replicate 2		Replicate 3		Replicate 4		Average	
	BATS Engine Activity Method	BATS Fuel Use Method	BATS Engine Activity Method	BATS Fuel Use Method	BATS Engine Activity Method	BATS Fuel Use Method	BATS Engine Activity Method	BATS Fuel Use Method	BATS Engine Activity Method	BATS Fuel Use Method
Low Idle	42.2	42.7	44.9	42.5	40.6	40.2	43.1	42.8	42.7	42.0
High Idle	62.6	64.1	61.5	63.8	55.5	58.2	57.7	59.7	59.3	61.4
DB[a]	-	99.3	-	98.9	-	89.7	-	66.3	-	88.6
1	58.0	58.6	62.0	58.4	58.8	61.4	60.2	54.0	59.7	58.1
2	57.7	59.4	60.6	59.1	58.5	61.6	56.8	58.9	58.4	59.7
3	75.5	76.3	74.3	76.0	73.8	75.4	72.6	78.3	74.0	76.5
4	84.8	87.7	81.4	86.8	82.9	89.9	80.1	89.1	82.3	88.4
5	99.9	100	94.2	100	95.0	101	92.0	101	95.3	100
6	116	116	110	116	111	114	108	112	111	114
7	127	128	123	127	125	125	123	126	124	127
8	152	155	150	154	148	154	148	153	149	154

[a] *The BATS Engine Activity Method requires the measurements of engine activity parameters and exhaust concentrations on the PME and HEP Engine. The engine activity parameters for PME and HEP Engine were recorded during the current testing. However, the exhaust concentrations for PME and HEP Engine have been referenced from baseline measurements on NC 1859. The baseline measurements did not include dynamic braking. Hence, no results are available for dynamic braking based on BATS Engine Activity Method.*

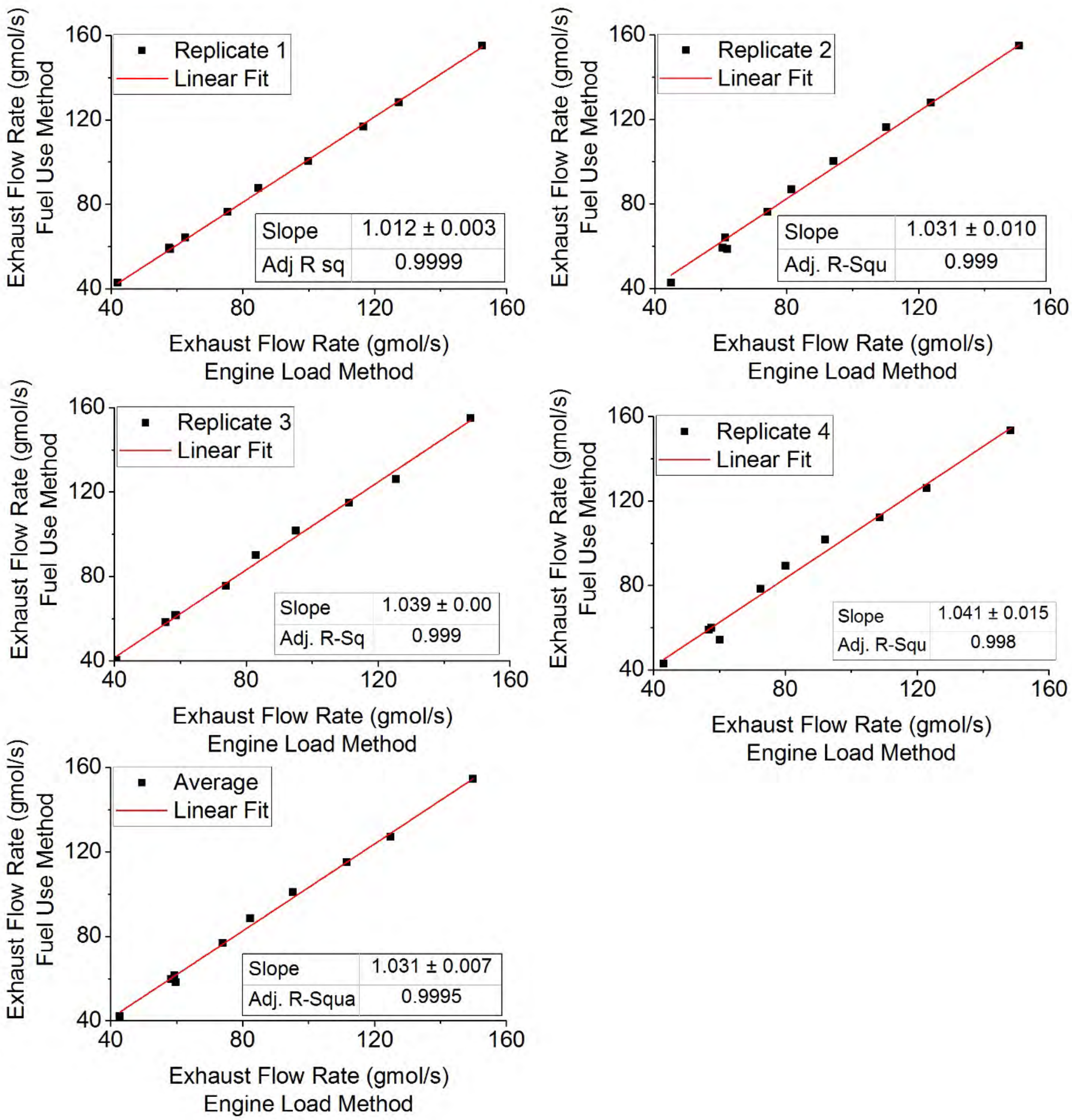

FIGURE 6-3. Comparison between Molar Exhaust Flow Rates Estimated by Engine Activity Method and Fuel Use Rate Method for the Measurements Conducted at BATS Outlet of Locomotive NC1859 Running on ULSD

The notch average fuel use rate was also estimated based on the BATS Engine Activity Method for the BATS outlet and compared to the gravimetric fuel use rate for each of the replicates. The fuel use method requires the gravimetric fuel use rate to estimate molar exhaust flow rates, hence the fuel use rate cannot be estimated separately by this method.

The fuel use rates estimated through BATS Engine Activity Method for Axion PEMS measured exhaust concentrations are given in Table 6-7. The fuel use rates increased monotonically with increasing notch position. The fuel use rates ranged between 9.07 g/s and 137 g/s. The fuel use rates were consistent with the gravimetric fuel use rate. The notch average fuel use rates did not vary much across replicates.

TABLE 6-7. Notch Average Fuel Use Rate at BATS Outlet Estimated from Molar Exhaust Flow Rates and Axion PEMS Measured Exhaust Concentrations for the Locomotive NC1859 Running On ULSD

Throttle Notch Position	Notch Average Fuel Use Rate at BATS Outlet (g/sec)									
	Replicate 1		Replicate 2		Replicate 3		Replicate 4		Average	
	BATS Engine Activity Method	Gravi-metric Fuel Use	BATS Engine Activity Method	Gravi-metric Fuel Use	BATS Engine Activity Method	Gravi-metric Fuel Use	BATS Engine Activity Method	Gravi-metric Fuel Use	BATS Engine Activity Method	Gravi-metric Fuel Use
Low Idle	9.07	11.5	10.8	10.2	10.8	10.7	10.8	10.7	10.4	10.8
High Idle	13.9	14.3	12.2	12.7	12.2	12.9	12.2	12.7	12.7	13.1
DB[a]	-	20.3	-	19.0	-	17.9	-	18.4	-	18.9
1	18.1	20.3	19.3	18.2	19.3	20.2	19.3	17.4	19.0	19.0
2	22.8	26.8	25.2	24.7	25.3	26.7	25.3	26.4	24.7	26.1
3	38.8	41.3	38.1	39.1	38.2	39.2	38.2	41.3	38.3	40.2
4	51.0	54.5	48.4	51.8	48.5	52.8	48.5	54.1	49.1	53.3
5	67.7	68.8	62.5	66.6	62.6	67.1	62.5	69.2	63.8	67.9
6	79.2	82.3	79.8	84.3	79.9	82.7	79.8	82.5	79.7	82.9
7	103	105	104	107	104	104	104	107	103	106
8	134	135	130	135	130	137	130	135	131	135

[a] DB = Dynamic Brake

Note: The BATS Engine Activity Method requires the measurements of engine activity parameters and exhaust concentrations on the PME and HEP engine. The engine activity parameters for PME and HEP Engine were recorded during the current testing. However, the exhaust concentrations for PME and HEP engine have been referenced from baseline measurements on NC 1859. The baseline measurements did not include dynamic braking. Hence, no results are available for dynamic braking based on BATS Engine Activity Method.

Scatter plots were prepared for each replicate to compare the fuel use rates estimated through BATS Engine Activity Method. A linear regression was performed between the fuel use rate estimated by BATS Engine Activity Method and the fuel use rate measured gravimetrically to study the relation between them. The intercept was set to 0 and the slope is reported. The scatter plots and results of linear regression are shown in Figure 6-4. The slope of the linear fit was very close to 1 with a strong adjusted R^2 value (>0.99) for all the plots, indicating strong agreement between the methods. The fuel use rate estimated using the BATS Engine Activity Method was consistently lower than the gravimetrically measured fuel use rate, although, the difference between them was typically less than 5 percent.

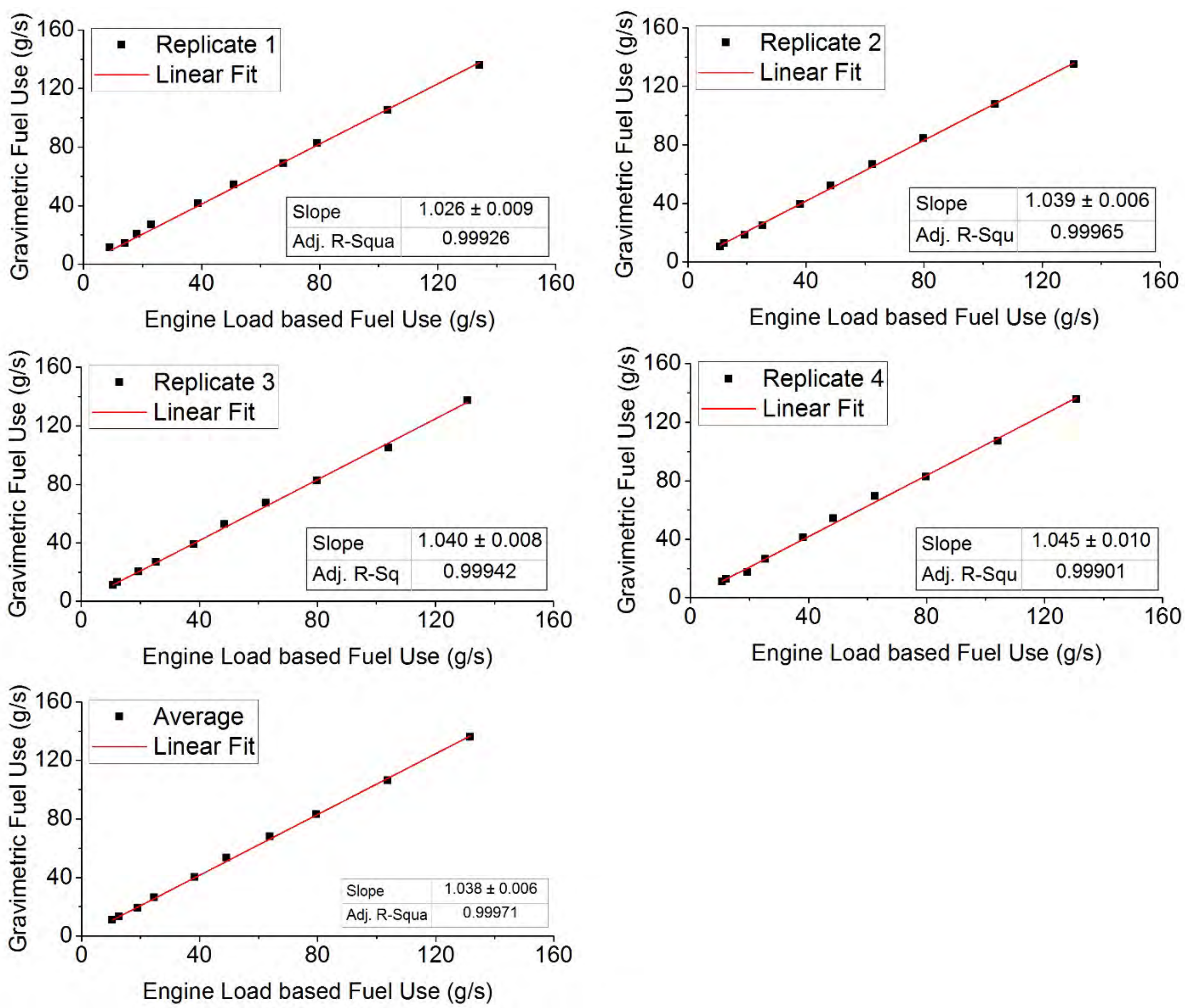

FIGURE 6-4. Comparison between Fuel Use Rate Estimated by BATS Engine Activity Method and Fuel Use Rate Measured Gravimetrically for the Measurements Conducted at BATS Outlet of Locomotive NC1859

6.4.4 *BATS NO_x control efficiency*

BATS NO_x control efficiency was estimated using BATS engine activity and BATS fuel use methods. BATS NO_x control efficiency is given in Table 6-8. The BATS was able to achieve a NO_x reduction of 96.2 percent at Notch 4. NO_x reduction was greater than 90 percent at idle, Notch 3 and Notch 5. Notch 2, Notch 6, Notch 7 and Notch 8 had a control efficiency of 74.9 percent, 80.5 percent, 89.6 percent and 87.7 percent, respectively. Only Notch 1 and high idle had lower NO_x control efficiency of 53.3 percent and 50.3 percent, respectively. Both methods were found to provide comparable estimates.

6.4.5 *Benchmarking PEMS to LEMS*

After the estimation of notch average molar exhaust flow rates and fuel use rates, notch average emission rates of CO_2, CO, HC, NO and PM were estimated using the two methods and compared with the LEMS results to determine the accuracy and precision of Axion PEMS in estimating notch average emission rates. The notch average CO_2, CO, HC, NO and PM emission rates estimating using the BATS engine activity and fuel use methods for each replicate are given in Appendix C. The emissions rates estimated through each method were compared to the LEMS results. The results of the comparison are given in Appendix C.

TABLE 6-8. NO_x Control Efficiency of the Blended After Treatment System estimated using the BATS Engine Activity Method and the BATS Fuel Use Method for the Railyard Test on the Locomotive NC 1859 operating on Ultra-Low Sulfur Diesel.

Throttle Notch Position	Load on Prime Mover Engine [hp]	Load on Head End Power Engine [kW]	BATS NO_x Control Efficiency [%]	
			BATS Engine Activity Method	BATS Fuel Use Method
Low Idle	9	118	92.1	92.2
High Idle	9	118	57.9	53.3
DB[a]	9	127	-[b]	-[b]
1	190	120	49.0	50.3
2	350	127	76.0	74.9
3	675	120	93.5	93.2
4	1000	120	96.5	96.2
5	1300	126	93.2	92.6
6	1600	112	81.8	80.5
7	2200	126	90.0	89.6
8	2700	120	87.7	87.7

[a] *DB = Dynamic Brake*

[b] *Baseline measurements were not conducted for dynamic brake hence NO_x control efficiency for dynamic brake could not be estimated.*

The notch average CO_2 emission rate estimated with LEMS for the locomotive ranged from 33.2 g/s at low idle to 437 g/s at Notch 8. Notch average CO_2 emission rate increased monotonically with the increasing notch position. Notch average CO_2 emission rate estimated using the BATS Engine Activity Method and the fuel use method were consistently lower than LEMS estimated notch average CO_2 emission rate. However, the difference of the estimates from LEMS was less than 10 percent. Notch average CO_2 emission rates based on BATS engine activity method were typically lower by around 1 percent at low idle to around 10 percent at Notch 8. However, notch average CO_2 emission rates from fuel use method were comparable to the LEMS estimates, differing only by less than 1 percent in most of the cases. Notch average CO_2 emission rates based on BATS Engine Activity Method had a lower correlation coefficient with LEMS results compared to the notch average CO_2 emission rates based on fuel use method. The slope estimate for the fuel use method was significantly different from 1 for the BATS Engine Activity Method ($p\text{-value} > 0.05$), whereas, the slope estimate for the fuel use method was not significantly different from 1 ($p\text{-value} < 0.05$). Hence, the fuel use method is better at estimating notch average CO_2 emission rates.

The notch average NO_x emission rate estimated with LEMS for the locomotive ranged from 0.027 g/s at low idle to 2.392 g/s at Notch 8. The notch average NO_x emissions rate are a function of urea injection rate into the SCR, hence varied a lot for the same notch positions for different replicates. The urea injection rate was varied to find the optimum NO_x control efficiency for a given notch position. Notch average NO_x emission rate estimated using the BATS Engine Activity Method and the fuel use method were consistently lower than LEMS estimated notch average NO_x emission rate. However, the difference of the estimates from LEMS varied from less than 1 percent to around 30 percent. Both the methods had comparable estimates of slope and correlation coefficient with the LEMS results.

Notch average CO and HC emission rates were not comparable to the LEMS estimates as CO and HC concentrations were mostly below the detection limit of the Axion PEMS. Based on the comparison of PEMS-based emission rates and LEMS-based emission rates, the Axion PEMS is reasonably good at estimating the notch average emission rates for CO_2 and NO_x.

Notch average PM emission rates estimated with Axion PEMS measured PM concentrations were very low compared to the filter-based PM measured with LEMS. However, the PEMS-based PM emission rates were corelated with LEMS-based PM emission rates, with a correlation coefficient of 0.8. The Axion PEMS is known to have a bias in PM measurement and typically the PM emission rates are increased by a factor of 5 to account for the bias. However, the bias corrected emission rates were also quite lower than LEMS estimates. This large difference of PM emission rates could be the artifact of the sampling hoses. The sample hoses had many bends which might have significantly affected the PM flow into the sample hose.

A new sampling rake was designed to minimize PM sampling loss. The new rake collects exhaust from a point location inside the BATS channel instead of collecting a composite sample from several locations inside the BATS channel as done in this study. This way, several sharp bends were avoided. However, sampling from a point location could be biased if the exhaust is not uniformly distributed across the BATS channel. Thus, a test was later conducted by placing the newly designed sampling rake at several BATS locations and measuring exhaust concentrations of CO_2 and NO. This test was called as 'BATS Mapping test' to determine the most suitable sampling location. The details of BATS mapping test are described in Appendix D.

6.5 Conclusions

The BATS was able to achieve a notch average NO_x reduction of 96.2 percent at Notch 4. NO_x reduction was greater than 90 percent at idle, Notch 3 and Notch 5. Notch 2, Notch 6, Notch 7 and Notch 8 had a control efficiency of 74.9 percent, 80.5 percent, 89.6 percent and 87.7 percent, respectively. Only Notch 1 and high idle had lower NO_x control efficiency of 53.3 percent and 50.3 percent, respectively. Overall, cycle average NO_x emission rates were 0.8 g/bhp-hr for the EPA Line-haul and average Piedmont duty cycles which is lower than the level of Tier 4 standards.

Notch average fuel use rate increased for all notch positions, except at idle after BATS installation. However, the increase in fuel use rate was only between 0.1 percent and 1.6 percent. Similar trends were observed for notch average CO_2 emission rates. Notch average CO and HC emission rates remain unaffected. Notch average CO and HC emissions were very low. Notch average PM emission rates could not be estimated because of invalid PM concentration measurements.

PEMS-based notch average CO_2 and NO_x emission rates were highly correlated with LEMS. PEMS measurements provide reliable estimates of notch average CO_2 and NO_x emission rates. Indirect fuel estimation based on PEMS and engine activity measurements was highly correlated with actual fuel use measurement. CO and HC pollutant concentrations were below PEMS detection limit and, hence, were not compared. The PEMS-based PM emission rates were correlated with LEMS-based PM emission rates, with a correlation coefficient of 0.8. BATS engine activity and fuel use methods give comparable estimates of NO_x control efficiencies. The choice of method depends upon the measured data. Fuel use method for blended exhaust is based on actual fuel use data; thus, is expected to be more accurate than engine activity method. The BATS engine activity method is a reliable alternative in the absence of fuel use measurements and is suitable for OTR measurements.

Chapter 7. Locomotive Operation

This chapter discusses about the resistive forces that affect engine load, which in turn, affect locomotive fuel use and emissions. Real-world locomotive operation involves shifting among throttle notch positions by the engineer, to increase or decrease engine load as warranted by the track curvature, track grade, grade crossings, track condition, stations, speed restrictions and required acceleration. Higher fraction of time at higher notch positions leads to higher FUER and vice-versa. However, high instantaneous FUER may not always correspond to poor air quality in a given region. Air quality of a region is affected by total emissions in that region. Thus, it is important to visualize spatial distribution of pollutant emissions.

The Piedmont track is divided into 0.25-mile segments. Segment average speed, positive acceleration, grade and curvature are estimated for each track segment. One-Hz FUER estimated in Chapter 5 for a single locomotive operation are summed to estimate segment total fuel use and emissions. From the six one-way trips, two trips with highest and lowest fuel use are compared to illustrate the effect of locomotive operation on FUER. Segments with top 20th percentile speed, acceleration, grade and curvature are identified as potential hotspots for fuel use and emissions. Such segments are compared to segments with top 20th percentile fuel use and emissions to identify factors affecting fuel use and emissions.

7.1 Background

The motion of a train is opposed by several resistive forces which must be overcome by the tractive effort of the locomotive. Tractive effort is quantified here as Locomotive Power Demand (LPD). LPD is a function of train activity and track geometry. Train activity includes speed and acceleration. Track geometry includes rail-grade and curvature. Curvature is typically measured as degree of curvature. The degree of curvature is defined as the central angle to the ends of an arc or chord of agreed length. LPD also depends on the number and the weight per axle of the locomotives and passenger cars and their frontal area. However, these factors are constant for a particular train consist. Thus, for a particular train consist, LPD depends on the speed, acceleration, grade and curvature only. Higher the LPD, higher will be fuel use and emissions. The large weight of a train may impart inertia sufficient to overcome resistance for the next few seconds. Thus, fuel use and emissions in the current second may also be impacted by LPD from previous seconds.

7.1.1 *Resistive Forces*

The motion of a train is opposed by several resistive forces. The higher the magnitude of resistive forces, the higher is the required tractive effort and, thus, higher will be the fuel use and emissions for a train. The resistive forces on a train include (*6*, *7*): (1) starting resistance; (2) journal resistance; (3) flange resistance; (4) air resistance; (5) wind resistance; (6) curve resistance; (7) grade resistance; (8) acceleration resistance; and (9) internal resistance.

Starting resistance is encountered during the initial instance in which the train begins to move from a stop. Starting resistance depends on the inertia of the train and the low temperature of journal lubricants. Starting resistance is typically estimated at 18 lbs/ton, although it can be up to 50 lbs/ton due to cold temperatures, long halts or poor lubrication (*6*, *7*, *54*).

$$R_{s,t} = \begin{cases} 18 \frac{lbs}{ton} & if\ v_{t-1} = 0\ and\ v_t > 0 \\ 0 & otherwise \end{cases} \quad (19)$$

Where,

$R_{s,t}$ = Starting resistance at time *t* (*lbs/ton*)
v_t = Train speed at time *t* (*mph*)
v_{t-1} = Train speed at time *t-1* (*mph*)

Journal resistance includes journal friction, rolling resistance and track resistance, and varies with axle load. Journal resistance is independent of train speed. The American Railway Engineering and Maintenance-of-way Association (AREMA) specifies the equation for Journal resistance as (*6*, *7*, *54*):

$$R_j = \left(0.6 + \frac{20}{w}\right) = A \quad (20)$$

Where,

R_j = journal resistance (*lbs/ton*)
w = weight of locomotive per axle (w_l) or passenger car per axle (w_p) (*tons/axle)*
A = journal resistance for a particular train consist (constant)

Flange resistance includes flange friction between track and wheel flange, and oscillation (swaying and concussion). Flange resistance varies directly with speed. The coefficient of proportionality between flange resistance and train speed is called the flange resistance coefficient. According to AREMA, the Flange resistance is calculated as (*6*, *7*, *55*):

$$R_{f,t} = B \times v_t \quad (21)$$

Where,

$R_{f,t}$ = flange resistance at time *t* (*lbs/ton*)
B = flange resistance coefficient (*lbs/ton-mph*)

Air resistance is the drag on a train due to still air and varies with the square of speed. Air resistance for speeds up to 60 mph is estimated as (*6*, *7*, *55*):

$$R_{d,t} = \frac{C_d \times F \times {v_t}^2}{w \times n} = C \times {v_t}^2 \quad (22)$$

Where,

$R_{d,t}$ = air resistance for trains with speeds less than 60 mph at time *t* (*lbs/ton*)
C_d = drag coefficient of the locomotive or a passenger car based on the shape of the front end and the overall configuration, including turbulence from car trucks, air brake fittings under the cars, space between cars, skin friction and eddy currents, and the turbulence and partial vacuum at the rear end (lbs/ft^2-mph^2)
F = frontal cross-sectional area of the locomotive (F_l) or passenger car (F_p) in (ft^2)
n = number of axles in a locomotive (n_l) or a passenger car (n_p)

C = proportionality coefficient for drag (constant for a particular train consist)

For speeds greater than 60 mph, equations involve complex calculations, the data for which may or may not be available. Hence, most studies only use Equation 22 as an estimate for air resistance to simplify the calculations for low speed trains (typically up to 100 mph) (*56–58*). Drag coefficients and frontal areas of typical train systems are given in Table 7-1.

Wind resistance (R_w) occurs due to wind blowing near the tracks and can be accounted for by incorporating wind speed to the air resistance equation. The effect of wind is typically ignored as the trains travel back and forth on a given route, thereby negating the net impact of wind direction over time. When wind is ignored, v_w is set to 0 and only air resistance is considered as a source of drag.

Curve resistance is encountered on a horizontal curve. Curve resistance occurs due to the longitudinal and transverse sliding between wheel and rail on curve and the increased friction on the surface of the flange and inner rail because of the effect of lateral forces. Curve resistance is directly proportional to the degree of curve. The degree of a curve is the angle subtended by a 100-ft chord at the center of a curve. Curve resistance is estimated as (*54*):

$$R_{c,t} = D \times d_t \tag{23}$$

Where,

$R_{c,t}$ = curvature resistance at time t (*lbs/ton*)

D = unit curve resistance (*lbs/ton-degree of curve*) = 0.8

d_t = degree of a curve at time t (*degrees*)

TABLE 7-1. Drag Coefficients and Frontal Area for Typical Diesel Locomotives and Passenger Cars in the U.S. (Source: Hay, 1984)

Equipment Type	Drag coefficient, C_d (*lbs/ft²-mph²*)	Frontal area, F (*ft²*)
Locomotives (> 50 tons)	0.0024	105
Locomotives (> 70 tons)	0.0024	110
Locomotives (> 100 tons)	0.0024	120
Locomotives streamlined	0.0017	120
Freight cars	0.0005	85 to 90
Passenger cars	0.00034[a]	120

[a] *The passenger car is always behind the locomotive. Thus, only a part of full frontal area of the passenger car faces the drag resistance. Thus, a passenger car and a locomotive with similar frontal areas do not face the same drag. The drag coefficient for passenger cars being 7 to 10 times lower than that of the locomotives with similar frontal areas suggests that the effect of reduced frontal area is included in the drag coefficient of the passenger car.*

Grade resistance is encountered while ascending a vertical curve. Grade resistance can be negative while descending a curve as the gravitational force assists the train motion. Grade resistance is directly proportional to rail-grade. Rail-grade in defined as change in elevation per unit length and expressed as percentage. The grade resistance is estimated as (*6*, *7*, *54*):

$$R_{x,t} = E \times x_t \tag{24}$$

Where,

$R_{x,t}$	=	grade resistance at time *t* (*lbs/ton*)
E	=	unit grade resistance (*lbs/ton-percent grade)* = 20
x_t	=	rail-grade at time *t* (*%*)

Acceleration resistance is encountered when the train speed is increasing resulting in a change in kinetic energy. Based on Newton's second law, the force required to accelerate a body is directly proportional to its acceleration. The resistive force per unit train weight is estimated as:

$$R_{a,t} = 200 \times a = G \times a_t \tag{25}$$

Where,

$R_{a,t}$	=	acceleration resistance at time *t* (*lbs/ton*)
G	=	unit acceleration resistance (*lbs- s^2/ton-m*) = 200
a_t	=	train acceleration at time *t* (*m/s^2*)

7.1.2 *Traction Resistance*

The resistances associated with train movement are called traction resistance. Traction resistance includes starting resistance, journal resistance, flange resistance, air resistance, wind resistance, curve resistance, grade resistance and acceleration resistance. Journal, flange and air resistance are always present during train movement. AREMA recommended to multiply the journal, flange and air resistances by a factor of 0.85 to account for improved train and rail designs. Other resistances are only encountered intermittently, e.g., starting resistance is only encountered when the train starts to move after a stop. Curve and grade resistances are only encountered while traversing on curves and grades, respectively. Acceleration resistance is only present during train acceleration. The traction resistance is estimated as:

$$R_{T,t} = R_{s,t} + (R_j + R_{f,t} + R_{w,t}) \times I + R_{c,t} + R_{x,t} + R_{a,t} \tag{26}$$

Where,

$R_{T,t}$	=	traction resistance at time *t* (*lbs/ton*)
I	=	factor for modernized train equipment (post 1950) to account for improved train and rail designs = 0.85

7.1.3 *Internal Resistance*

The internal resistance (R_i) arises from forces inside the locomotive including engine and shaft losses, cylinder friction, bearing friction, windage in motors and generators, and power used by auxiliaries for lighting, heating and space conditioning. Thus, a part of the tractive effort produced by the locomotive is needed to overcome internal resistance. For diesel-electric locomotives, a locomotive efficiency factor of 0.82 is applied to the traction resistance to account for losses associated with internal resistance (*6, 7, 55*).

7.1.4 *Gross Train Resistance*

Gross train resistance is sum of all the resistive forces opposing the train movement. The locomotive efficiency factor is used to account for the internal resistance of a train. The gross train resistance is estimated as:

$$R_{g,t} = \frac{R_{T,t}}{\eta} \tag{27}$$

Where,

$R_{g,t}$	=	gross train resistance at time t (*lbs/ton*)
η	=	locomotive efficiency factor = 0.82 for diesel-electric locomotives

Substituting the value of $R_{T,t}$ from Equation 8,

$$R_{g,t} = \frac{R_{s,t}+(R_j+R_{f,t}+R_{w,t})\times I+R_{c,t}+R_{x,t}+R_{a,t}}{\eta} \tag{28}$$

Ignoring wind resistance and substituting the values of $R_{j,t}$, $R_{f,t}$, $R_{d,t}$, $R_{c,t}$, $R_{x,t}$ and $R_{a,t}$, from Equations (20-25):

$$R_{g,t} = \frac{R_s+\left(\left(0.6+\frac{20}{w}\right)+Bv_t+\frac{C_d\times F}{w\times n}v_t^2\right)\times I+Dd_t+Ex_t+Ga_t}{\eta} \tag{29}$$

Equation 29 is applicable for either locomotives or passenger cars as the terms w, C_d, F and n are different for locomotives and passenger cars. The gross train resistance for any train system, taking into account, the number of locomotives and passenger cars can be expressed as:

$$R_{g,t} = \frac{\left[R_{s,t}+\left\{N\left(0.6+\frac{20}{w_l}+Bv_t+\frac{C_{d,l}F_l}{w_l\,n_l}v_t^2\right)+P\left(0.6+\frac{20}{w_p}+Bv_t+\frac{C_{d,p}F_p}{w_p\,n_p}v_t^2\right)\right\}\times\left(\frac{I}{N+P}\right)+Dd_t+Ex_t+Ga_t\right]}{\eta} \tag{30}$$

Where,

N	=	number of locomotives per train
P	=	number of passenger cars per train
n_l	=	number of axles per locomotive
n_p	=	number of axles per passenger car
w_l	=	weight per unit axle of locomotive (*tons*)
w_p	=	weight per unit axle of passenger car (*tons*)
$C_{d,l}$	=	drag coefficient for locomotive from Table 7-1 (lbs/ft^2-mph^2)
$C_{d,p}$	=	drag coefficient for passenger car from Table 7-1 (lbs/ft^2-mph^2)
F_l	=	frontal area of locomotive (ft^2)
F_p	=	frontal area of passenger car (ft^2)

The coefficients R_s, B, I, D, E, G and η are constant, irrespective of any train systems. These coefficients, independent of the train system, are given in Table 7-2. The coefficients $\mathrm{N}, \mathrm{w}_l, n_l, C_{d,l}, F_l, P, \mathrm{w}_p, n_p, C_{d,p}$ and F_p depend on the type of locomotive or passenger car, and on the train consist. The weight of passenger car per unit axle (w_p) is also affected by the number of passengers onboard a train. These coefficients for the Amtrak Piedmont rail route are given in Table 7-3. Train speed and acceleration are dependent on train operation and are referred to as "train activity." Rail grade and curve radius depend on the track geometry and alignment.

7.2 Methods

This section describes the methods to estimate rail-grade and curvature from GPS data. Train speed was measured using locomotive activity recorder. Acceleration was inferred from change in speed. Track geometry and train activity hotspots were identified as potential hotspots for fuel use and emission hot spots since these factors affect fuel use and emissions. Potential hotspots were compared to fuel use and emission hotspots to identify what factors affect regional air quality.

TABLE 7-2. Train Resistance Equation Parameters Independent of the Train System Based on Gross Train Resistance Equation

Coefficient	Significance	Value (Hay, 1984)
$R_{s,t}$	Starting resistance	18 *lbs/ton*
B	Flange resistance coefficient	0.01 *lbs/ton-mph*
I	Adjustment factor for modern trains	0.85
D	Unit curve resistance	0.8 *lbs/ton-degree of curve*
E	Train resistance per unit grade	20 *lbs/ton-percent grade*
G	Train resistance per unit acceleration	200 $lbs\text{-}s^2/ton\text{-}m$
η	Locomotive efficiency factor	0.82

TABLE 7-3. Train Resistance Equation Parameters Dependent on the Train System Based on Gross Train Resistance Equation

Coefficient	Significance	Amtrak Piedmont
N	Number of locomotives	1
w_l	Locomotive weight per unit axle (*tons*)	33.5
n_l	Number of axles per locomotive	4
$C_{d,l}$	Locomotive drag coefficient ($lbs/ft^2\text{-}mph^2$)	0.0024
F_l	Locomotive frontal cross-sectional area (ft^2)	165.35
P	Number of passenger cars[a]	3
w_p	Passenger car weight per unit axle (*tons*)	17.5
n_p	Number of axles per passenger car	4
$C_{d,p}$	Passenger car drag coefficient ($lbs/ft^2\text{-}mph^2$)	0.00034
F_p	Passenger car frontal cross-sectional area (ft^2)	142
S	Seating capacity (passengers per car)	66

[a] *The number of passenger includes any baggage car, lounge/cafĕ car etc. For the sake of simplicity, all cars are assumed to be equivalent to a passenger car with same* w_p, n_p, $C_{d,p}$ *and* F_p.

7.2.1 *Rail-grade and Curvature Estimate*

Track geometry data such as rail-grade and curve radius were inferred from prior GPS measurements on the same route. Multiple GPS receivers fitted with barometric altimeter were placed inside the locomotive cab during each of the 100 one-way trips. The number of such receivers varied between 4 and 10 for each one-way trip. Each receiver recorded 1 Hz position and elevation data. Data from GPS receivers with no missing data during entire trip were used. Any receiver that lost signal or that could not record data for some part of the trip was excluded from further analysis.

The rail route was divide into 0.25-mile segments. Segment distance was selected to be long enough to include sufficient 1 Hz data points to obtain precise estimates of average grade and curve radii, and short enough such that actual changes in elevation were approximately linear and the curves were approximately arcs of a circle.

Rail grade was quantified along the track for non-overlapping adjacent equal-distance segments (*59*). This method included the following steps: (1) aligning 1-Hz elevations based on GPS coordinate from multiple GPS measurements in each segment; (2) combining 1-Hz measurements from multiple GPS measurements into a single dataset; (3) projecting the dataset onto the segmented track; (4) using GIS, calculating the distance of each point from the start point of each segment; (5) fitting a linear regression for elevation versus distance in each segment; and (6) inferring grade from the slope of the linear regression.

Curve radii were estimated for the same track segments that were used for grade estimation. The tracks in each segment were assumed to be simple curves that are arcs of a circular path. The least squares fit (LSF) is a robust method to fit circular arcs to data that contain random errors (*60*). LSF is based on minimizing the mean square distance from the fitted curve to the data points. GPS data were grouped into track segments and a circle was fit to the position data in each segment using LSF.

7.2.2 *Locomotive Power Demand*

A locomotive must provide power to overcome the resistive forces for train movement. Power is defined as work done per unit time and is estimated as the product of force and speed. LPD is estimated as the product of gross train resistance, train speed and train weight using an equation recommended by Profillids, 2014 and applying unit conversion factors (*6*):

$$LPD_t = 0.00377 \times R_{g,t} \times v_t \times W \tag{31}$$

Where,

LPD_t = locomotive power demand at time t (kW)

W = total train weight (*tons*)

$R_{g,t}$ is estimated using Equation 30.

Using Equation 30 and Equation 31, and plugging the values of the respective coefficients from Table 7-2 and Table 7-3, LPD for Piedmont rail route is estimated as:

$$LPD_t = (6.0 \times 10^{-3} + 4.0 \times 10^{-5}\, v_t + 5.0 \times 10^{-6}\, {v_t}^2 + 4.0 \times 10^{-3}\, d_t + 9.0 \times 10^{-2}\, x_t + 4.0 \times 10^{-1}\, a_t)\, v_t \times W \qquad (32)$$

From Equation 32, LPD is a third order function of speed. Thus, one a 1-Hz basis, FUER are directly related to cube of speed. At any given speed, FUER are a monotonically increasing linear function of curvature, grade and acceleration. Curvature is inversely related to curve radii. Thus, FUER are inversely related to curve radii. However, at any given speed, LPD is most sensitive to a unit change in acceleration compared to grade and curvature. A unit change in acceleration leads to highest change in LPD, followed by grade and curvature. Grade, curvature and acceleration are each multiplied by train speed. Thus, a unit change in these factors at lower train speeds results in a lower change in FUER compared to unit change at higher train speeds.

7.2.3 *Identifying Hotspots*

Second by second FUER are useful for identifying instances of high fuel use and emissions. For regional air quality, emissions in a given area are more useful than emissions at a given instant of time. Thus, emission rates are typically quantified in terms of mass of pollutants per unit travel distance. Hotspots are typically quantified by dividing the route into segments of fixed length. Longer segments tend to average out peak emission events, whereas, small segments may not have enough data to provide an accurate representation of emissions in a segment. For the Piedmont route, a distance of 0.25 miles was chosen as a segment length. The top speed on the Piedmont route is restricted to 79 mph. Thus, with a segment length of 0.25 miles, a minimum of 11 points at 1 Hz frequency could be measured per trip.

The Piedmont rail route was divided into 692 segments, each of length 0.25 mile. Two trips from the OTR measurements on NC 1859 in a single locomotive operation with highest and lowest fuel use were chosen. These trips were compared with respect to the driver behavior on grades and curves which resulted in highest differences in trip fuel use and emissions. The trips with highest and lowest fuel use also typically have highest and lowest emissions, respectively. Thus, comparison of trips with highest and lowest fuel use trips illustrates differences in driver behavior that lead to differences in fuel use and emissions. Mass per time-based FUER were estimated for each second of data. Speed and acceleration were also measured for every second of data. For each track segment, FUER were summed to obtain mass per distance-based segment total fuel use and emissions. Speed and positive acceleration were averaged for each segment. Average positive acceleration is defined as average of all seconds with positive acceleration only, since 0 or negative acceleration do not demand any power. Segment average grade and curve radii were estimated as discussed in the next section.

Hotspots of fuel use and emissions are identified as track segments with top 20th percentile mass per distance-based fuel use and emissions. Hotspots of segment average speed, positive acceleration, grade and curve were identified as segments with top 20th percentile average speed, acceleration, grade and curvature, respectively. Hot spots were identified based on the trip with highest fuel consumption. The same cutoff ranges are used for the trip with lowest fuel consumption to enable consistent comparison between the two trips. Typically, such hotspots result in high fuel use and emissions.

Spearman's rank correlation of segment total fuel use and emissions with speed, positive acceleration, grade and curve were estimated. The Spearman correlation between two variables is equal to the Pearson correlation between the rank values of those two variables; while Pearson's correlation assesses linear relationships, Spearman's correlation assesses monotonic relationships (whether linear or not). If there are no repeated data values, a perfect Spearman correlation of +1 or −1 occurs when each of the variables is a perfect monotone function of the other.

7.3 Results and Discussion

The effect of locomotive operation is discussed in terms of parameters affecting train energy use and emissions. Segment total fuel use and emissions are compared to segment average speed, positive acceleration, rail-grade and curve radii. Results are illustrated for two one-way trips. These two trips were selected from six one-way trips measured for Locomotive NC 1859 with two passenger cars and one baggage/café car. The locomotive was running on ULSD. Detailed FUER and duty cycles are discussed in Chapter 5 Section 2. The selected trips represent the lowest and highest total fuel use among the six measured trips.

Trip 1 had the highest fuel consumption amongst 6 one-way trips at 762 kgs as given in Table 5-7. Trip 2 had the lowest fuel consumption of the 6 one-way trips, with fuel consumption of 532 kgs. Compared to Trip 1, Trip 2 had 30 percent lower fuel consumption. On a trip duration basis, Trip 2 was the longest of all the trips. Despite being the longest trip, as given in Table 5-4, Trip 2 had lowest fuel consumption. This is mainly due to the low fraction of time spent in Notch 8 (Table 5-4), which has highest fuel use rate. The locomotive operator for this trip preferred to operate more at lower notch positions compared to the average Piedmont Duty cycle. Trip 1 had the highest fraction of time spent at Notch 8 amongst other trips resulting in highest fuel consumption.

Track geometry data were estimated from 180 GPS measurements. Remaining GPS measurements were excluded from analysis due to incomplete trip data. With 180 GPS measurements, each 0.25-mile track segment had at least 1,758 data points and up to 9,363 data points, with an average of 2,709 data points. The grade estimated from the GPS data varied between -1.9 percent and 1.5 percent in the direction from Charlotte to Raleigh. Approximately 70 percent of the track segments had an average grade within ± 1.0 percent.

The track segment radii estimated based 180 GPS measurements varied between 410 m and 3470 m corresponding to curvature between 4.3 degrees and 0.1 degrees, respectively. Curves of less than 0.2 degrees were assumed to be straight. About 50 percent of the segments did not have horizontal curvature. Curves with less than 1-degree curvature accounted for about 25 percent of the track segments. Curves exceeding 2 degrees were less than 10 percent of the track segments.

Train speed was measured, and acceleration was inferred from change in speed. For both the trips, the train idled for about 10 percent of the total time. Speeds between 60 mph and 80 mph accounted for about 50 percent of the measured data. The average speed on this route was 52.6 mph. The acceleration varied between -2.3 mph/s and 2.3 mph/s. The train was cruising or stopped (no acceleration) for about 50 percent of the total trip time. About 80 percent of the accelerations were within ±0.5 mph/s.

Maps were prepared to display segment total fuel use and emissions, and segment average speed, acceleration, grade and curve radii for the two selected trips. For each variable, segments are categorized into five groups each with 20^{th} percent frequency of data based on the trip with highest fuel consumption. The same cutoff ranges are used for the trip with lowest fuel consumption to enable consistent comparison between the two trips. The maps for the trip with highest and lowest fuel use are shown in Figure 7-1 and Figure 7-2, respectively.

Hotspots were identified based on cut-off points for the trip with highest fuel use. FUER vary directly with speed, acceleration and grade, and inversely with curve radius, as discussed in Section 8.2.2. Thus, top 20 percent frequency range for speed, acceleration and grade, and bottom 20 percent frequency range for curve radii was selected to be a hotspot. Top 20 percent frequency range for fuel use and emissions is also identified. Only NO_x and PM emissions were considered for analysis. CO_2 emissions show a similar trend to fuel use and CO and HC emissions are typically low for diesel engines. The cutoff points for grade, speed, acceleration, fuel use, NO_x emissions and PM emission were higher than 0.66 percent, 77 mph, 0.18 mph/s, 7.5 kg/mile, 398 g/mile and 10 g/mile, respectively. Curves with radii lower than 800 m were identified as hotspots.

Grade-based hotspots were distributed along the entre Piedmont route. Curvature-based hotspots were mostly located between Raleigh and Burlington. Trains typically ran at lower speeds on these stretches compared to between High Point and Charlotte, which had fairly straight tracks for most of the segments. Highest segment average train speeds were observed between High Point and Charlotte. The stretch between Raleigh and Burlington had variation in acceleration. There were few segments with zero average positive acceleration between Raleigh and Burlington. The route between High Point and Charlotte had several consecutive segments with zero average acceleration at highest train speeds.

Based on choosing the top 20 percent of segments out of the total of 692 segments, there are expected to be 138 hotspot segments. However, the actual number of hotspot segments varied because of repeated values in a sample. For example, 50 percent of the segments were straight on this route. Thus, any frequency range from bottom, below 50 percent will have the same cut-off point. In such a case, if the cut-off point is chosen based on 20 percent frequency range, the number of segments will be 50 percent of the total segments. When choosing 20 percent range resulted in a large number of segments, the cut-off was lowered by 1 or 2 percent such that the number of hotspots are as close to 138, as possible.

The trip with highest fuel use had 135, 133, 136, 136, 139, 135 and 137 hotspots for grade, curve, speed, acceleration, fuel use, NO_x emissions and PM emissions, respectively. Many of the hotspots were around railway stations where the train halts for a while and then accelerates out of the station. Other hotspots were found on positive grades. Segments with high train speeds were not found to be hotspots even though FUER are at high speeds, as discussed in Section 8.2.2. This happens because at high speed, very little time is spent in the segment. For example, fuel use rate at Notch 8 is approximately 120 g/s. idle fuel use rate is approximately 3 g/s. Thus, if a train spends 400 seconds in a segment at idle instead of passing that segment in 10 seconds at Notch 8, fuel use

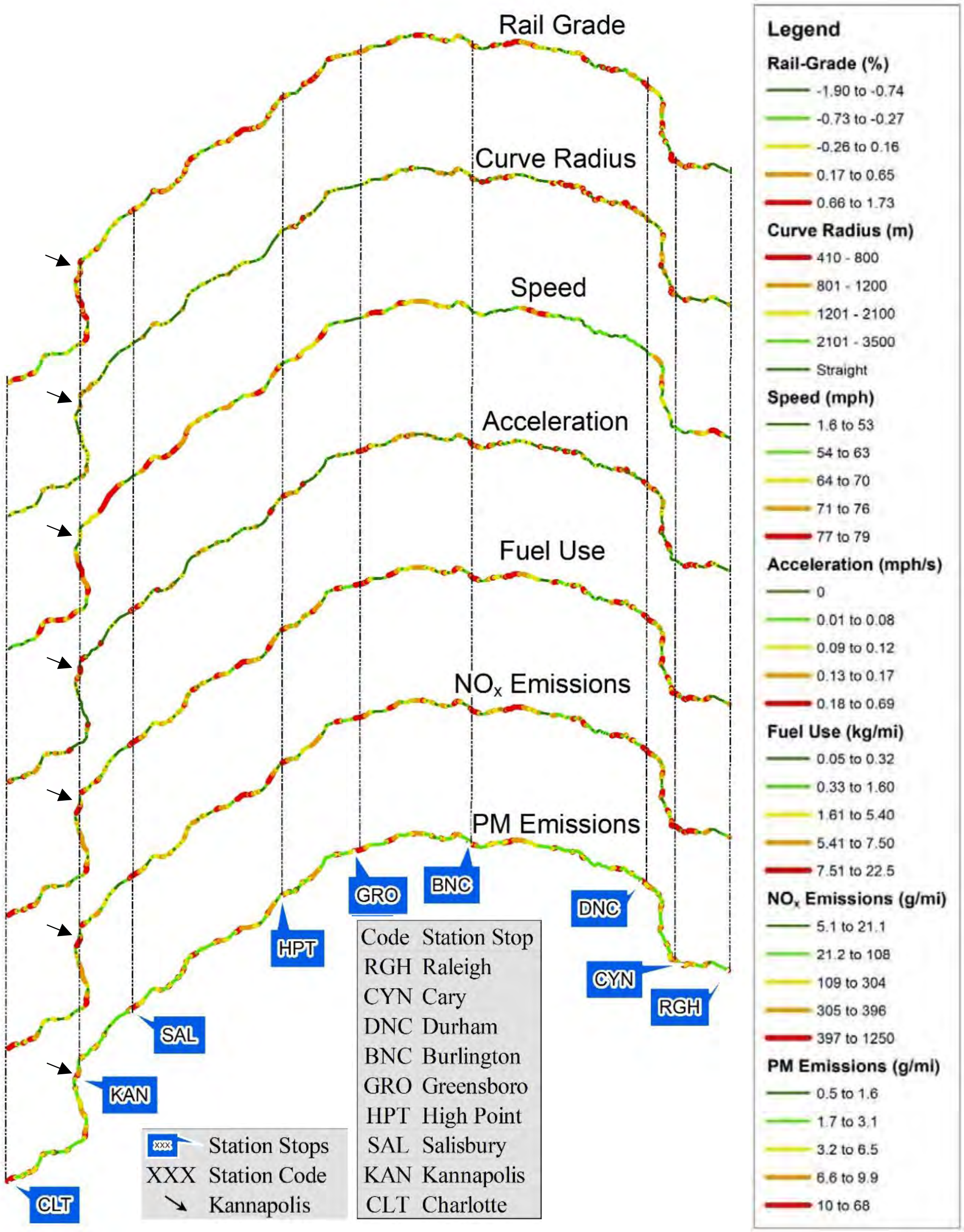

FIGURE 7-1. Estimated train activity, track geometry, fuel use and emissions for the observed trip with highest fuel use for locomotive NC 1859 running on ULSD. Train consist included one locomotive and three cars. Each variable is divided into 5 ranges with cutoff points indicating 20 percent frequency ranges based on the trip with highest fuel use. Red indicates the segments with top 20 percent frequency range and green represents the bottom 20 percent frequency range.

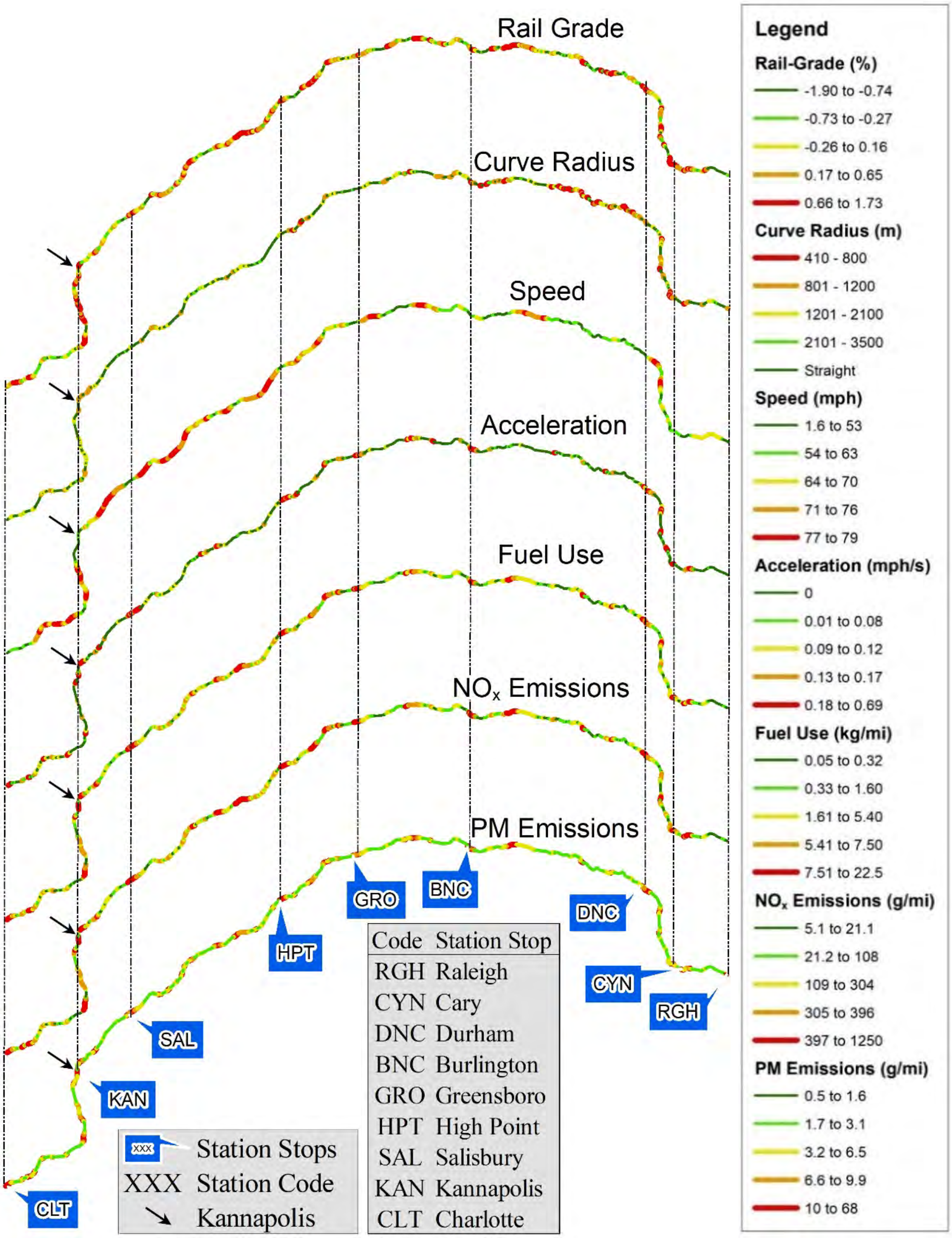

FIGURE 7-2. Estimated train activity, track geometry, fuel use and emissions for the observed trip with lowest fuel use for locomotive NC 1859 running on ULSD. Train consist included one locomotive and three cars. Each variable is divided into 5 ranges with cutoff points indicating 20 percent frequency ranges based on the trip with highest fuel use. Red indicates the segments with top 20 percent frequency range and green represents the bottom 20 percent frequency range.

and emissions for that segment will be higher at idle. The curves also serve as potential hotspots. However the trains moved at low speeds between 30 mph and 50 mph on the curves. As shown in Equation 31, FUER on curves depend on product of curvature and speed. Thus, low train speeds on curves mitigate the effect of curves of FUER. Thus, on curves, fuel use and emission hotspots were not typically observed on the Piedmont route. Overall, most of the hotspots were mainly due to acceleration and grade or a combination of both

The spearman's rank correlation also shows these trends. Spearman correlation for fuel use was 0.59 with grade, 0.36 with acceleration, 0.05 with curvature, and -0.37 with speed. Spearman correlation for NO_x emissions was 0.61 with grade, 0.37 with acceleration, 0.03 with curvature, and -0.41 with speed. Spearman correlation for PM emissions was 0.57 with grade, 0.35 with acceleration, 0.06 with curvature, and -0.41 with speed.

Out of 139 fuel use hotspots, 36 hotspots were due to grade only, 39 were due to acceleration only, and 9 were due to curvature only. None of the fuel use hotspots coincided with speed hotspots. Remaining hotspots were due to the combination of grade, curve and acceleration. Accounting for combinations, 65 hotspots were due to grade, and any, or both of curvature and acceleration. The number of fuel use hotspots due to curvature, and any, or both of grade and acceleration were 30. The number of fuel use hotspots due to acceleration, and any, or both of grade and curvature were 57. Out of 139 fuel use hotspots, 95 hotspots were also hotspots for NO_x and PM emissions. Thus, most of fuel use hotspots are also emission hotspots.

Out of 135 NO_x emission hotspots, 35 hotspots were due to grade only, 40 were due to acceleration only, and 5 were due to curvature only. None of the NO_x emission hotspots coincided with speed hotspots. Remaining hotspots were due to the combination of grade, curve and acceleration. Accounting for combinations, 44 hotspots were due to grade, and any, or both of curvature and acceleration. The number of NO_x emission hotspots due to curvature, and any, or both of grade and acceleration were 28. The number of NO_x emission hotspots due to acceleration, and any, or both of grade and curvature were 60.

Out of 137 PM emission hotspots, 30 hotspots were due to grade only, 35 were due to acceleration only, 8 were due to curvature only, and 3 were due to speed only. Remaining hotspots were due to the combination of grade, curve, speed and acceleration. Accounting for combinations, 58 hotspots were due to grade, and any, or both of curvature and acceleration. The number of PM emission hotspots due to curvature, and any, or all of grade, speed and acceleration were 30. The number of PM emission hotspots due to acceleration, and any, or all of grade, speed and curvature were 58. The number of PM emission hotspots due to speed, and any, or all of grade, acceleration and curvature were 4.

The trip with lowest fuel use had 135, 133, 145, 100, 73, 104 and 110 hotspots for grade, curve, speed, acceleration, fuel use, NO_x emissions and PM emissions, respectively. Compared to Trip 1, Trip 2 had more number of segments with high segment average speed even though the overall average train speed was lower. The number of acceleration hotspots was almost half of the acceleration hotspots in Trip 1. Thus, a reduction in fuel use and emissions was observed.
Spearman correlation for fuel use was 0.61 with grade, 0.47 with acceleration, 0.03 with curvature, and -0.39 with speed. Spearman correlation for NO_x emissions was 0.63 with grade, 0.44 with

acceleration, 0.03 with curvature, and -0.39 with speed. Spearman correlation for PM emissions was 0.58 with grade, 0.43 with acceleration, 0.04 with curvature, and -0.45 with speed.

Out of 73 fuel use hotspots, 19 hotspots were due to grade only, and 18 were due to acceleration only. None of the fuel use hotspots coincided with speed or curvature hotspots. Remaining hotspots were due to the combination of grade, curve and acceleration. Accounting for combinations, 41 hotspots were due to grade and any or both of curvature and acceleration. The number of fuel use hotspots due to curvature and any or both of grade and acceleration were 16. The number of fuel use hotspots due to acceleration and any or both of grade and curvature were 37. Out of 73 fuel use hotspots, 64 hotspots were also hotspots for NO_x and PM emissions. Thus, most of fuel use hotspots are also emission hotspots. The remaining hotspots were hotspots for either NO_x or PM emissions along with fuel use hotspots.

Out of 104 NO_x emission hotspots, 31 hotspots were due to grade only, 26 were due to acceleration only, and 2 were due to curvature only. None of the NO_x emission hotspots coincided with speed hotspots only. Remaining hotspots were due to the combination of grade, curve and acceleration. Accounting for combinations, 57 hotspots were due to grade and any or both of curvature and acceleration. The number of NO_x emission hotspots due to curvature and any or both of grade and acceleration were 21. The number of NO_x emission hotspots due to acceleration and any or both of grade and curvature were 48.

Out of 110 PM emission hotspots, 30 hotspots were due to grade only, 35 were due to acceleration only, and 1 were due to speed only. None of the PM emission hotspots coincided with curvature hotspot only. Remaining hotspots were due to the combination of grade, curve, speed and acceleration. Accounting for combinations, 58 hotspots were due to grade and any or both of curvature and acceleration. The number of PM emission hotspots due to curvature and any or all of grade, speed and acceleration were 19. The number of PM emission hotspots due to acceleration and any or all of grade, speed and curvature were 50. The number of PM emission hotspots due to speed and any or all of grade, acceleration and curvature were 2.

For both the trips, fuel use and emission hotspots were inversely related to speed. Although, 1-Hz FUER are higher at higher speeds, less amount of time spent in a segment compensates for higher instantaneous fuel use and emissions. None of the fuel use and emission hotspots was due to curvature hotspots only. Only the segments that had acceleration or grade hotspots or both, along with curves were hotspots. In general, the train slowed down to speeds between 30 mph and 50 mph on curves. This was a moderate speed, lower than average speed on route. The speed was not slow enough such that a large amount of time was spent in the segment, resulting in higher fuel use and emissions in that segment. The speed was also not fast enough to result in higher instantaneous fuel use and emissions.

7.4 Conclusions

The effect of locomotive operation on FUER is demonstrated in this chapter. On a mass per time basis, FUER are directly related to grade, speed and acceleration, and inversely related to curve radii, as discussed in Section 8.2.2. However, segment total fuel use and emissions were found to be directly related to grade and acceleration, and inversely related to train speed. The effect of higher mass per time fuel use and emissions at high speed was compensated by lower amount of time spent over a segment. Curves also impact fuel use and emission directly. However, on this route trains typically operate at reduced speeds between 30 mph and 50 mph on curves. Thus, higher FUER due to curves were mitigated by lower train speeds.

The operator of the trip with lowest trip consumption typically operated the train at zero acceleration and high train speeds for long periods of time. This enabled the operator to operate the locomotive at lower notch positions. The operator also typically coasted the train to a stop. These strategies resulted in a reduction of 30 percent, 20 percent and 18 percent in trip total fuel use, NO_x emissions and PM emissions by mass, respectively.

Most of the fuel use hotspots coincided with the emission hotspots. Thus, any strategy that reduces fuel use will also reduce emissions. Out of all fuel use or emission hotspots, about 50 percent of the hotspots were due to combination of grade, acceleration and curvature. About 25 percent of the hotspots were due to grade only and 25 percent were due to acceleration only. Higher train speeds resulted in lower segment total fuel use and emissions due to less amount of time spent. Curves may serve as potential hotspots, however low train speeds on curves mitigate the effect of curves. Thus, grade and acceleration were key factors for fuel use and emission hotspots. Low train speeds and acceleration at or near stations also affects regional air quality as the fuel use and emission hotspots were inversely related to segment average train speed.

Chapter 8. Fuels

Different fuels have different energy intensity. Thus, switching fuels may change the FUER of a locomotive. However, some fuels such as propane and natural gas may require modifications to the engine which can be costly. Biodiesel is a naturally oxygenated diesel replacement fuel made from renewable sources such as vegetable oils or animal fats. Biodiesel can be used directly in diesel engines without major modifications to the engines and vehicles (*61*). Biodiesel can be blended with petroleum diesel fuel at any ratio. A common blend rate is 20% renewable source and 80% petroleum diesel, referred to as B20.

One of the key motivations for the use of biodiesel is to reduce life cycle greenhouse gas emissions. The fossil energy contribution to the energy life cycle for a 20 percent biodiesel and 80 percent petro diesel blend (B20) is 83 percent, versus 37 percent for pure biodiesel blend stock (*62*). The use of B20 instead of petro diesel reduces life cycle fossil energy consumption and CO_2 emissions by 9 percent compared to ULSD, based on soy-based biodiesel stock. The life cycle CO_2 reduction for B100 versus ULSD is 42 percent (*62*). These percentages could increase if the share of non-fossil energy resources in power generation and transportation increase (*62*).

There have been many studies in which the effect of biodiesel fuel on emissions of smaller four stroke engines used in highway and nonroad applications, such as front loaders, backhoes, and motor graders (*63–68*). For example, an EPA (2002) review of engine dynamometer test data for a variety of diesel engines indicates that, on average, there is a reduction in the cycle average emission rates of PM, CO, and HC and an increase in the cycle average emission rate of NO_x. An overall average among all engine types is that emissions decreased for B20 biodiesel versus petroleum diesel by 10% for PM, 11% for CO, and 21% for HC, but increased by 2% for NO_x. However, the actual emission difference could differ by engine and duty cycle.

NCSU conducted RY and OTR measurements on three locomotives of NCDOT fleet were conducted in a prior study (*20*) to characterize the effect of biodiesel blends on FUER. The results from prior work are used to compare the benefits of biodiesel over petroleum diesel over specific duty cycles. In later chapters, these results will be used to assess the combined impacts of emission control technology and locomotive operations on trip total fuel use and emissions. Key fuel properties and their effect on fuel use and emissions are described here. These properties were estimated in prior work from standard tests.

8.1 Methods

This section summarizes key fuel properties that affect FUER of diesel-powered locomotives. Methods to conduct FUER measurements are also described here.

8.1.1 *Fuel Characteristics*

The emissions and fuel use of a diesel vehicle are influenced by fuel properties. Fuel density, net heat of combustion, Cetane Number (CN), elemental composition, viscosity, and distillation range have individual or combined effects on one or more of each of the fuel use rate and emission rates of CO_2, CO, HC, NO_x and PM (*61*, *69*). The energy density of the fuel will have an effect on the apparent fuel economy (e.g., gallons of fuel used per duty cycle) (*70*).

Fuel Density

The density (ρ) of petroleum products is the mass of fuel per volume, sometimes expressed in units of grams per milliliter (g/*ml*). However, often the density is described by specific gravity. Specific gravity is defined as the ratio of the density of the fuel to the density of water, at 60°F. An increase in fuel density could mean that more fuel is injected into the cylinder, if a constant volume of fuel is injected. More mass of fuel can translate into a higher heat release rate. A higher heat release rate would lead to higher peak combustion temperatures. Density and specific gravity were determined using the ASTM D4052 test method in prior study (*20*, *25*).

Net Heat of Combustion

The heating value of a fuel is the enthalpy of reaction for combustion of the fuel. Thus, the heating value is the amount of energy released when the fuel is completely burned in a steady-flow process. The magnitude of the heating value depends on the fate of H_2O in the combustion products. In most real systems, the H_2O leaves the engine or combustor in the vapor phase. For this situation, the Lower Heating Value (LHV) is used. When comparing fuels with different heating values and densities, there can be an apparent difference in fuel economy (e.g., miles of vehicle travel per gallon of fuel consumed) but not necessarily a difference in energy efficiency. The LHV is also referred to as the net heating value, which was measured using ASTM D240 test method in prior study (*20*, *25*).

Cetane Number

The CN is a descriptor of the ignition quality of a diesel fuel (*69*, *71*). Higher CN indicates shorter times between injection of the fuel and its ignition, therefore ensures better fuel combustion (*69*, *72*). Typically, CN decreases linearly with increasing specific gravity (*73*). Very high and low CN can cause operational problems in an engine. A high CN can start the combustion even before the air and fuel have properly mixed, resulting in incomplete combustion and smoke generation. Low CN can result in engine misfiring, slower engine warm-up and incomplete combustion (*71*). Thus, most engine manufacturers in the U.S. recommend CN to be between 40 and 50 (*71*). The CN was measured using ASTM test method D613 test method in prior study (*20*, *25*).

Ultimate Analysis

The ultimate analysis of a fuel describes the weight percent of major elements in the fuel, such as carbon, hydrogen, oxygen, sulfur (S), and nitrogen (N). Data regarding the density and weight percent of carbon enables estimation of the CO_2 emission rate in grams of CO_2 per gallon of fuel consumed. Similarly, S content of fuel enables estimation of grams of sulfur dioxide (SO_2) emitted per gallon of fuel consumed. Sulfur in fuel is also emitted as sulfates which contribute to PM. The weight percent of C increases with increasing biofuel blend stock ratio. More oxygen in the fuel typically promotes complete combustion of the fuel, thereby reducing emissions of soot, CO and HC. However, NO_x emissions are independent of oxygen content (*74*). The weight percent of C, H, and N was measured using ASTM D5291, and the weight ratio of S (in ppm) was measured using ASTM D2622 test method in prior study (*20*, *25*). The remaining weight percent was assumed to be comprised entirely of oxygen.

Viscosity

Viscosity is a measure of the resistance of a fuel to shear or flow and is a measure of the fuel's adhesive/cohesive or frictional properties. Viscosity affects the atomization of the fuel injected into the engine combustion chamber (*75*). A high viscosity fuel will produce a larger droplet of fuel that may not burn well in an engine. A smaller droplet may produce more complete combustion (*72*). Viscosity is typically measured in terms of dynamic viscosity and kinematic viscosity. Dynamic viscosity is the resistance to flow under an external force. Dynamic viscosity is the force needed to make the fluid flow at a certain rate. Kinematic viscosity is the resistance to flow under gravity. Kinematic viscosity is a measure of how fast the fluid moves under gravity. Thus, kinematic viscosity is a better indicator of fluid movement inside the engine. Kinematic viscosity was measured using ASTM D445.

Distillation Range

Distillation range refers to the range of boiling points of different liquid fractions of the fuel, which are observed when separating the fuel into its components (*76*, *77*). The distillation range was measured using ASTM test method D86. The distillation range is generally expressed in terms of the temperatures at which 10 percent (T10), 50 percent (T50), and 90 percent (T90) of the fuel will be evaporated. T10 is called the light end or the beginning point, and affects the ability of an engine to start. T50 is the middle distillation point and influences the performance of engines at cruising speeds. T90 is the end distillation point and affects air to fuel ratio, coke formation, and soot emission rates. The highest temperature recorded during distillation is called the final boiling point.

8.1.2 *Effects of Fuel Properties on Fuel Use and Emission Rates*

The effect of biodiesel versus petroleum diesel on emissions is reviewed here based on literature.

Fuel Economy

Fuel consumption is proportional to the volumetric energy density of the fuel, which in turn depends on the heating value and the density of the fuel (*78*). Biodiesel has lower energy density compared to petroleum diesel. Thus, a higher proportion of biodiesel in the blend will lower the fuel economy. Tsolakis *et al.* (2003) estimated that fuel economy will decrease when comparing biodiesel with petroleum diesel (*79*). B20 biodiesel has a 2.21 percent lower volume-based heating value than petroleum diesel. This implies that a reduction in fuel economy of approximately two percent is expected when switching from petroleum diesel to B20 biodiesel fuel.

Carbon Dioxide

CO_2 emissions are directly related to fuel use. Thus, CO_2 emissions from biodiesel blends are expected to be higher than petroleum diesel. However, a significant portion of the carbon in biodiesel is based upon biomass from soybeans or other vegetable oils, which in turn is based upon CO_2 taken up by the plants from the ambient air. Thus, biodiesel provides a reduction in net CO_2 emissions when considering the entire fuel cycle (*76*, *77*). The net CO_2 emissions from the soy-based blend stock component of the fuel are approximately zero (*72*, *80*). In contrast, the CO_2 emitted from the petroleum portion of the fuel results in a net increase in CO_2 flux to the atmosphere. The total CO_2 emissions on a per energy basis depend on the weight percent of carbon in the fuel, the combustion efficiency, and the heating vale of the fuel (*76*).

Carbon Monoxide

CO is a result of incomplete combustion and is formed mostly when fuels containing carbon are burned where there is too little oxygen, as a result of poor fuel and air mixing, or as a result of insufficient reaction time for oxidation reactions to reach completion. CO emissions from diesel engines are generally low since diesel engines operate fuel lean. However, oxygenated fuels such as biodiesel can further reduce CO emissions because of the oxygen content in the fuel itself, which further promotes complete combustion (*81*).

Hydrocarbons
HC emissions can be either unburned or partially burned fuel molecules (*32*). HC emissions are typically from incomplete combustion. According to EPA (2002), a 19 to 32 percent decrease of HC emissions can be expected after switching from petroleum diesel to B20 fuel (*61*). This might be in part because of the higher oxygen content of B20, which tends to promote more complete combustion.

Nitrogen Oxides
Nitrogen oxides are typically formed during combustion process. Thus, NO_x emissions are higher at higher temperatures, typically greater than 2000 K (*82*). Reported average NO_x emissions from biodiesel are slightly higher than those from petroleum diesel fuel (*61*). The higher NO_x emissions are theorized to come from the higher density of fuel (*81*). Durbin and Norbeck (2002) reported that an increase in fuel density of 3.5 percent is associated with an increase in NO_x emissions of 3 to 4 percent (*81*). Cetane number also tends to have a role in slight increase of nitrogen oxides emission effects for heavy duty diesel engines. However, there is substantial inter-vehicle variability in whether NO_x emissions increase or decrease for B20 versus petroleum diesel, and there is some indication that results obtained for real world duty cycles may differ than those from dynamometer tests (*64*).

Particulate Matter
Particulate Matter is typically formed due to high temperatures (between 1500 K and 1900 K) and low oxygen content (stoichiometric air to fuel ratio less than 0.6) (*83*). Diesel engines emit significant quantities of PM. PM emission rates increase with increasing sulfur content due to increased emissions of sulfates (*69*). Substantial reduction in PM emissions can be obtained through the addition of oxygenates to diesel fuel and by reduction of sulfur content (*75*). B20 has approximately 2.20 weight percent oxygen, compared to no oxygen in petroleum diesel. According to Akasaka *et al.*(1997) and McCormick *et al.*(2001), PM reduction using B20 instead of petroleum diesel is between 0 to 16 percent during turbocharged engine operation (*80*, *84*).

However, PM reduction is affected by factors other than oxygen content because PM concentration can be increased due to a decrease in Cetane number and increase in distillation end point. Higher distillation end point temperatures might minimize deposits of carbonaceous soot in the combustion chamber. Thus, biodiesel, which has high Cetane number, but a lower distillation end point, can reduce PM emission rates (*80*, *84*, *85*). Denser and more viscous fuels also tend to have higher PM emission rates (*69*).

8.1.3 *Fuel Use and Emission Rates*
The three NCDOT locomotives include an F59PHI locomotive NC 1797, and two F59PH locomotives NC 1810 and NC 1859. Each of the locomotives was operated on ULSD and biodiesel blends B10, B20 and B40. Additional blends such as B60, B80 and B100 were also tested on NC 1859. Measurements were conducted on ULSD to obtain baseline FUER of each locomotive. Prior to each test, the locomotive was run for at least two weeks on the alternative fuel to be tested. This

ensured that the locomotive was purged with the new fuel. B20 biodiesel was found to be the best fuel since B20 lead to reduced fuel consumption, reduced PM emissions and a small increase in NO_x emissions. Other blends resulted in significant increases in one or more of these. Fuel samples were sent to South West Research Institute (SWRI) to quantify the fuel properties.

RY and OTR measurements were conducted as explained in Chapter 3. FUER for all three locomotives on all fuel blends were estimated (*20*, *25*). Significant differences were found between RY and OTR estimates for some of the throttle notch positions. Here, only the OTR measurements are used to quantify the effect of fuels. Only B10, B20 and B40 biodiesel blends are considered for comparison as measurements on multiple locomotives were done using these blends. The three locomotives at the time of study represented 50 percent of the NCDOT locomotive fleet of two F59PHIs and four F59PHs. Effect of each fuel is evaluated for an average NCDOT locomotive based on the average of measurements of the three locomotives. Detailed notch average FUER for the three locomotives running on ULSD and three biodiesel blends are given in Appendix E.

8.2 Results and Discussion

This section summarizes measure fuel properties and discusses their effect on FUER. FUER of NCDOT locomotives are also summarized here. Fuel properties affecting FUER were estimated by SWRI in prior work (*20*, *25*). Estimated properties are given in Table 8-1.

TABLE 8-1. Measured Fuel Properties for Ultra-Low Sulfur Diesel (ULSD), B10, B20 and B40 Biodiesel Fuel[a] (Frey *et. al.*, 2016)

Properties	Test Method	Unit	Fuel			
			ULSD[b]	B10	B20[c]	B40[c]
Bio Diesel Content	Infrared	vol%	N/A	6.6	22.3	40.5
Specific Gravity @60°F	ASTM D4052		0.8416	0.8416	0.8534	0.8580
Density @15°C		g/ml	0.8412	0.8411	0.8530	0.8576
Net Heat of Combustion	ASTM D240	BTU/lb	18,471	18,279	17,726	17,470
Cetane Number	ASTM D613		47.2	49.0	48.6	53.0
Carbon	ASTM D5291	wt%	86.74	85.72	83.41	82.36
Hydrogen		wt%	13.02	13.29	12.9	12.78
Nitrogen		wt%	0.02	0.20	0.09	0.10
Sulfur	ASTM D2622	ppm	10.8	8.0	7.8	6.7
Oxygen	Difference	wt%	0.22	0.79	3.60	4.76
Kinematic Viscosity	ASTM D445	cSt	2.498	2.510	2.820	3.042
Distillation 10% (T10)	ASTM D86	°F	400.5	398.9	415.5	431.6
Distillation 50% (T50)		°F	504.1	510.3	567.8	585.4
Distillation 90% (T90)		°F	621.6	624.9	639.2	637.8

[a] *Biodiesel Blends: B10 is 10% biodiesel and 90% ULSD blend; B20 is 20% biodiesel and 80% ULSD blend; and B40 is 40% biodiesel and 60% ULSD blend.*

[b] *ULSD results are averages based on three measurements. B20 and B40 results are averages based on two measurements each. B10 results are based on one measurement.*

8.2.1 *Fuel Characteristics*

The density and specific gravity of the fuel increased as the biodiesel content increased in the blend. Thus, petroleum diesel had the lowest density and B40 had the highest density. However, B10 biodiesel blend had similar density as ULSD due to low biodiesel content. Net heat of combustion decreased with increasing biodiesel content as biodiesels have low energy content compared to ULSD. Cetane Number increased with increased biodiesel content. Carbon content decreased with increasing biodiesel content. Hydrogen content did not show any trend in general. Biodiesel blends had higher nitrogen content compared to ULSD, but did not increased linearly with biodiesel content. Sulfur content decreased with increased biodiesel content. Oxygen content increased with increasing biodiesel content. Kinematic viscosity and distillation range also increased with increasing biodiesel content.

8.2.2 *Effects of Fuel Properties on Fuel Use and Emission Rates*

This section describes the effect of estimated fuel characteristics on FUER. Biodiesels have low volumetric energy density compared to ULSD. Thus, ULSD should have the highest fuel economy of all the fuels included here. Consequently, B40 would have the lowest fuel use. CO_2 emissions are also expected to show a similar trend. CO and HC emission rates depend on viscosity and oxygen content of the fuel. Increasing viscosity with biodiesel content promotes incomplete combustion. Whereas, increasing oxygen content promotes complete combustion. Thus, emission rates of CO and HC may not show any trend with biodiesel content. NO_x emission rates are expected to increase with increasing biodiesel content, as the fuel gets denser with increasing biodiesel content. Weight percent of nitrogen in fuel also increases with biodiesel content, thus adding to NO_x emission rates. PM emission rates are expected to decrease with increasing biodiesel content because of increasing oxygen content, distillation range, and decreasing sulfur content, all of which lead to reduced PM emissions.

8.2.3 *Fuel Use and Emission Rates*

Over 40 hours of rail yard and over 270 hours of over the rail data were collected and reported previously (*20*, *25*). For each locomotive, typically three replicates of a prime mover engine test cycle were made at the NCDOT rail yard located in Raleigh, NC. For over-the-rail measurements, typically six one-way trips were measured between Raleigh, NC and Charlotte, NC on Amtrak's Piedmont train service. Typically, less than one percent of total data collected were excluded after quality assurance screening. OTR measurements for each locomotive and each fuel are given in Table 8-2. Notch average FUER for an average of three NCDOT locomotives were estimated for each of the fuels based on OTR measurements on each locomotive. Average FUER for ULSD, B10, B20 and B40 are given in Table 8-3.

TABLE 8-2. Data Available for Each Locomotive and Fuel (*Frey et. al.*, 2016).

Fuel	Number of one-way trips measured		
	NC 1810	NC 1859	NC 1797
ULSD	6	6	6
B10	6	6	6
B20	6	6	5
B40	5	6	6

TABLE 8-3. Notch Average Fuel Use and Emission Rates for an Average[d] Locomotive based on Over-the-rail Tests Operated on (a) Ultra-Low Sulfur Diesel; (b) B10; (c) B20, and (d) B40 biodiesel blends (*Frey et. al.*, 2016).

(a) Ultra-Low Sulfur Diesel

Notch	Average engine load (hp)	Fuel use rate (g/s)	Emission Rates (g/s)				
			CO_2	CO	HC[a]	NO_x[b]	PM[c]
Idle	10	3.81	11.5	0.06	0.47	0.35	0.01
DB[e]	10	5.01	15.1	0.10	0.65	0.38	0.02
1	190	9.12	28.0	0.09	0.64	0.74	0.02
2	350	14.1	43.8	0.09	0.53	1.26	0.03
3	675	26.3	81.5	0.15	0.90	2.43	0.04
4	1000	37.9	117	0.15	1.07	3.44	0.06
5	1300	52.8	164	0.19	1.29	4.23	0.07
6	1600	64.5	200	0.23	1.37	4.39	0.10
7	2270	81.5	212	0.34	1.21	4.27	0.13
8	2800	120	373	0.82	1.44	5.74	0.23

(b) B10 biodiesel blend

Notch	Average engine load (hp)	Fuel use rate (g/s)	Emission Rates (g/s)				
			CO_2	CO	HC[a]	NO_x[b]	PM[c]
Idle	10	4.00	12.1	0.05	0.40	0.41	0.01
DB[e]	10	4.88	13.7	0.04	0.29	0.32	0.01
1	190	9.25	27.0	0.04	0.27	0.69	0.01
2	350	13.7	39.0	0.04	0.24	1.09	0.02
3	675	25.0	71.5	0.06	0.31	2.07	0.02
4	1000	36.4	102	0.07	0.40	2.97	0.03
5	1300	50.9	144	0.11	0.49	3.85	0.04
6	1600	61.4	174	0.14	0.53	4.30	0.05
7	2270	75.6	214	0.23	0.58	4.30	0.08
8	2800	116	337	0.53	0.67	5.65	0.13

Table 8-3 Continued on next page

Table 8-3 Continued from previous page

(c) B20 biodiesel blend

Notch	Average engine load (hp)	Fuel use rate (g/s)	Emission Rates (g/s)				
			CO_2	CO	HC[a]	NO_x[b]	PM[c]
Idle	10	4.36	13.0	0.12	0.58	0.48	0.01
DB[e]	10	5.13	15.4	0.12	0.45	0.41	0.01
1	190	9.24	28.3	0.06	0.30	0.84	0.02
2	350	12.4	38.3	0.06	0.35	1.20	0.02
3	675	24.4	75.2	0.08	0.44	2.54	0.03
4	1000	34.8	107	0.10	0.64	3.51	0.04
5	1300	48.2	148	0.12	0.65	4.49	0.06
6	1600	58.4	180	0.11	0.57	5.05	0.07
7	2270	56.9	175	0.13	0.38	3.65	0.09
8	2800	113	351	0.47	0.59	6.17	0.18

(d) B40 biodiesel blend

Notch	Average engine load (hp)	Fuel use rate (g/s)	Emission Rates (g/s)				
			CO_2	CO	HC[a]	NO_x[b]	PM[c]
Idle	10	3.74	11.4	0.05	0.32	0.35	0.01
DB[e]	10	5.42	16.5	0.07	0.47	0.40	0.01
1	190	9.99	30.8	0.06	0.48	0.80	0.02
2	350	14.4	44.8	0.06	0.36	1.25	0.02
3	675	26.4	82.0	0.07	0.53	2.48	0.03
4	1000	39.3	122	0.10	0.55	3.50	0.05
5	1300	52.5	163	0.15	0.99	4.30	0.07
6	1600	63.9	198	0.17	0.64	4.81	0.09
7	2270	90.8	282	0.45	0.89	5.58	0.17
8	2800	119	372	0.91	0.76	6.11	0.24

[a] *HC was measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factor of 2.5 to approximate total HC.*

[b] *NO_x includes NO and NO_2. Only NO was measured. Typically, NO_x is comprised of 95 vol-% NO. NO_x is always reported as equivalent mass of NO_2. Results include multiplicative correction factor of 1.053 to approximate total NO_x.*

[c] *PM was measured using a light scattering technique, which provides useful relative comparisons of particle levels in the exhaust. Results include multiplicative correction factor of 5 to approximate total PM.*

[d] *Average Locomotive- Average of locomotives NC 1810, NC 1859 and NC 1797.*

[e] *DB = Dynamic Brake*

Notch average FUER for an average locomotive for ULSD were compared to B10, B20 and B40 to quantify the effect of alternative fuels. The detailed comparison is given in Table 8-4. Compared to ULSD, B10 had a reduced fuel use for idle, Notch 5, Notch 6 and Notch 8. However, the reduction was only between 0.1 and 1.6 percent. B10 had an increased fuel use rate for other notch positions, as high as 11.5 percent for some positions. However, such notch positions typically account for a very small fraction of total trip time. Thus, B10 and ULSD have comparable trip total fuel use.

B20 had a reduced fuel use rate for all notches except idle and Notch 1. The reductions varied between 2.6 percent and 7.2 percent. Notch 1 had 1.4 percent higher fuel use and idle had 5.1 percent. Idle accounts for a significant fraction of trip total time. However, idle has lowest fuel use rate of all notches. Thus, idle typically contributes 1 percent to 3 percent of trip total fuel use. Hence, a 5.1 percent increase in fuel use at idle would still not significantly affect trip total fuel use.

B40 had a reduced fuel use rate for all notches except idle, dynamic brake and Notch 1. The reduction varied between 4.9 percent and 30.2 percent. Idle had a 14.5 increase in fuel use rate. Dynamic brake and Notch 1 had 2.3 percent and 1.3 percent increased fuel use. These lower notch positions have low notch average fuel use rates. Therefore, their contribution to trip total fuel use is very low, typically less than 5 percent. On an Average Piedmont cycle, B10, B20 and B40 had 0.2 percent higher, 3.3 percent lower and 5.4 percent lower fuel use compared to ULSD, respectively. Thus, B40 was found to be the best fuel as it would result in lowest mass of fuel consumed on Piedmont route.

For notch average CO_2 emission rates, trends similar to the fuel use were obtained. B40 was found to the best fuel for reducing CO_2 emission rates. Higher biodiesel content of B40 results in higher life cycle CO_2 reductions. Thus, B40 provides substantial benefits over other fuels. All fuels resulted in a substantial reduction in CO and HC emissions compared to petro diesel. However, CO and HC emissions are low for diesel engines. Prior work has shown that CO and HC emissions for Tier 0+ compliant locomotives are comparable to the level of Tier 4 standards (*20*, *22*, *24*, *25*).

Notch average NO_x emission rates were higher for B10 for all notch position except idle and Notch 2. For these two notch positions, reduction was less than 2.4 percent. Other notch positions had 1.6 percent to 9.7 percent higher notch average NO_x emission rates. Thus, B10 would result in increased cycle average NO_x emission rates. B20 had 10 percent to 16 percent lower notch average NO_x emission rates for dynamic brake and Notches 2 through 6. Idle had 15 percent higher NO_x emission rate. However, idle has the lowest NO_x emission rate. Thus, even a 15 percent increase in emission rate is minimal. B40 had increased notch average NO_x emission rates for all notches except Notch 2 and Notch 7. Idle had 34.4 percent higher NO_x emission rates compared to ULSD. Extended idling can result in very high NO_x emissions due to such high NO_x emission rate. For an average Piedmont cycle, B20 had 1.9 percent reduction in trip total NO_x emissions compared to ULSD. B10 and B40 resulted in a 7.4 increase in trip-total NO_x emissions.

TABLE 8-4. Relative Percentage Differences in Notch average Fuel Use and Emission Rates for B10, B20 and B40 Biodiesel Blends versus Ultra-Low Sulfur Diesel for an Average Locomotive

Notch	Notch average Relative Percentage Difference with Respect to Ultra-Low Sulfur Diesel (%)																	
	Fuel Use			CO_2			CO			HC[a]			NO_x[b]			PM[c]		
	B10	B20	B40	B10	B20	B40	B10	B20	B40	B10	B20	B40	B10	B20	B40	B10	B20	B40
Idle	-1.6	5.1	14.5	-1.7	5.1	13.9	-16.5	-25.3	81.6	-30.8	-15.1	23.9	-2.4	15.1	34.4	-21.5	-17.6	0.9
DB[d]	8.3	-2.6	2.6	8.7	-2.3	2.7	-32.8	-57.5	14.7	-27.6	-55.0	-30.7	5.1	-15.4	8.8	-25.8	-50.7	-3.1
1	9.5	1.4	1.3	9.5	1.3	1.3	-34.2	-52.7	-28.7	-24.5	-57.6	-52.8	8.8	-6.1	13.4	-23.3	-40.9	-19.9
2	2.3	-3.1	-11.9	2.5	-3.4	-11.6	-30.7	-55.8	-29.0	-31.8	-53.8	-33.9	-1.2	-13.2	-4.8	-23.4	-37.4	-30.4
3	0.5	-4.8	-7.1	0.8	-4.9	-7.4	-50.3	-60.5	-43.1	-40.7	-65.1	-51.6	1.9	-14.9	4.2	-20.6	-42.7	-26.2
4	3.5	-3.9	-8.2	3.1	-3.6	-8.6	-30.0	-55.5	-30.7	-49.1	-62.8	-40.7	1.9	-13.4	2.2	-13.2	-40.5	-32.2
5	-0.6	-3.7	-8.8	-0.6	-3.7	-8.3	-19.5	-43.1	-36.6	-23.2	-61.9	-49.6	1.6	-9.0	6.1	-5.2	-40.0	-23.5
6	-0.9	-4.8	-9.4	-0.9	-4.8	-9.4	-25.8	-42.4	-53.1	-53.2	-61.5	-58.6	9.7	-1.9	15.2	-6.7	-47.5	-30.8
7	11.5	-7.2	-30.2	11.9	-7.1	-33.2	31.0	-33.6	-60.8	-26.4	-52.4	-68.4	30.7	0.7	-14.7	33.9	-33.6	-31.7
8	-0.1	-3.2	-4.9	-0.1	-3.2	-4.9	10.8	-35.3	-42.8	-47.3	-53.6	-59.0	6.5	-1.5	7.6	2.7	-44.7	-20.4
AP[e]	0.2	-3.3	-5.4	0.3	-3.5	-5.7	9.6	-35.6	-42.5	-50.0	-57.1	-57.1	7.4	-1.9	7.4	0.0	-47.6	-23.8

[a] *HC was measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factor of 2.5 to approximate total HC.*

[b] *NO_x includes NO and NO_2. Only NO was measured. Typically, NO_x is comprised of 95 vol-% NO. NO_x is always reported as equivalent mass of NO_2. Results include multiplicative correction factor of 1.053 to approximate total NO_x.*

[c] *PM was measured using a light scattering technique, which provides useful relative comparisons of particle levels in the exhaust. Results include multiplicative correction factor of 5 to approximate total PM.*

[d] *DB = Dynamic Brake*

[e] *AP* = Average Piedmont duty cycle as described in Table 3-4.

Average locomotive: Average locomotive is defined as an average of NC 1810, NC 1859 and NC 1797

The use of biodiesel resulted in reduced notch average PM emission rates for all blends. B10 had 13 percent to 26 percent lower notch average PM emission rate compared to ULSD for all notches except for Notches 5 through 8. Notches 5 and 6 also had lower notch average emission rates. B20 had lower PM emission rates for all notch positions. Reductions were between 33 percent and 50 percent for all notch position except at idle. Idle had a reduction of 17.6 percent. Thus, B20 biodiesel can result in substantial reduction in notch average PM emission rates. With B40 biodiesel, notch average PM emission rates were lower between 19 percent and 30 percent. For an average Piedmont cycle, B10 had comparable trip total PM emissions to ULSD. B20 and B40 resulted in a 47.6 percent and 23.8 percent reduction in trip-total fuel use, respectively. Thus, B20 was found to be the best fuel in terms of PM emissions on the Piedmont route.

Cycle average emission rates were estimated for each of the fuel based on time-weighted notch average emission rates. The results for average Piedmont duty cycle and the EPA line-haul cycle are given in Table 8-5. On a cycle average basis, fuel use was 1 percent higher, 3.4 percent lower and 6.3 percent lower for B10, B20 and B40 biodiesel blends, respectively. Cycle average CO_2 emissions also had similar trends as notch average fuel use rates. CO and HC emission rates were lower for B20 and B40. NO_x emission were 4 percent lower for B20 compared to ULSD. B10 and B40 had higher NO_x emissions. PM emissions were also lowest for B20. B40 also had lower emissions compared to ULSD. B10 had comparable PM emission rates. Overall, B20 was found to be the most suitable fuel as B20 had the lowest cycle average NO_x and PM emission rates on the Average Piedmont cycle. B40 had the lowest cycle average fuel use rate on the Average Piedmont cycle. However, B20 also had a lower cycle average fuel use rate compared to ULSD on the Average Piedmont cycle. Thus, B20 provide a reliable alternative fuel.

TABLE 8-5. Cycle Average Fuel Use and Emission Rates for an Average Locomotive Running on ULSD, B10, B20 and B40.

Quantity	Cycle	Unit	Fuel			
			ULSD	B10	B20	B40
Fuel Use	EPA Line-haul	g/bhp-hr	92.7	93.2	89.5	86.7
	Average Piedmont		109.1	109.3	105.5	103.2
CO_2	EPA Line-haul	g/bhp-hr	287	290	259	268
	Average Piedmont		339	340	307	319
CO	EPA Line-haul	g/bhp-hr	0.59	0.64	0.38	0.34
	Average Piedmont		0.73	0.80	0.47	0.42
HC[a]	EPA Line-haul	g/bhp-hr	1.3	0.7	0.6	0.6
	Average Piedmont		1.4	0.7	0.6	0.6
NO_x[b]	EPA Line-haul	g/bhp-hr	4.9	5.2	4.7	5.2
	Average Piedmont		5.4	5.8	5.3	5.8
PM[c]	EPA Line-haul	g/bhp-hr	0.17	0.18	0.10	0.13
	Average Piedmont		0.21	0.21	0.11	0.16

[a] *HC was measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factor of 2.5 to approximate total HC.*

[b] *NO_x includes NO and NO_2. Only NO was measured. Typically, NO_x is comprised of 95 vol-% NO. NO_x is always reported as equivalent mass of NO_2. Results include multiplicative correction factor of 1.053 to approximate total NO_x.*

[c] *PM was measured using a light scattering technique, which provides useful relative comparisons of particle levels in the exhaust. Results include multiplicative correction factor of 5 to approximate total PM.*

Average Locomotive- Average of NC 1810, NC 1859 and NC 1797.

Chapter 9. Combined Effects of Technology, Operation, and Fuels

In Chapters 3 and 4, baseline FUERs for locomotive NC 1859 operated on ULSD were estimated based on static-load RY tests and dynamic-load OTR tests. NC 1859 was retrofitted with an SCR-based BATS NO_x after treatment system. The effects of BATS on FUER were quantified in RY measurements based on before and after comparison measurements in Chapter 6. The effect of locomotive operation on FUER was quantified by conducting OTR measurements. NC 1859 was operated on the Piedmont route on ULSD under different duty cycles by different operators during revenue generating passenger service as discussed in Chapter 7. Variability in locomotive operation affected trip total fuel use by as much as 30 percent. The effect of fuel was quantified based on results of a prior study (*20*, *25*), as discussed in Chapter 8. B20 was found to be the most suitable fuel in terms of reduced fuel use, NO_x emissions and PM emissions compared to ULSD.

This chapter focuses on quantifying the combined effect of technology, operation, and fuels on locomotive FUER. Technology refers to the retrofitted BATS. Operation refers to variability in duty cycles. Fuel refers to B20 versus ULSD. This chapter discusses the following possible combinations: (a) technology-operation; (b) fuels-operation; (c) technology-fuels; and (d) technology, operations, and fuels.

The technology-operation combination includes quantifying the effect of FUER for a locomotive retrofitted with BATS under different duty cycles on the Piedmont route running on ULSD. The operation-fuels combination includes quantifying the effect of FUER for a locomotive operated under different duty cycles on the Piedmont route and running on B20 and ULSD. The technology-fuels combination includes quantifying the effect of FUER for a locomotive retrofitted with BATS and operated on B20 and ULSD. The technology, operations, and fuels combination includes quantifying the effect of FUER for a locomotive retrofitted with BATS under different duty cycles on the Piedmont route when operated on B20 and ULSD.

9.1 Methods

Baseline notch average FUER of locomotive NC 1859 running on ULSD were quantified based on OTR measurements for 6 one-way trips. Similarly, notch average FUER of the locomotive NC 1859 retrofitted with BATS were quantified based on OTR measurements of 6 one-way trips. As discussed in Chapter 5, each one-way trip had a different duty cycle which led to differences in trip total fuel use and emissions. Therefore, to enable a consistent basis for comparing the effect of BATS on FUER, the locomotive was assumed to run on a selected duty cycle with ULSD and retrofitted with BATS. Relative percentage differences in notch average FUER for BATS versus without BATS were estimated in Chapter 6. Thus, 1-Hz FUER for the selected trip with BATS were estimated from uncontrolled 1-Hz FUER on ULSD and the differences in controlled versus uncontrolled emissions inferred from the RY test with BATS. To quantify the effect of locomotive operation on FUER, two one-way trips with highest differences in trip total fuel use and emissions were compared, as discussed in Section 8.2.3. To quantify the effect of B20 versus ULSD, the locomotive without BATS was assumed to run on B20 instead of ULSD. Relative percentage differences in notch average FUER for B20 versus without ULSD estimated in Chapter 8 were used to quantify the effect of fuel on FUER.

The relative percentage differences in notch average FUER due to BATS and fuel (B20 versus ULSD) are quantified in Chapters 6 and 8, respectively. The same notch average relative percentage differences in FUER were applied to 1-Hz FUER of the two selected OTR trips on ULSD to estimate 1-Hz FUER for various combinations of technology, operations, and fuels:

$$m'_{s,t,n_t,T,O,F} = m_{s,t,n_t,T,O,F} \times \left(1 + \frac{r_{s,t,n_t,T,O,F}}{100}\right) \quad (33)$$

Where,

$m'_{s,t,n_t,T,O,F}$	=	estimated mass per time-based rate (*g/s*) of species *s* at time *t* for notch n_t for technology *T*, operation *O* and Fuel *F*.
$m_{s,t,n_t,T,O,F}$	=	baseline mass per time-based rate (*g/s*) of species *s* at time *t* for notch n_t for technology *T*, operation *O* and Fuel *F*.
s	=	species: Fuel use, CO_2, CO, HC, NO_x or PM.
n_t	=	throttle notch position at time *t*
T	=	index for technology (= 1 for BATS and =0 for without BATS)
O	=	index for operation (=1 for trip with highest fuel use, and =2 for trip with lowest fuel use)
F	=	index for fuel (=1 for ULSD and =2 for B20)
$r_{s,n,T,F}$	=	relative percentage difference in notch average rates with respect to baseline rates for species *s* for notch *n* for technology *T* and Fuel *F* with respect to OTR trip on NC 1859 on ULSD without BATS installed.

9.1.1 *Technology-Operation*

The effect of BATS and locomotive operation is quantified based on multiple duty cycles on the Piedmont route running on ULSD. The effect of technology is quantified for the selected two one-way trips assuming the locomotive to be retrofitted with BATS. Relative percentage differences in notch average in FUER were estimated for a locomotive retrofitted with BATS and operated on ULSD in Chapter 6 based on RY measurements. One-Hz mass per time based FUER for selected trips operated with BATS installed were estimated as:

$$m_{s,t,n_t,1,O,1} = m_{s,t,n_t,0,O,1} \times \left(1 + \frac{r_{s,n,1,1}}{100}\right) \quad (34)$$

Where,

$r_{s,n,1,1}$	=	notch average relative percentage difference for species *s* for notch *n* for locomotive with BATS operated on ULSD (See Table 6-5 for Fuel Use and CO_2 Emission Rate and Table 6-8 for NO_x Emission Rate, 0 percent for others).

One Hz FUER were estimated for each selected trip and plotted as a segmented map of the Piedmont route. The number of hotspots were estimated for the selected trips. Trip total fuel use and emissions were also estimated.

9.1.2 *Fuels-Operation*

This section focuses on the combined effect of fuels and operation on FUER. The effect of ULSD and locomotive operation was discussed in Chapter 8. This section focuses on the effect of B20 biodiesel fuel and locomotive operation. FUER for B20 was estimated as:

$$m_{s,t,n_t,0,O,2} = m_{s,t,n_t,0\ ,O,1} \times \left(1 + \frac{r_{s,n\ ,0,2}}{100}\right) \tag{35}$$

Where,

$r_{s,n\ ,0,2}$ = Notch average relative percentage difference for species *s* for notch *n* for locomotive without BATS operated on B20 versus ULSD (See Table 8-3).

9.1.3 *Technology-Fuels*

The combined effect of retrofitting emission control and switching from ULSD to B20 was estimated. This estimate takes into account the relative percentage differences in FUER for B20 versus ULSD and the effect of BATS on FUER as follows:

$$m_{s,t,n_t,1,O,2} = m_{s,t,n_t,0\ ,O,1} \times \left(1 + \frac{r_{s,n\ ,1,1}}{100}\right) \times \left(1 + \frac{r_{s,n\ ,0,2}}{100}\right) \tag{36}$$

Equation 36 can also be written as:

$$m_{s,t,n_t,1,O,2} = m_{s,t,n_t,0\ ,O,1} \times \left(1 + \frac{r_{s,n\ ,1,2}}{100}\right) \tag{37}$$

Where:

$r_{s,n\ ,1,2}$ = Notch average relative percentage difference for species *s* for notch *n* for locomotive with BATS operated on B20.

Using Equation 36 and Equation 37, $r_{s,n\ ,1,2}$ was estimated as:

$$r_{s,n\ ,1,2} = \left\{\left(1 + \frac{r_{s,n\ ,1,1}}{100}\right) \times \left(1 + \frac{r_{s,n\ ,0,2}}{100}\right) - 1\right\} \times 100 \tag{38}$$

9.1.4 *Technology-Fuel-Operation*

The method for quantifying the effect of locomotive operations with BATS installed and running on ULSD on FUER is given in Section 9.1.1. This section describes the effect of locomotive operations with BATS installed and running on B20. Notch average relative percentage difference for species *s* for notch *n* for locomotive with BATS operated on B20 with respect to an OTR trip on ULSD without BATS have been estimated in Section 9.1.2.

9.2 Results and Discussion

This section focuses on segment total fuel use and emissions for the combinations of emission control, operation, and fuel discussed above. For each combination, trip total fuel use and emissions are estimated and compared to the baseline fuel use and emissions. The baseline fuel use and emissions correspond to a locomotive without BATS and running on ULSD for the trip that has highest trip total fuel use among the 6 one-way trips. Baseline notch average FUER are given in Table 5-5 and baseline trip total fuel use and emissions are given in Table 5-7. Trip 1 had the highest fuel use rate and is the base case. Trip 2 had the lowest fuel use. Key fuel use and emission hotspots are also identified and compared to the base case. The trip total fuel use and emissions for each of the combinations are summarized in Table 9-1 and the number of hotspots for each case are summarized in Table 9-2.

9.2.1 *Technology-Operation*

Segment total fuel use and emissions for the combined effect of technology and operation were estimated for each quarter mile segment for two selected OTR trips. Segment average speed, positive acceleration, grade and curve are same as shown in Figure 7-1 and Figure 7-2. Segment total fuel use and emissions are shown Figure 9-1 and Figure 9-2 for the two trips.

With BATS installed and locomotive running on ULSD, the trip total fuel use increased from 713 kg to 720 kg for the trip with the highest fuel use, and from 531 kg to 536 kg for the trip with lowest fuel use compared to without BATS. Thus, the trip with highest fuel use had an estimated 1 percent increase in fuel use due to BATS installation. The trip with lowest fuel consumption had an estimated 1.1 percent increase in fuel use. In terms of gallons of ULSD consumed, switching to BATS lead to an estimated increase in fuel consumption between 1 gallon and 2 gallons per one-way trip. Compared to the trip with ULSD without BATS installed, the estimated number of fuel use hotspots increased from 139 to 151, and from 71 to 83, for trips with highest and lowest fuel use, respectively. Increase in the number of hotspots is attributed to increase in fuel use rate for all notch positions. The fuel use hot spots also correspond to CO_2 emission hotspots.

The estimated trip total NO_x emissions decreased from 38.9 kg to 4.9 kg for the trip with highest fuel use, and from 33.8 kg to 4.4 kg for the trip with lowest fuel use. Thus, BATS installation reduced the trip total NO_x emissions by 87 percent for both the trips. As a result, the entire route was free of any NO_x emission hotspots. PM emissions were unaffected by BATS installation.

9.2.2 *Fuels-Operation*

Segment total fuel use and emissions for the combined effect of fuels and operation were estimated for each quarter mile segment for two OTR trips. Segment average speed, positive acceleration, grade and curve are the same as shown in Figures 7-1 and 7-2 for the trips with highest and lowest fuel use, respectively. Estimated segment total fuel use and emissions are shown Figures 9-3 and 9-4 for the trips with highest and lowest fuel use, respectively.

Use of B20 instead of ULSD for locomotive operation without BATS installed lowered the estimated trip total fuel consumption. The trip with highest fuel use consumed an estimated 694 kg or 215 gallons of B20 biodiesel. The trip with lowest fuel use consumed an estimated 518 kg or 160 gallons of B20 biodiesel. Thus, on a volume of fuel basis, a reduction of 7 gallons in fuel use was estimated for both the trips. Compared to ULSD, trip with highest fuel use had an estimated 3.3 percent reduction in fuel use and the trip with lowest fuel use had an estimated 4.4 percent reduction in fuel use. Compared to the trip with ULSD without BATS installed, the estimated number of fuel use hotspots decreased from 139 to 83 (40 percent reduction), and from 71 to 63 (11 percent reduction) for trips with highest and lowest fuel use, respectively. The fuel use hot spots also correspond to CO_2 emission hotspots.

TABLE 9-1. Trip Total Fuel Use and Emissions for Individual and Combined Effects of Technology, Operation, and Fuels on Diesel Locomotives

Technology	Operation	Fuel	Fuel Use (kg)	NO_x (kg)	PM (kg)	CO (kg)	HC (kg)
None	Highest Fuel Use	ULSD	713	38.9	1.12	2.3	2.5
	Lowest Fuel Use		531	33.8	0.98	1.2	2.2
None	Highest Fuel Use	B20	694	38.5	0.66	1.5	1.3
	Lowest Fuel Use		518	33.4	0.60	0.8	1.2
BATS	Highest Fuel Use	ULSD	720	4.9	1.12	2.3	2.5
	Lowest Fuel Use		536	4.4	0.98	1.2	2.2
BATS	Highest Fuel Use	B20	715	4.9	0.66	1.5	1.3
	Lowest Fuel Use		532	4.4	0.60	0.8	1.2

TABLE 9-2. Fuel Use and Emission Hotspots for Individual and Combined Effects of Technology, Operation, and Fuels on Diesel Locomotives

Technology	Operation	Fuel	Number of Hotspots				
			Fuel Use	NO_x	PM	CO	HC
None	Highest Fuel Use	ULSD	139	135	137	137	135
	Lowest Fuel Use		71	104	110	61	96
None	Highest Fuel Use	B20	83	128	29	57	65
	Lowest Fuel Use		63	100	21	27	49
BATS	Highest Fuel Use	ULSD	165	0	137	137	135
	Lowest Fuel Use		115	0	110	61	96
BATS	Highest Fuel Use	B20	138	0	29	57	65
	Lowest Fuel Use		73	0	21	27	49

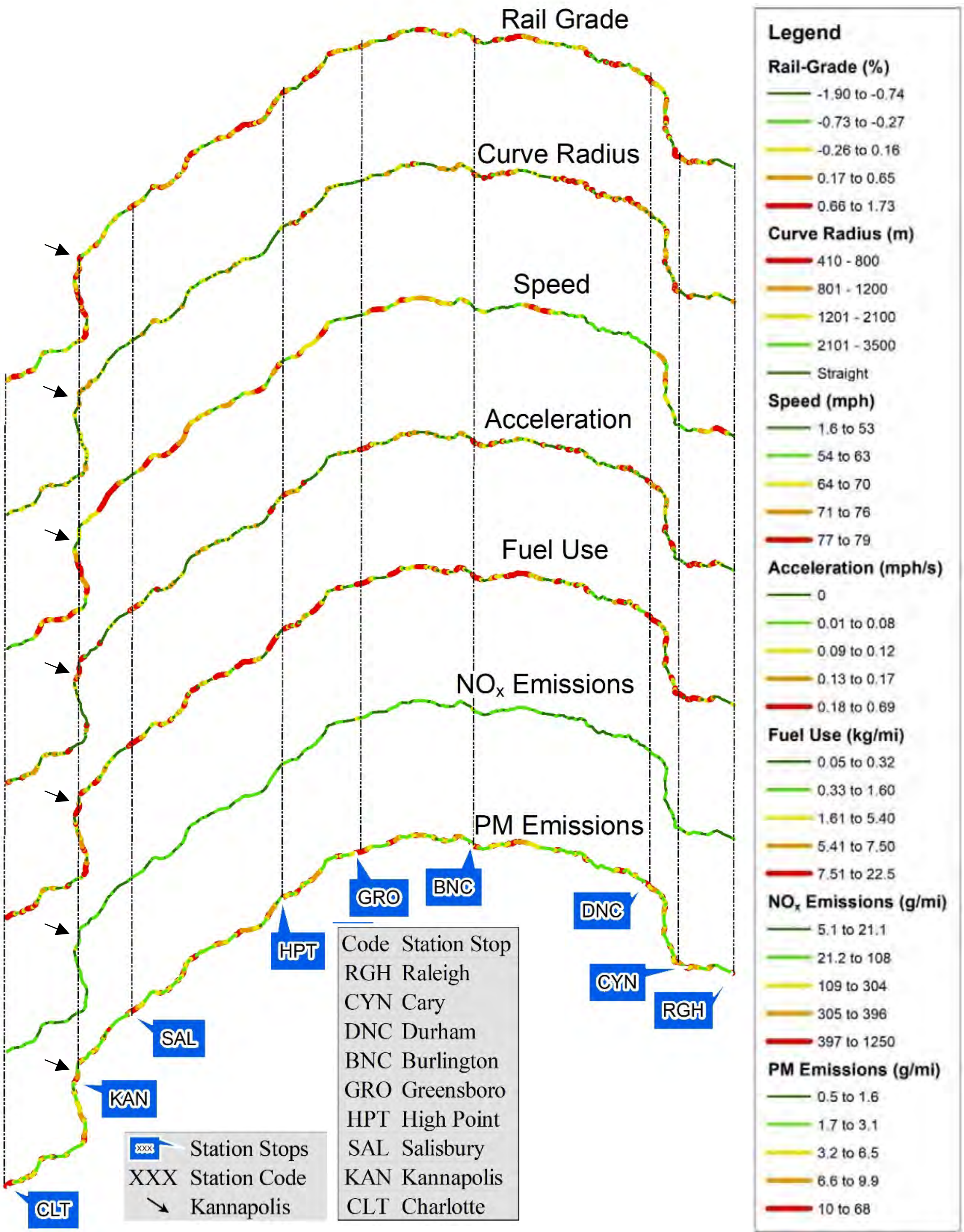

FIGURE 9-1. Estimated train activity, track geometry, fuel use and emissions for the observed trip with highest fuel use for locomotive NC 1859 running on ULSD with BATS installed. Train consist included one locomotive and three cars. Each variable is divided into 5 ranges with cutoff points indicating 20 percent frequency ranges based on the trip with highest fuel use. Red indicates the segments with top 20 percent frequency range and green represents the bottom 20 percent frequency range.

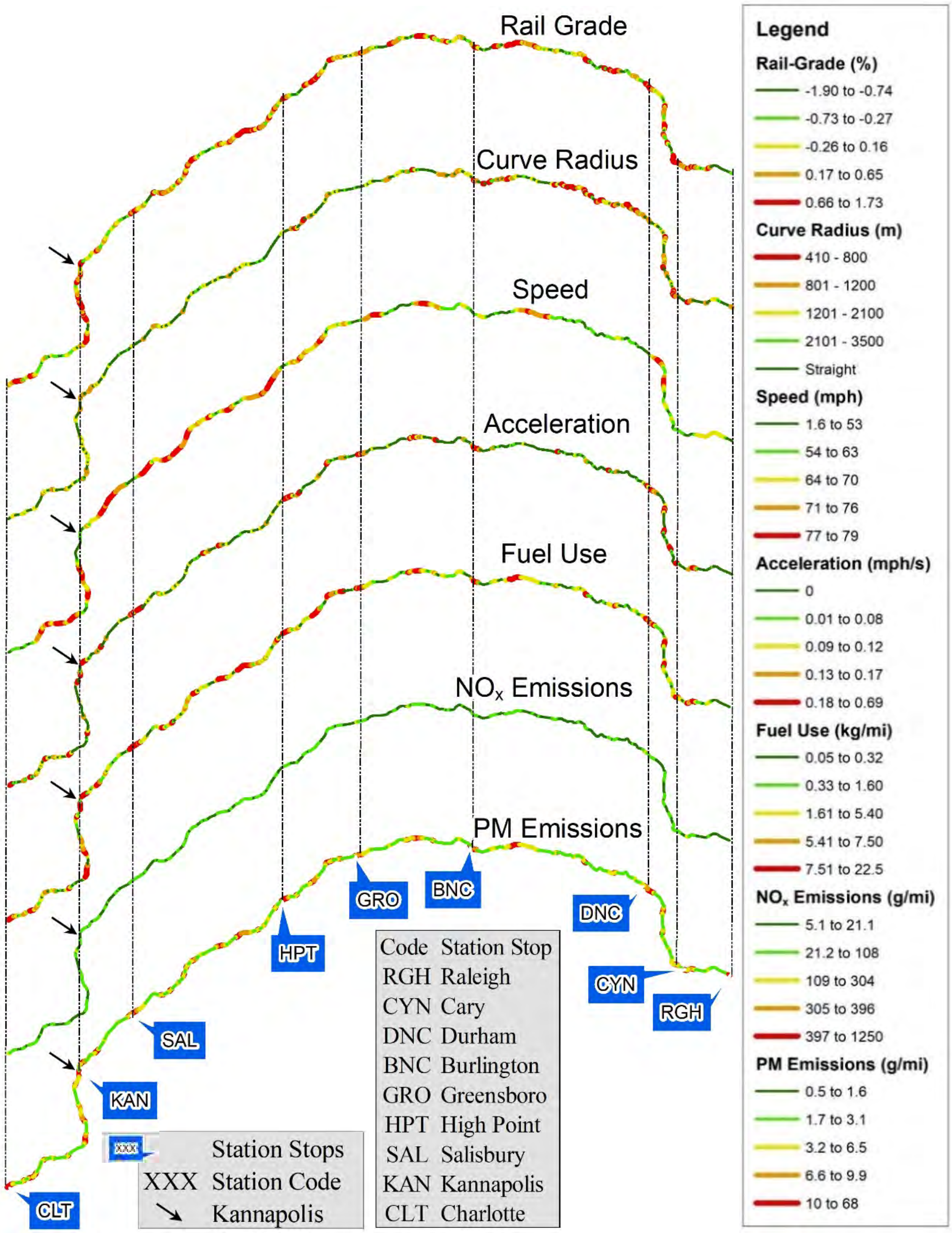

FIGURE 9-2. Estimated train activity, track geometry, fuel use and emissions for the observed trip with lowest fuel use for locomotive NC 1859 running on ULSD with BATS installed. Train consist included one locomotive and three cars. Each variable is divided into 5 ranges with cutoff points indicating 20 percent frequency ranges based on the trip with highest fuel use. Red indicates the segments with top 20 percent frequency range and green represents the bottom 20 percent frequency range.

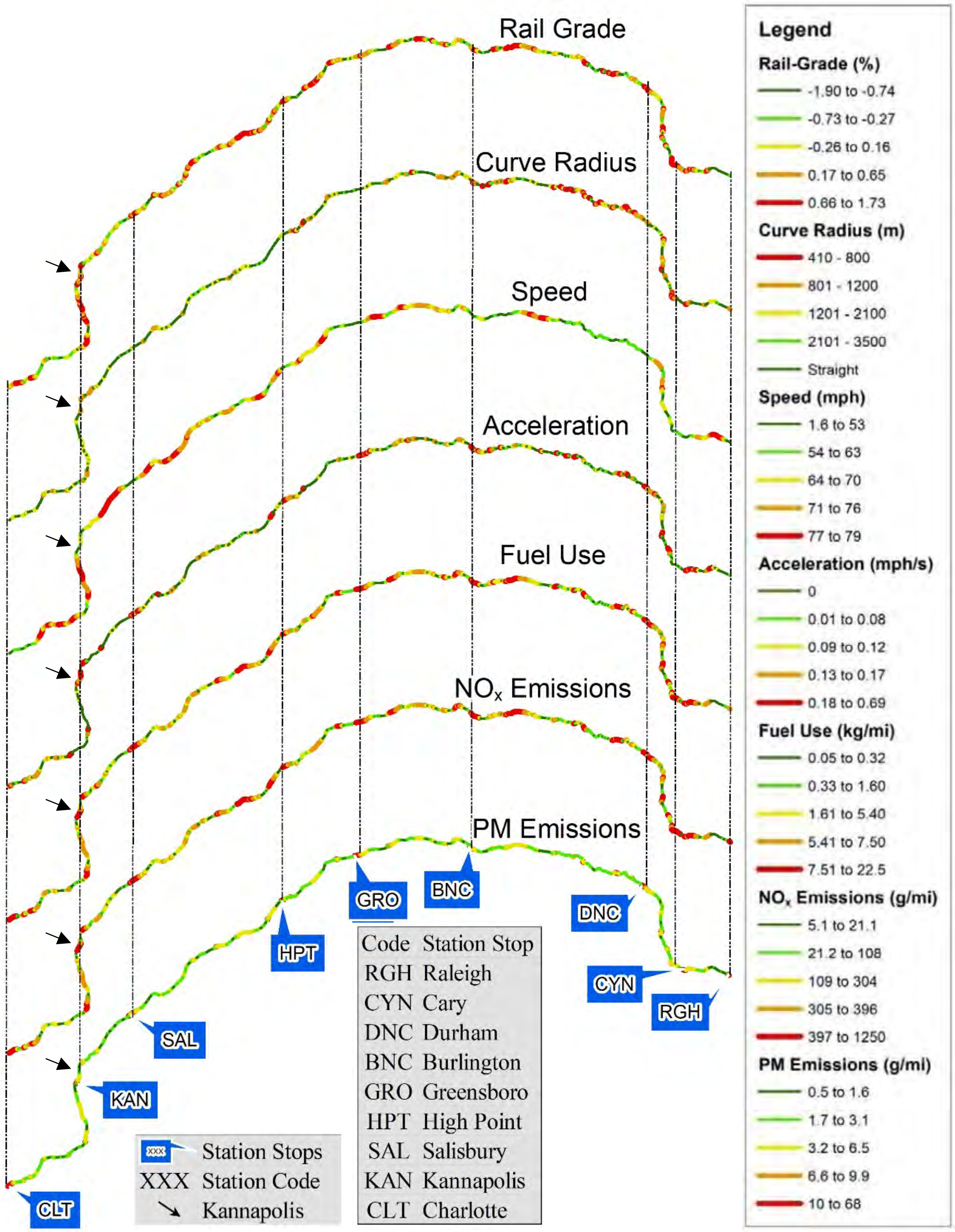

FIGURE 9-3. Estimated train activity, track geometry, fuel use and emissions for the observed trip with highest fuel use for locomotive NC 1859 running on B20 without BATS installed. Train consist included one locomotive and three cars. Each variable is divided into 5 ranges with cutoff points indicating 20 percent frequency ranges based on the trip with highest fuel use. Red indicates the segments with top 20 percent frequency range and green represents the bottom 20 percent frequency range.

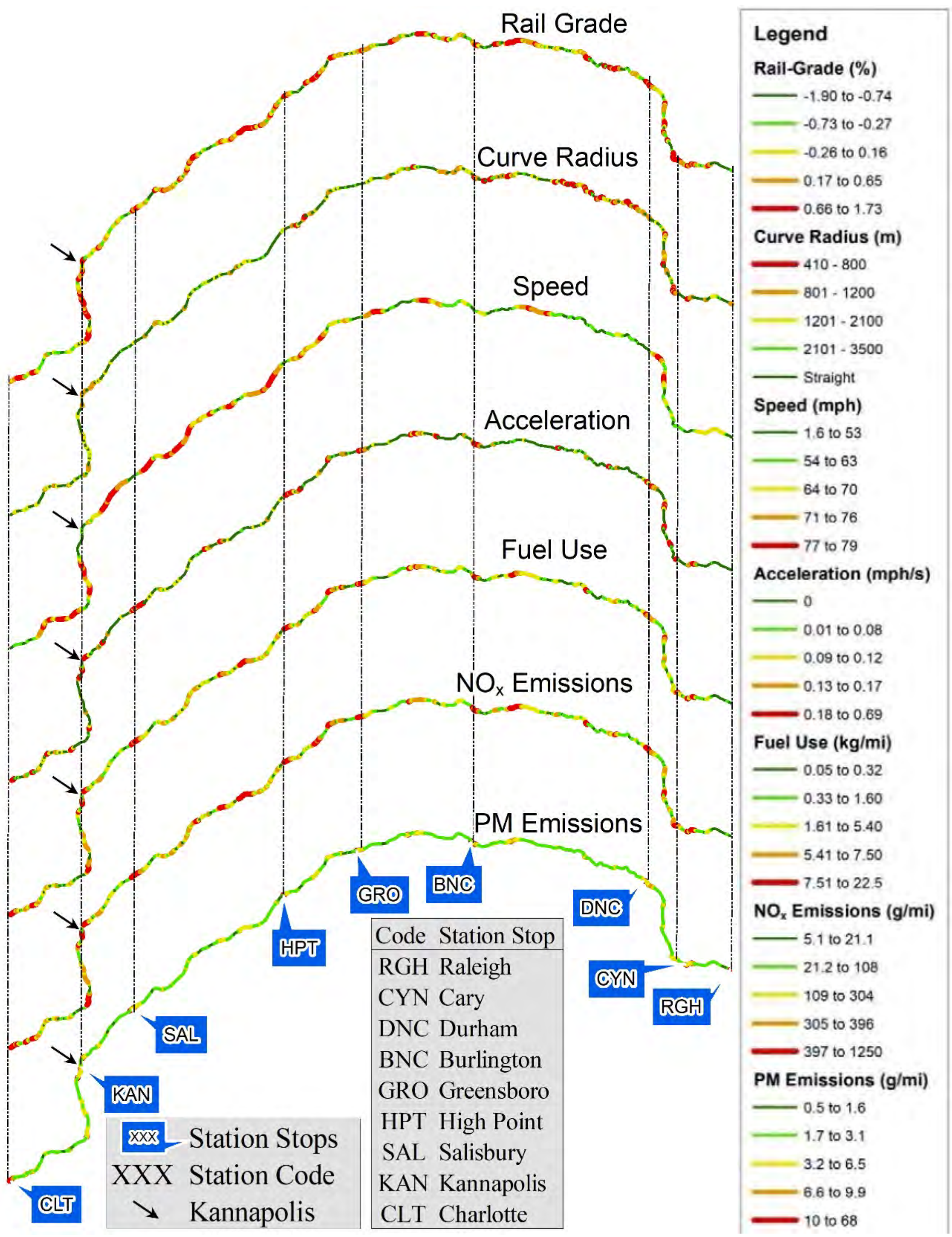

FIGURE 9-4. Estimated train activity, track geometry, fuel use and emissions for the observed trip with lowest fuel use for locomotive NC 1859 running on B20 without BATS installed. Train consist included one locomotive and three cars. Each variable is divided into 5 ranges with cutoff points indicating 20 percent frequency ranges based on the trip with highest fuel use. Red indicates the segments with top 20 percent frequency range and green represents the bottom 20 percent frequency range.

Although, use of B20 instead of ULSD was estimated to reduce the fuel consumption by only 3.3 percent to 4.4 percent, the number of estimated fuel use and CO_2 emission hotspots decreased by 40 percent for the trip with highest fuel use, and 11 percent for the trip with lowest fuel use.

The estimated trip total NO_x emissions reduced from 38.9 kg to 38.5 kg, and from 33.8 kg to 33.4 kg when comparing the two trips due to fuel switching. The combined effect of fuels and operation is estimated to reduce trip total NO_x emissions from 38.9 kgs to 33.4 kgs. The estimated NO_x emissions reduction due to B20 biodiesel was just 0.4 kg over 173 miles. The estimated number of NO_x emission hotspots decreased by just 4 for each of the two trips due to fuel switching. Thus, most of the estimated reduction in NO_x emissions was due to better operation.

The trip total PM emissions decreased by an estimated 40 percent by switching from ULSD to B20 biodiesel. The estimated trip total PM emissions decreased from 1.12 kg to 0.66 kg, and 0.98 kg to 0.60 kg, for the two trips, respectively. For fuel and operation combined, trip total PM emissions were estimated to decrease from 1.12 kgs to 0.60 kgs, most of which was estimated due to fuel switching. Estimated PM emission hotspots decreased by 80 percent for each of the two trips due to fuel switching. The number of PM emission hotspots decreased from 137 to 29, and 110 to 21 for the two trips. For the combined effect of fuels-operation, the estimated number of PM emission hotspots decreased from 137 to 21, most of which was due to fuel switching.

9.2.3 *Technology-Fuels*

The effect of both technology and fuels is estimated based on a locomotive with BATS operated on B20 versus without BATS operated on ULSD. Using Equation 38, notch average relative percentage difference in FUER were estimated. The results are given in Table 9-3.

Notch 8 has the highest fuel use rate and typically contributes the highest fraction of fuel consumption in each trip. With the combination of BATS and B20 biodiesel, the net change in fuel use rate at Notch 8 is just 0.5 percent. Thus, the use of B20 biodiesel on a locomotive retrofitted with BATS mitigates the increased fuel use due to BATS installation. The idle fuel use rate is about 40 times lower than Notch 8 fuel use rate. Thus, idle contributes very little to trip total fuel use. Small changes in idle fuel use rate do not significantly affect trip total fuel use.

9.2.4 *Technology-Fuel-Operation*

Segment total fuel use and emissions for the combined effect of technology, operations, and fuels were estimated for each quarter mile segment for two OTR trips. Segment total fuel use and emissions are shown Figures 9-5 and 9-6 for the two trips, respectively.

BATS was found to be most effective in reducing NO_x emissions but resulted in slight estimated increases in fuel use and CO_2 emissions. The use of B20 biodiesel partly compensates for the increased fuel use due to BATS. However, the major benefit of using B20 biodiesel is a 40 percent reduction in PM emissions. These two techniques, when combined with efficient locomotive operation, can lead to a 30 percent reduction in fuel use and CO_2 emissions.

Compared to the trip with highest fuel use, using a locomotive retrofitted with BATS, operated on B20 on a duty cycle corresponding to a trip with lowest fuel use, would result in an estimated reduction in fuel use of 25 percent from 713 kg of ULSD to 538 kg of B20 biodiesel.

TABLE 9-3. Notch average Relative Percentage Difference in Fuel Use and Emission Rates for Locomotive Operated on B20 and retrofitted with BATS with respect to Locomotive Operated on ULSD without BATS

Throttle Notch Position	Relative Percentage Difference in Fuel Use and Emission Rates for Locomotive operated on B20 and retrofitted with BATS (%) with respect to Locomotive Operated on ULSD without BATS		
	Fuel Use Rate	NO_x Emission Rate	PM Emission Rate
Idle	8.6	-82.1	-17.6
DB	0.6	-86.8	-50.7
1	-2.7	-53.4	-40.9
2	1.4	-78.2	-37.4
3	1.2	-94.3	-42.7
4	6.8	-96.8	-40.5
5	6.0	-93.3	-40.0
6	0.5	-81.0	-47.5
7	-5.1	-89.6	-33.6
8	0.5	-87.4	-44.7

The combination of BATS and B20 resulted in a significant reduction in estimated trip total NO_x and PM emissions for each of the high and low fuel use trips. No NO_x emission hotspots were estimated. The trip total PM emissions decreased from 1.12 kg to 0.66 kg, and 0.98 kg to 0.60 kg, for the high and low fuel use trips, respectively. Estimated PM emission hotspots decreased by 80 percent for each of the high and low fuel use trips, respectively. The number of estimated PM emission hotspots decreased from 137 to 29, and 110 to 21 for the two trips, respectively. Thus, B20 is estimated to be effective in reducing PM emissions.

Use of BATS resulted in 87 percent reduction in estimated trip total NO_x emissions compared to without BATS on ULSD, as discussed in Section 9.2.1. Use of B20 instead of ULSD only resulted in a 1 percent reduction in trip total NO_x emissions, as discussed in Section 9.2.2. Thus, the BATS resulted in a significant reduction in NO_x emissions. BATS did not affect notch average PM emission rates. Thus, any reductions in PM emissions are solely due to B20 compared to ULSD.

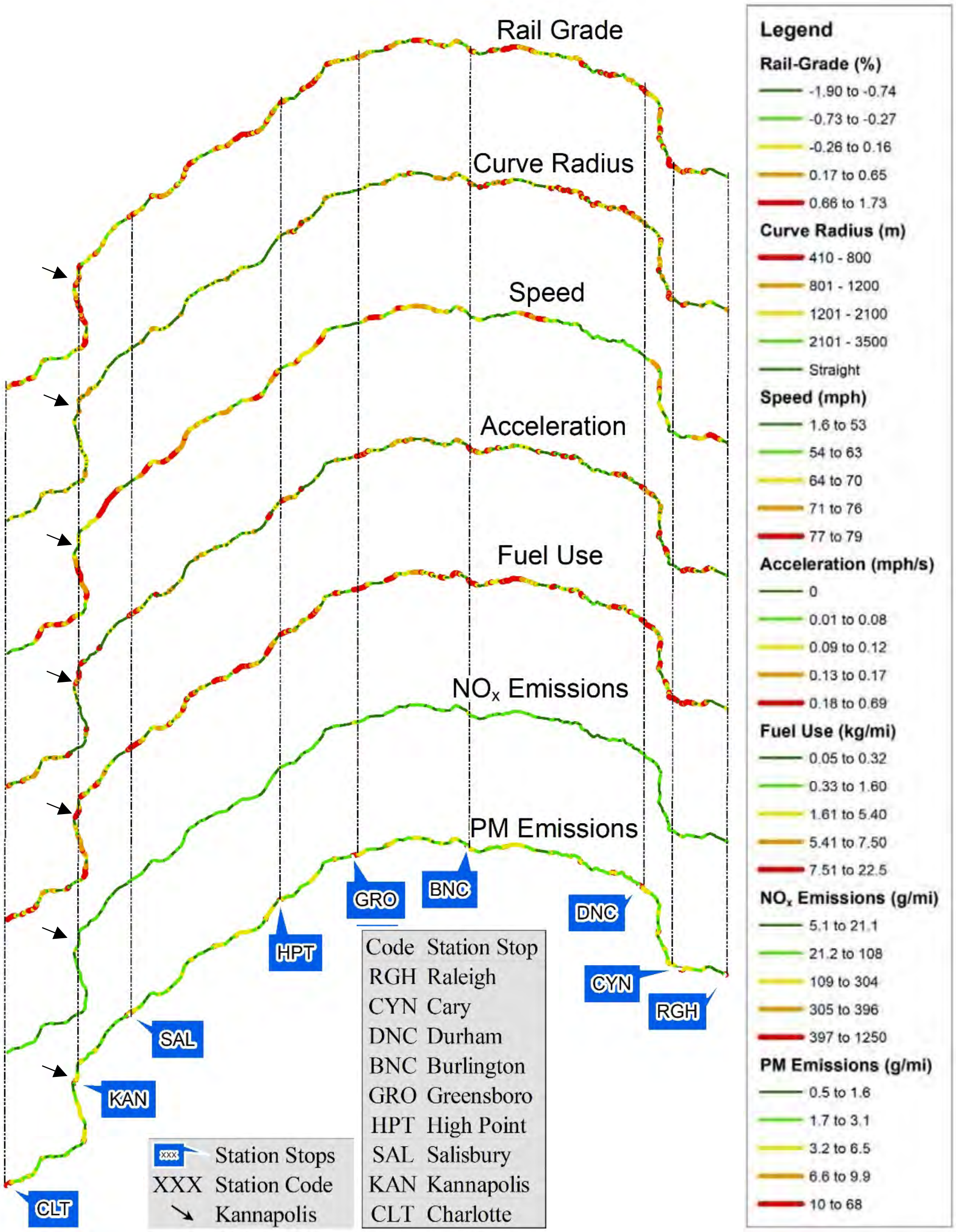

FIGURE 9-5. Estimated train activity, track geometry, fuel use and emissions for the observed trip with highest fuel use for locomotive NC 1859 running on B20 with BATS installed. Train consist included one locomotive and three cars. Each variable is divided into 5 ranges with cutoff points indicating 20 percent frequency ranges based on the trip with highest fuel use. Red indicates the segments with top 20 percent frequency range and green represents the bottom 20 percent frequency range.

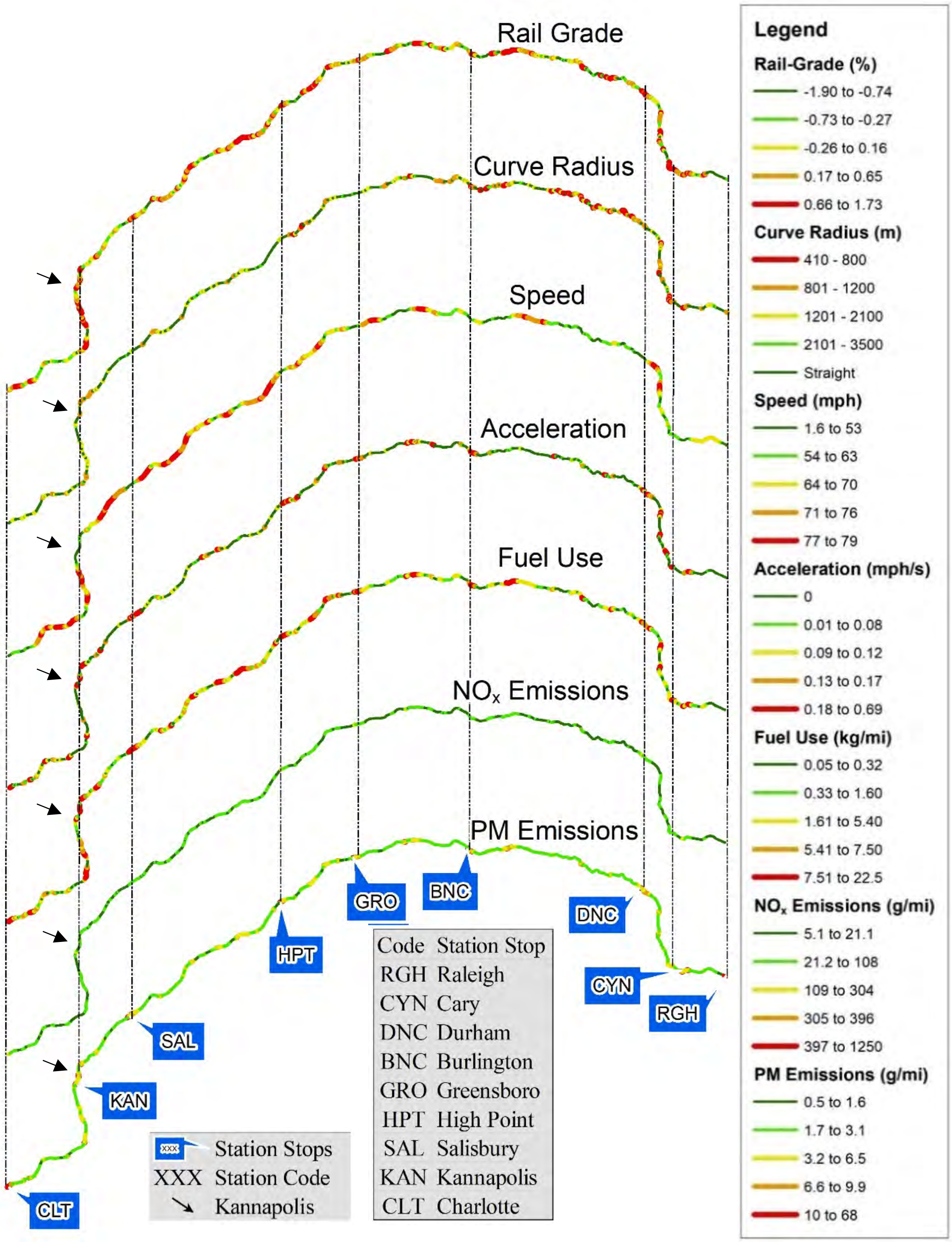

FIGURE 9-6. Estimated train activity, track geometry, fuel use and emissions for the observed trip with lowest fuel use for locomotive NC 1859 running on B20 with BATS installed. Train consist included one locomotive and three cars. Each variable is divided into 5 ranges with cutoff points indicating 20 percent frequency ranges based on the trip with highest fuel use. Red indicates the segments with top 20 percent frequency range and green represents the bottom 20 percent frequency range.

Chapter 10. Conclusions and Recommendations

In the prior chapters, factors affecting locomotive emissions were discussed. The effect of an exhaust after-treatment system on NO_x emissions was discussed as an example of technology. PEMS-based FUER were compared with FUER estimated based on a certification test method. Several one-way trips with different duty cycles were compared to quantify the effect of locomotive operation on FUER. Single and tandem locomotive operation were discussed. The effect of using biodiesel fuel bends instead of ULSD was studied. This chapter summarizes the effect of each combination of technology, operation, and fuels.

10.1 Benchmarking Axion PEMS

The PEMS-based fuel use rates were highly correlated with gravimetric measured fuel use rates, with a mean error ranging from only 7.1 percent at idle to 1.3 percent at notch 8. The range of errors in fuel use rates for individual notch average rates from a given replicate were from –1.5 g/s to + 1.2 g/s. The CO_2 and NO_x emission rates from the PEMS measurements also agreed well with those from the LEMS, with mean errors ranging from 4.2 percent at idle to 0.8 percent at notch 8 for CO_2 and 3.3 percent for NO_x emission rates. The Axion PEMS-based PM emission rates had a correlation of 0.8 with LEMS-based PM emission rates. Thus, Axion PEMS is a reliable alternative to the more equipment-intensive gravimetric fuel-based method.

10.2 Technology

NO_x emission rates were consistently lower for all notches with the retrofitted BATS compared to the baseline. The BATS was able to achieve NO_x emission rate reductions of 80 percent or higher for notches 3 through 8. The cycle average NO_x control efficiency was 85 percent. Overall, cycle average NO_x emission rates were 0.8 g/bhp-hr for the EPA Line-haul and average Piedmont duty cycles, which is lower than the level of Tier 4 standards. Fuel use rate increased for all notch positions with versus without the BATS, except idle. However, the increase was less than 1.6 percent. Thus, the BATS can significantly reduce NO_x emissions without significantly affecting engine fuel use rate. CO_2 emission rates had similar trends as fuel use rate. Notch average CO and HC emission rates were not significantly affected.

10.3 Operation

Train speed, acceleration, grade and curve radius were found to be the key factors affecting train energy use and emissions based on literature review. Segment total fuel use and emissions are directly related to grade and acceleration, and inversely related to train speed. Curves also impact fuel use and emissions directly. However, on this route, trains typically operate at reduced speeds between 30 mph and 50 mph. Thus, the effect of curves on FUER is lower at lower speeds. Grade and curves affect driver behavior as the driver may decide to change the throttle notch position which in turn affects FUER. Two of 6 one-way trips of NC 1859 operated on ULSD were selected for comparison. These trips had highest and lowest trip total fuel use.

Trip 1 had the highest fuel consumption amongst 6 one-way trips, with trip total fuel consumption of 762 kgs. The operator of the trip with the lowest trip total fuel consumption typically operated the train at zero acceleration and high train speeds for long periods of time. Changes in speed were gradual compared to the trip with the highest fuel use. This enabled the operator to operate the locomotive at lower notch positions. Dynamic braking use was also lowest for Trip 2 compared to all trips. The operator typically coasted the train to a stop on most occasions. Compared to Trip 1, this strategy resulted in a reduction of 30 percent, 20 percent and 18 percent in trip total fuel use, NO_x emissions and PM emissions by mass, respectively.

The effect of train consist was also studied to quantify the effect of single locomotive versus two locomotives operated in tandem on trip total fuel use and emissions. Two locomotives back to back were used to provide power to pull extra passenger cars that were added to the typical train consist in anticipation of higher passenger demand during the measurement. Both single and tandem operation resulted in similar trip total fuel use per passenger car. However, NO_x and PM emissions per passenger car were lower by 17 percent and 14 percent, respectively for tandem operation. The fuel use and emissions per passenger car could have been lower if only one locomotive was used to pull 5 passenger cars. The effect of such a train consist has not been measured yet. Several train systems use just one locomotive in consists with 4 to 8 passenger cars.

10.4 Fuels

Notch average FUER for an average locomotive for B10, B20 and B40 were compare to ULSD to quantify the effect of alternative fuels. B10 resulted in a 0.2 percent increase in cycle average fuel use rate for the average Piedmont duty cycle. B20 and B40 resulted in a reduction in cycle average fuel use rate of 3 percent and 5 percent, respectively. For CO_2 emissions, trends similar to those for fuel use were obtained. B40 was found to have the largest reduction in CO_2 emissions by 5 percent. The biodiesel content of B40 results in life cycle CO_2 reductions. B10 and B20 has lower CO_2 emissions compared to ULSD. B10 and B20 also lead to reductions in life cycle CO_2 emissions compared to ULSD. All fuels resulted in a substantial reduction in cycle average CO and HC emission rates compared to ULSD.

Cycle average NO_x emission rates for the average Piedmont duty cycle increased by 7 percent for B10 and B40. Cycle average NO_x emission rates for B20 were lower by 2 percent. Cycle average PM emission rates for B10 were similar to ULSD for the average Piedmont duty cycle. However, B20 and B40 had reductions in cycle average PM emission rates of 48 percent and 24 percent, respectively. Overall, B20 was found to be the most suitable fuel as it had the lowest NO_x and PM emissions. B40 had the lowest fuel use rate. However, B20 also had a lower fuel use rate compared to ULSD.

10.5 Recommendations

To reduce energy consumption of the train, the train can be operated in a more efficient manner. Some operators could operate more efficiently or more poorly than in the observed trips. The most effective way to reduce fuel consumption is to adopt efficient locomotive operation. This involves fewer notch changes and avoiding rapid accelerations and decelerations. Such operation entails a low rate of acceleration to a cruising speed and aiming for constant cruising speed. Coasting the train to a stop instead of braking also leads to a reduction in fuel use. BATS installation increases the fuel use by only one percent, which is not a significant increase. Switching to B20 biodiesel blend lowers the fuel consumption by about 3 percent to 4 percent.

For reducing NO_x emissions, the use of BATS is highly recommended. With the BATS installed, cycle average NO_x emission rates were estimated to be below the level of Tier 4 standards on the EPA Line-Haul and average Piedmont duty cycle. The estimated trip total NO_x emission can be further reduced by 20 percent based on more efficient locomotive operation. Switching to biodiesel blends does not substantially affect NO_x emission rates. With BATS installed, no NO_x emission hotspots were estimated for the Piedmont route.

Cycle average CO and HC emission rates for the EPA Line-haul and average Piedmont duty cycles were lower than the levels of Tier 4+ standards for ULSD. Better operation and switching to biodiesels can further lower CO and HC emissions. The BATS did not significantly affect cycle average CO and HC emission rates.

For reducing PM emissions, switching to B20 biodiesel resulted in an estimated 40 percent reduction in cycle average PM emission rates for both duty cycles. The estimated number of PM emission hotspots was also reduced by about 25 percent. The use of a diesel particulate filter (DPF) upstream of the BATS is recommended. DPF are already in use for highway diesel trucks and can reduce PM emission rates by over 90 percent.

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Appendix A. Detailed Results for Baseline Rail Yard Tests on NC 1859

Rail yard measurements were conducted in November 2015 on the prime mover engine of locomotive NC 1859 (City of High Point) operated on ULSD using a portable emissions measurement system (PEMS). The prime mover engine is an EMD 12-710G3B. The engine was originally manufactured in 1988 and was rebuilt by AMTRAK in 2012. The 140-Liter engine has a peak engine output of 3000 horsepower (hp) at an engine speed of 900 revolutions per minute (rpm). The prime mover engine operated on ULSD.

Three rail yard emissions measurement replicates on the prime mover engine of NC 1859 were conducted on November 18, 2015. Results for the rail yard measurements are presented and discussed in this section. There was little variability between replicate measured engine activity data, given in Figure A-1. This indicates that the prime mover engine was operating consistently during all three replicate measurements.

An increasing trend in notch average fuel use rates is apparent as notch position increased during the rail yard measurements, as shown in Figure A-2. The CV for time-based fuel use rate was less than 0.04 for all the notches. Notch average NO emission rates for the three replicates were fairly consistent, as shown in Figure A-3. There is variability in the estimated notch average HC emission rates between the three replicate measurements as shown in Figure A-4. Inter-replicate variability in the estimated notch average HC emission rates were, on average, 22 percent. There is also variability in the estimated notch average CO emission rates between the three replicate measurements, as shown in Figure A-5. The higher variability amongst HC and CO could be attributed to very low exhaust concentrations that are near the detection limit of the PEMS and therefore, not much significantly different from zero. The PM concentrations between the three replicate measurements are also consistent, as shown in Figure A-6. However, the PM concentrations measured were of the same magnitude as previous rail yard measurements.

Table A-2 summarizes the average measured engine speed (RPM), intake air temperature (IAT), and manifold absolute pressure (MAP) for each throttle notch position and for each replicate of the rail yard (RY) test. The volumetric efficiency and air to fuel ratios are summarized in Table A-3. Engine rpm ranges from 238 to 904 RPM. For the RY measurements, engine rpm is highly repeatable, with a standard deviation of less than 1 RPM for all notch positions. The intake air temperature varies with ambient temperature and was generally in the range of 58 to 85 degrees C during all measurements. MAP was highly repeatable in the RY tests, ranging from 98 to 223 kPa with an inter-test standard deviation of less than 3 kPa for most notch settings. The ratio of the standard deviation to the mean of the run average MAP values for each notch position is typically 0.02 or less. Overall, the engine activity during the measurements was consistent from test to test for the three replicates in the rail yard.

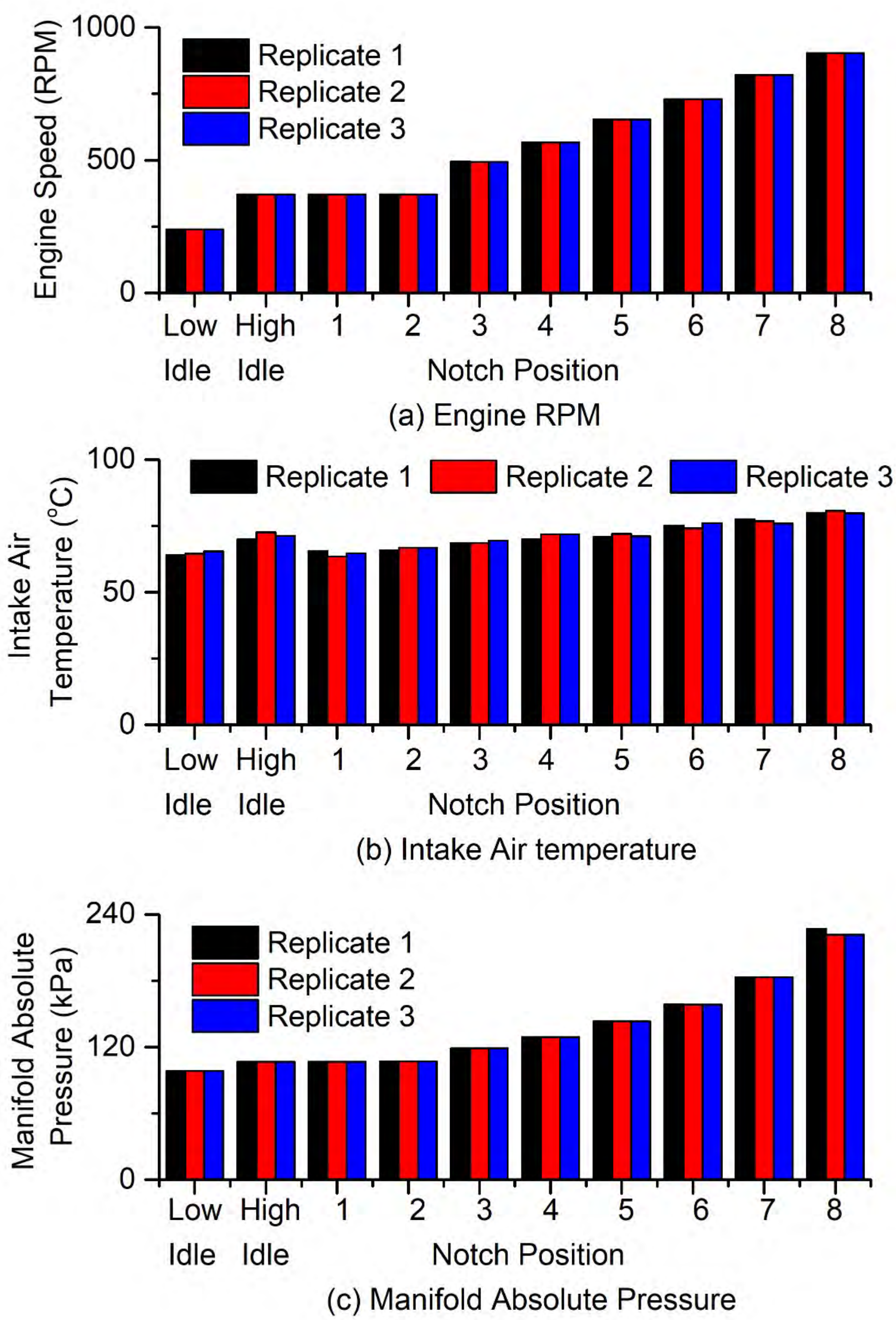

FIGURE A- 1. Measured Engine Activity Parameters during Rail Yard Measurements on the Prime Mover Engine of NC 1859 Operated on ULSD: (a) Engine RPM; (b) Intake Air Temperature; and (c) Manifold Absolute Pressure.

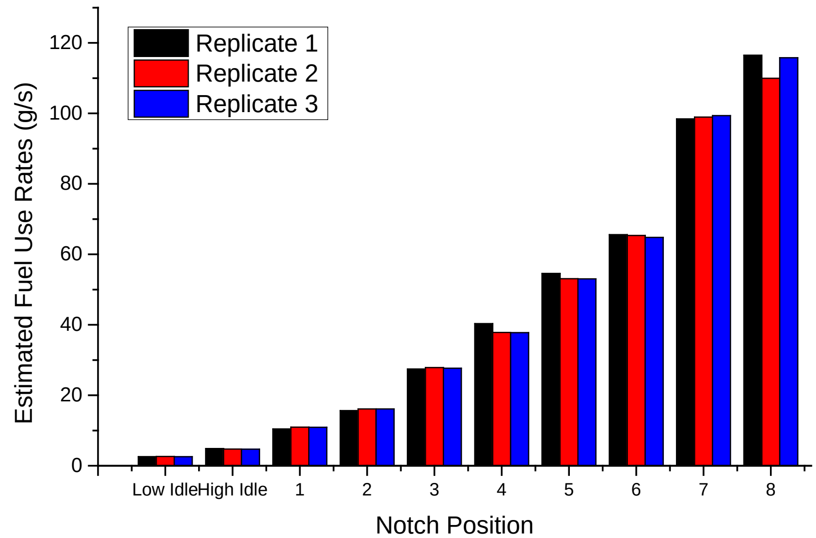

FIGURE A- 2. Estimated Notch Average Fuel Use Rates during Rail Yard Measurements of the NC 1859 Prime Mover Engine with ULSD.

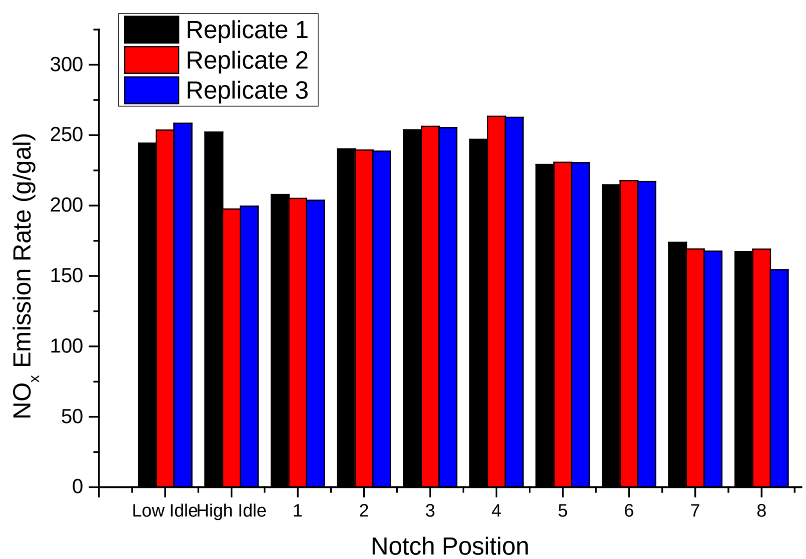

FIGURE A- 3. Estimated Notch Average NO Emission Rates during Rail Yard Measurements of the NC 1859 Prime Mover Engine with ULSD

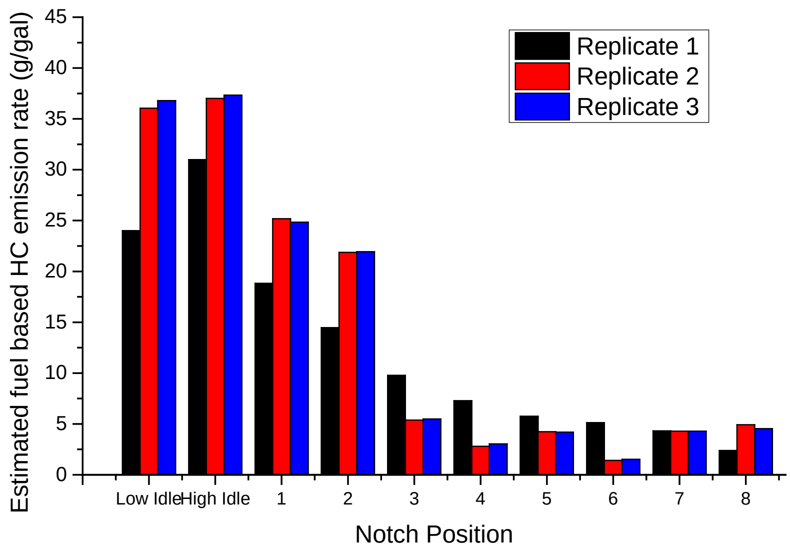

FIGURE A- 4.Estimated Notch Average HC Emission Rates during Rail Yard Measurements of the NC 1859 Prime Mover Engine with ULSD

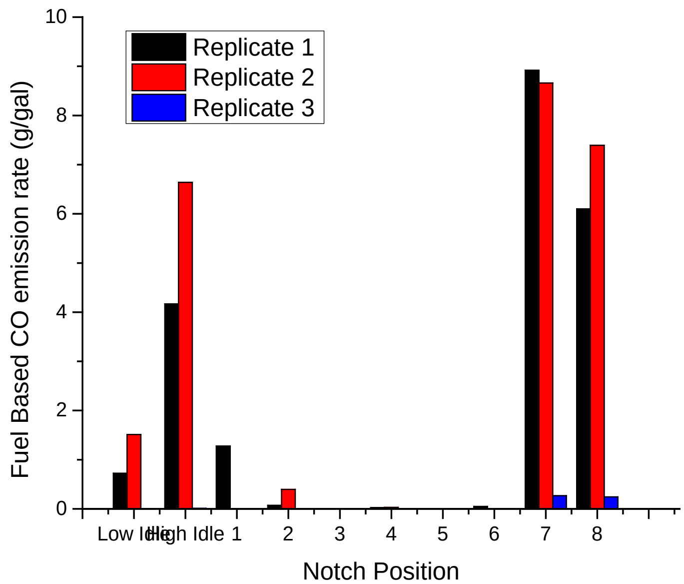

FIGURE A- 5. Estimated Notch Average CO Emission Rates during Rail Yard Measurements of the NC 1859 Prime Mover Engine with ULSD

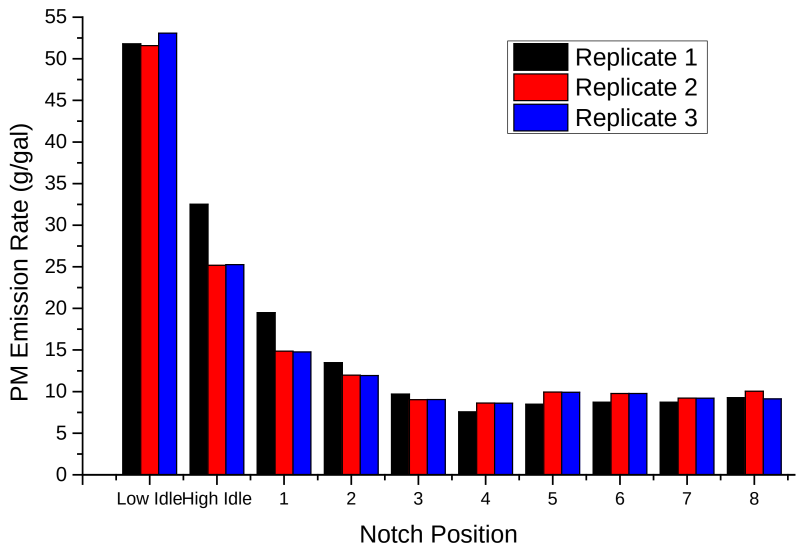

FIGURE A- 6. Measured Notch Average PM Emission Rates during Rail Yard Measurements of the NC 1859 Prime Mover Engine with ULSD

TABLE A- 1. Cycle Average Emission Rates for Rail Yard Replicate Measurements of NC 1859 Prime Mover Engine with ULSD

	NO_x (g/bhp-hr)	CO (g/bhp-hr)	HC (g/bhp-hr)	Opacity-based PM (g/bhp-hr)
Replicate 1	9.41	*0.22*	*0.26*	0.40
Replicate 2	9.24	*0.24*	*0.32*	0.41
Replicate 3	9.02	*0.23*	*0.32*	0.40
Average of three replicates	9.2	*0.2*	*0.3*	0.4
Coefficient of Variation	0.02	*0.05*	*0.13*	0.03

Values shown in italics correspond to notch average pollutant concentrations that were below the gas analyzer detection limit.

† NO_x, HC, and PM are adjusted with multipliers of 1.05, 2.5, and 5, respectively, as bias correction.

Table A-4 summarizes the estimated notch average fuel use rates inferred from the engine data of Table A-2. For the RY tests, notch average fuel use rates range from 3.0 to 114 g/sec depending on notch position, and was highly repeatable, with a coefficient of variation (CV, which is standard deviation divided by the mean) of typically 0.04 or less at high engine load. There is more variability in run-to-run estimates of fuel use for the OTR measurements, in part because the amount of time spent in some notch positions was low. The OTR estimated fuel use ranged from 3 to 106 g/sec, with CV ranging from 0.02 to 0.14.

The measured NO exhaust concentration and the estimated notch average NO_x emission rates are given in Table A-7 for each notch position, each RY test replicate, and each OTR one-way run. The average measured concentrations range among notch positions from approximately 144 to 1016 ppm in the RY tests, and 155 to 1039 ppm in the OTR measurements. The measurements are highly repeatable for the RY and OTR measurements, with CVs typically less than 0.15 for the former and less than 0.17 for the latter. The estimated notch average mass emission rates range from 0.20 to 5.77 g/sec for the RY measurements and 0.24 to 5.57 g/sec for the OTR measurements. Because the observed concentrations tend to be lower for the OTR versus RY measurements, notch average mass emission rates also tend to be slightly lower for the OTR versus RY measurements.

On a fuel basis, the notch average NO_x emission rates range from 164 to 258 g/gallon among notch positions for the RY measurements and 154 to 260 g/gallon for the OTR measurements. For the RY measurements, the fuel-based notch average emission rates are repeatable, with CV typically less than 0.05 for all notches except high idle. The OTR measurements have more run-to-run variability but are nonetheless consistent, with CVs ranging from 0.05 to 0.07 in all notches except 0.10 for Notch 8. The fuel-based notch average emission rates tend to be lowest at high load.

On an engine output basis, the notch average NO_x emission rates range from 8 g/bhp-hr at Notch 7.7 to 13.2 g/bhp-hr at Notch 1 in the RY measurements, with very high values at idle during which engine output is very low. For the OTR measurements, notch average emission rates range from 6.3 g/bhp-hr at Notch 8 to 11.8 g/bhp-hr at Notch 1, with much higher values during idle and dynamic braking. In general, notch average emission rates on an engine output basis are lower for the OTR measurements than for the RY measurements. This results from a combination of lower exhaust concentration and higher engine output, especially at Notch 8.

Results are given for notch average exhaust concentrations and emission rates in Tables A-5 through A-8 for CO, HC, PM, and CO_2, respectively. Both notch average CO and HC emission rates are low on an absolute basis, and some of the measured average concentrations for a given notch position and replicate or run are below the gas analyzer detection limit. For PM, the measured exhaust levels tend to be lower for OTR than RY for a given notch position, and thus the cycle average PM emission rate tends to also be lower. The trends in notch average CO_2 emission rates are similar to those for fuel use on a mass per time and mass per engine output basis. Notch average CO_2 emission rates are also shown on a g/gallon basis. Since typically over 99 percent of the carbon in the fuel is emitted as CO_2, the fuel-based notch average CO_2 emission rates are approximately constant.

Differences in notch average emission rates are attributable to differences in measured exhaust concentrations. Values for engine activity parameters (RPM, IAT, and MAP) were similar across all rail yard and over-the-rail measurements.

TABLE A- 2. Measured and Estimated Parameters of the Prime Mover Engine of NC 1859 running on ULSD during Rail Yard Measurements

Engine Speed (RPM)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	239	239	239	239	0.07	0.00
High Idle	371	371	371	371	0.18	0.00
Dyn Brk						
1	371	371	371	371	0.01	0.00
2	371	371	371	371	0.04	0.00
3	494	494	494	494	0.24	0.00
4	567	567	567	567	0.14	0.00
5	653	653	653	653	0.00	0.00
6	730	730	730	730	0.00	0.00
7	821	821	821	821	0.02	0.00
8	903	903	903	903	0.30	0.00

Intake Air Temperature (^{o}C)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	64	65	65	65	0.73	0.01
High Idle	70	73	71	71	1.36	0.02
Dyn Brk						
1	66	64	65	65	1.01	0.02
2	66	67	67	66	0.58	0.01
3	68	68	69	69	0.58	0.01
4	70	72	72	71	1.08	0.02
5	71	72	71	71	0.65	0.01
6	75	74	76	75	0.99	0.01
7	78	77	76	77	0.83	0.01
8	80	81	80	80	0.51	0.01

Manifold Absolute Pressure (kPa)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	98	98	98	98	0.04	0.00
High Idle	107	107	107	107	0.02	0.00
Dyn Brk						
1	107	107	107	107	0.05	0.00
2	107	107	107	107	0.05	0.00
3	119	119	119	119	0.09	0.00
4	129	129	129	129	0.06	0.00
5	143	143	143	143	0.03	0.00
6	159	158	158	158	0.24	0.00
7	183	183	183	183	0.04	0.00
8	227	222	222	223	3.18	0.01

Mass Air Flow (g/s)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	875	874	871	873	1.89	0.00
High Idle	1262	1252	1257	1257	5.19	0.00
Dyn Brk						
1	1279	1285	1281	1282	3.46	0.00
2	1281	1276	1276	1278	2.78	0.00
3	1702	1699	1694	1698	3.71	0.00
4	1993	1980	1980	1985	7.34	0.00
5	2392	2383	2390	2388	4.79	0.00
6	2770	2773	2757	2767	8.34	0.00
7	3346	3352	3362	3353	7.62	0.00
8	4195	4106	4120	4140	47.87	0.01

TABLE A- 3. Estimated Air/Fuel Ratio and Volumetric Efficiency of the Prime Mover Engine of NC 1859 running on ULSD during Rail Yard Measurements

Air to Fuel Ratio (g/g)						
Throttle Notch Position	RailYard Test (RY)					
	18-Nov RY Rep1	18-Nov RY Rep2	18-Nov RY Rep3	3 Rep Avg	3 Rep Std Dev	3 Rep CV
Low Idle	345	333	342	340	6.30	0.02
High Idle	258	266	269	264	5.27	0.02
Dyn Brk						
1	123	118	118	119	2.84	0.02
2	82	79	79	80	1.61	0.02
3	62	61	61	61	0.57	0.01
4	49	52	52	51	1.72	0.03
5	44	45	45	45	0.65	0.01
6	42	42	43	42	0.15	0.00
7	34	34	34	34	0.09	0.00
8	36	37	36	36	0.92	0.03

Volumetric Efficiency						
Throttle Notch Position	RailYard Test (RY)					
	18-Nov RY Rep1	18-Nov RY Rep2	18-Nov RY Rep3	3 Rep Avg	3 Rep Std Dev	3 Rep CV
Low Idle	1.65	1.65	1.65	1.65	0.00	0.00
High Idle	1.43	1.43	1.43	1.43	0.00	0.00
Dyn Brk						
1	1.43	1.44	1.44	1.43	0.00	0.00
2	1.43	1.43	1.43	1.43	0.00	0.00
3	1.29	1.29	1.29	1.29	0.00	0.00
4	1.21	1.21	1.21	1.21	0.00	0.00
5	1.13	1.13	1.13	1.13	0.00	0.00
6	1.07	1.07	1.07	1.07	0.00	0.00
7	1.00	1.00	1.00	1.00	0.00	0.00
8	0.91	0.92	0.92	0.92	0.00	0.00

TABLE A- 4. Estimated Notch Average Fuel Use Rates of the Prime Mover Engine of NC 1859 running on ULSD during Rail Yard Measurements

Time based fuel use rate (g/s)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	3	3	3	3	0	0.02
High Idle	5	5	5	5	0	0.02
Dyn Brk						
1	10	11	11	11	0	0.03
2	16	16	16	16	0	0.02
3	27	28	28	28	0	0.01
4	40	38	38	39	1	0.04
5	55	53	53	54	1	0.02
6	66	65	65	65	0	0.01
7	98	99	99	99	0	0.00
8	117	110	116	114	4	0.03

Engine output based fuel use rate (g/bhp-hr)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	3.2	3.1	3.2	3.1	0.1	0.02
High Idle	1.7	1.7	1.7	1.7	0.0	0.02
Dyn Brk						
1	14.7	14.0	14.1	14.3	0.4	0.03
2	18.1	17.5	17.6	17.7	0.3	0.02
3	19.9	19.6	19.7	19.7	0.2	0.01
4	19.6	20.9	21.0	20.5	0.8	0.04
5	19.5	20.1	20.1	19.9	0.3	0.02
6	19.7	19.8	19.9	19.8	0.1	0.01
7	18.4	18.3	18.2	18.3	0.1	0.00
8	18.7	19.8	18.8	19.1	0.6	0.03

TABLE A- 5. Measured Notch Average NO_x Emission Rates of the Prime Mover Engine of NC 1859 running on ULSD during Rail Yard Measurements

Time based NO_x Emission rate (g/s)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	0.19	0.21	0.20	0.20	0.01	0.04
High Idle	0.38	0.29	0.29	0.32	0.05	0.17
Dyn Brk						
1	0.67	0.70	0.69	0.69	0.01	0.02
2	1.17	1.20	1.19	1.19	0.02	0.02
3	2.16	2.22	2.19	2.19	0.03	0.01
4	3.09	3.09	3.08	3.09	0.01	0.00
5	3.88	3.80	3.80	3.83	0.05	0.01
6	4.37	4.42	4.37	4.39	0.03	0.01
7	5.31	5.20	5.17	5.23	0.07	0.01
8	6.05	5.77	5.55	5.79	0.25	0.04

Fuel based NO_x Emission rate (g/gal)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	244	254	258	252	7	0.03
High Idle	252	198	200	216	31	0.14
Dyn Brk						
1	208	205	204	206	2	0.01
2	240	239	239	239	1	0.00
3	254	256	255	255	1	0.01
4	247	263	263	258	9	0.04
5	229	231	230	230	1	0.00
6	215	218	217	217	2	0.01
7	174	169	168	170	3	0.02
8	167	169	154	164	8	0.05

Engine output based NO_x Emission rate (g/bhp-hr)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	69.3	74.5	73.7	72.5	2.8	0.04
High Idle	137.8	104.1	104.4	115.4	19.4	0.17
Dyn Brk						
1	12.8	13.2	13.1	13.0	0.2	0.02
2	12.0	12.3	12.3	12.2	0.2	0.02
3	11.5	11.8	11.7	11.7	0.2	0.01
4	11.4	11.4	11.3	11.3	0.0	0.00
5	10.6	10.4	10.4	10.4	0.1	0.01
6	9.8	9.9	9.8	9.9	0.1	0.01
7	8.5	8.4	8.3	8.4	0.1	0.01
8	8.1	7.7	7.4	7.7	0.3	0.04

Exhaust NO_x concentration (ppm)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	138	148	147	144	6	0.04
High Idle	186	144	144	158	24	0.15
Dyn Brk						
1	327	333	333	331	3	0.01
2	566	579	580	575	8	0.01
3	795	814	812	807	11	0.01
4	977	973	974	974	2	0.00
5	1027	1003	1002	1011	14	0.01
6	1000	1024	1024	1016	14	0.01
7	1009	991	992	997	10	0.01
8	924	880	880	895	26	0.03

TABLE A- 6. Measured CO Estimation rates of the Prime Mover Engine of NC 1859 running on ULSD during Rail Yard Measurements

*Time based CO Emission rate (g/s)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	*0.001*	*0.001*	*0.001*	0.001	0.000	0.36
High Idle	*0.006*	*0.010*	*0.010*	0.009	0.002	0.24
Dyn Brk						
1	*0.004*	*0.000*	*0.000*	0.001	0.002	1.62
2	*0.000*	*0.002*	*0.002*	0.001	0.001	0.66
3	*0.000*	*0.000*	*0.000*	0.000	0.000	
4	*0.000*	*0.000*	*0.000*	0.000	0.000	0.01
5	*0.000*	*0.000*	*0.000*	0.000	0.000	
6	*0.001*	*0.000*	*0.000*	0.000	0.001	1.73
7	*0.273*	*0.266*	*0.267*	0.269	0.003	0.01
8	*0.221*	*0.252*	*0.242*	0.238	0.016	0.07

*Fuel based CO Emission rate (g/gal)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	*0.7*	*1.5*	*1.4*	1.2	0.4	0.35
High Idle	*4.2*	*6.6*	*6.9*	5.9	1.5	0.26
Dyn Brk						
1	*1.3*	*0.0*	*0.1*	0.4	0.7	1.63
2	*0.1*	*0.4*	*0.4*	0.3	0.2	0.65
3	*0.0*	*0.0*	*0.0*	0.0	0.0	0.00
4	*0.0*	*0.0*	*0.0*	0.0	0.0	0.05
5	*0.0*	*0.0*	*0.0*	0.0	0.0	0.00
6	*0.0*	*0.0*	*0.0*	0.0	0.0	1.73
7	*8.9*	*8.7*	*8.7*	8.7	0.1	0.02
8	*6.1*	*7.4*	*6.7*	6.7	0.6	0.10

*Engine output based CO Emission rate (g/bhp-hr)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	*0.20*	*0.44*	*0.40*	0.35	0.13	0.36
High Idle	*2.28*	*3.50*	*3.61*	3.13	0.74	0.24
Dyn Brk						
1	*0.08*	*0.00*	*0.00*	0.03	0.04	1.62
2	*0.00*	*0.02*	*0.02*	0.01	0.01	0.66
3	*0.00*	*0.00*	*0.00*	0.00	0.00	
4	*0.00*	*0.00*	*0.00*	0.00	0.00	0.01
5	*0.00*	*0.00*	*0.00*	0.00	0.00	
6	*0.00*	*0.00*	*0.00*	0.00	0.00	1.73
7	*0.44*	*0.43*	*0.43*	0.43	0.01	0.01
8	*0.29*	*0.34*	*0.32*	0.32	0.02	0.07

*Exhaust CO concentration (vol %)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	*0.000*	*0.000*	*0.000*	0.000	0.000	0.36
High Idle	*0.001*	*0.001*	*0.001*	0.001	0.000	0.25
Dyn Brk						
1	*0.000*	*0.000*	*0.000*	0.000	0.000	1.62
2	*0.000*	*0.000*	*0.000*	0.000	0.000	0.66
3	*0.000*	*0.000*	*0.000*	0.000	0.000	0.00
4	*0.000*	*0.000*	*0.000*	0.000	0.000	0.01
5	*0.000*	*0.000*	*0.000*	0.000	0.000	0.00
6	*0.000*	*0.000*	*0.000*	0.000	0.000	1.73
7	*0.009*	*0.009*	*0.009*	0.009	0.000	0.01
8	*0.006*	*0.007*	*0.007*	0.006	0.000	0.07

*Values shown in italics correspond to notch average pollutant concentrations that were below the gas analyzer detection limit.

TABLE A- 7. Measured Notch Average HC Emission Rates of the Prime Mover Engine of NC 1859 running on ULSD during Rail Yard Measurements

*Time based HC Emission rate (g/s)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	*0.019*	*0.029*	*0.029*	0.026	0.006	0.23
High Idle	*0.047*	*0.054*	*0.054*	0.052	0.004	0.08
Dyn Brk						
1	*0.061*	*0.086*	*0.084*	0.077	0.014	0.18
2	*0.070*	*0.109*	*0.110*	0.096	0.023	0.24
3	*0.083*	*0.047*	*0.047*	0.059	0.021	0.36
4	*0.091*	*0.033*	*0.036*	0.053	0.033	0.62
5	*0.098*	*0.070*	*0.069*	0.079	0.016	0.21
6	*0.104*	*0.029*	*0.030*	0.055	0.043	0.79
7	*0.132*	*0.132*	*0.132*	0.132	0.000	0.00
8	*0.086*	*0.168*	*0.163*	0.139	0.046	0.33

*Fuel based HC Emission rate (g/gal)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	*24.0*	*36.1*	*36.8*	32.3	7.2	0.2
High Idle	*31.0*	*37.0*	*37.3*	35.1	3.6	0.1
Dyn Brk						
1	*18.8*	*25.2*	*24.8*	22.9	3.6	0.2
2	*14.5*	*21.9*	*21.9*	19.4	4.3	0.2
3	*9.8*	*5.4*	*5.5*	6.9	2.5	0.4
4	*7.3*	*2.8*	*3.0*	4.4	2.5	0.6
5	*5.8*	*4.2*	*4.2*	4.7	0.9	0.2
6	*5.1*	*1.4*	*1.5*	2.7	2.1	0.8
7	*4.3*	*4.3*	*4.3*	4.3	0.0	0.0
8	*2.4*	*4.9*	*4.5*	4.0	1.4	0.3

*Engine output based HC Emission rate (g/bhp-hr)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	*6.81*	*10.59*	*10.49*	9.29	2.15	0.23
High Idle	*16.93*	*19.50*	*19.54*	18.65	1.49	0.08
Dyn Brk						
1	*1.16*	*1.62*	*1.59*	1.46	0.26	0.18
2	*0.72*	*1.13*	*1.13*	0.99	0.23	0.24
3	*0.44*	*0.25*	*0.25*	0.31	0.11	0.36
4	*0.34*	*0.12*	*0.13*	0.20	0.12	0.62
5	*0.27*	*0.19*	*0.19*	0.21	0.04	0.21
6	*0.24*	*0.06*	*0.07*	0.12	0.10	0.79
7	*0.21*	*0.21*	*0.21*	0.21	0.00	0.00
8	*0.12*	*0.22*	*0.22*	0.19	0.06	0.33

*Exhaust HC concentration (ppm)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	*3*	*5*	*5*	4	1	0.23
High Idle	*5*	*6*	*6*	6	1	0.09
Dyn Brk						
1	*7*	*9*	*9*	8	1	0.17
2	*8*	*12*	*12*	11	2	0.23
3	*7*	*4*	*4*	5	2	0.35
4	*6*	*2*	*3*	4	2	0.62
5	*6*	*4*	*4*	5	1	0.21
6	*5*	*1*	*2*	3	2	0.78
7	*6*	*6*	*6*	6	0	0.01
8	*3*	*6*	*6*	5	2	0.34

*Values shown in italics correspond to notch average pollutant concentrations that were below the gas analyzer detection limit.

TABLE A- 8. Measured PM Estimation Rates of the Prime Mover Engine of NC 1859 running on ULSD during Rail Yard Measurements

Time based PM Emission rate (g/s)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	0.03	0.03	0.03	0.03	0.00	0.02
High Idle	0.04	0.03	0.03	0.03	0.01	0.18
Dyn Brk						
1	0.05	0.04	0.04	0.04	0.01	0.14
2	0.05	0.04	0.04	0.04	0.00	0.05
3	0.06	0.06	0.06	0.06	0.00	0.03
4	0.07	0.07	0.07	0.07	0.00	0.04
5	0.10	0.12	0.12	0.11	0.01	0.07
6	0.13	0.14	0.14	0.14	0.01	0.06
7	0.19	0.20	0.21	0.20	0.01	0.04
8	0.24	0.25	0.24	0.24	0.01	0.02

Fuel based PM Emission rate (g/gal)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	51.8	51.6	53.1	52.2	0.8	0.02
High Idle	32.5	25.2	25.3	27.7	4.2	0.15
Dyn Brk						
1	19.5	14.9	14.8	16.4	2.7	0.16
2	13.5	12.0	11.9	12.5	0.9	0.07
3	9.7	9.0	9.0	9.3	0.4	0.04
4	7.6	8.6	8.6	8.3	0.6	0.07
5	8.5	9.9	9.9	9.4	0.8	0.09
6	8.7	9.8	9.8	9.4	0.6	0.06
7	8.7	9.2	9.2	9.1	0.3	0.03
8	9.3	10.0	9.1	9.5	0.5	0.05

Engine output based PM Emission rate (g/bhp-hr)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	10.62	10.95	10.94	10.83	0.19	0.02
High Idle	12.84	9.59	9.55	10.66	1.89	0.18
Dyn Brk						
1	0.86	0.69	0.68	0.75	0.10	0.14
2	0.49	0.45	0.44	0.46	0.02	0.05
3	0.32	0.30	0.30	0.31	0.01	0.03
4	0.25	0.27	0.27	0.26	0.01	0.04
5	0.28	0.32	0.32	0.31	0.02	0.07
6	0.29	0.32	0.32	0.31	0.02	0.06
7	0.31	0.33	0.33	0.32	0.01	0.04
8	0.32	0.33	0.32	0.32	0.01	0.02

Exhaust PM concentration (mg/m^3)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	8.2	8.4	8.5	8.4	0.2	0.02
High Idle	6.7	5.2	5.1	5.7	0.9	0.16
Dyn Brk						
1	8.6	6.8	6.8	7.4	1.1	0.14
2	8.9	8.1	8.1	8.4	0.4	0.05
3	8.5	8.0	8.1	8.2	0.3	0.03
4	8.4	9.0	9.0	8.8	0.3	0.04
5	10.7	12.1	12.1	11.6	0.8	0.07
6	11.4	12.9	12.9	12.4	0.9	0.07
7	14.2	15.2	15.3	14.9	0.6	0.04
8	14.4	14.7	14.6	14.6	0.1	0.01

TABLE A- 9. Measured Notch Average CO_2 Emission Rates of the Prime Mover Engine of NC 1859 running on ULSD during Rail Yard Measurements

Time based CO_2 Emission rate (g/s)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	8	8	8	8	0	0.02
High Idle	15	15	15	15	0	0.02
Dyn Brk						
1	33	34	34	34	1	0.03
2	49	50	50	50	1	0.02
3	86	87	87	86	1	0.01
4	126	118	118	121	5	0.04
5	171	166	166	168	3	0.02
6	205	204	203	204	1	0.01
7	307	309	310	309	2	0.00
8	364	344	362	357	11	0.03

Fuel based CO_2 Emission rate (g/gal)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	10058	10050	10049	10053	5	0.00
High Idle	10049	10041	10040	10043	5	0.00
Dyn Brk						
1	10061	10059	10059	10059	1	0.00
2	10065	10060	10060	10062	3	0.00
3	10068	10071	10071	10070	2	0.00
4	10070	10072	10072	10072	2	0.00
5	10071	10072	10072	10071	1	0.00
6	10071	10073	10073	10073	1	0.00
7	10058	10058	10058	10058	0	0.00
8	10063	10060	10061	10061	2	0.00

Engine output based CO_2 Emission rate (g/bhp-hr)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	2854	2951	2865	2890	53	0.02
High Idle	5489	5289	5253	5344	127	0.02
Dyn Brk						
1	618	647	644	637	16	0.03
2	502	518	517	512	9	0.02
3	457	465	462	461	4	0.01
4	463	435	434	444	17	0.04
5	465	453	453	457	7	0.02
6	461	460	456	459	3	0.01
7	494	497	499	496	2	0.00
8	486	458	482	475	15	0.03

Exhaust CO_2 concentration (vol %)						
Throttle	RailYard Test (RY)					
Notch	18-Nov	18-Nov	18-Nov	3 Rep	3 Rep	3 Rep
Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV
Low Idle	0.62	0.64	0.63	0.63	0.01	0.02
High Idle	0.82	0.81	0.80	0.81	0.01	0.01
Dyn Brk						
1	1.74	1.80	1.81	1.78	0.03	0.02
2	2.61	2.68	2.69	2.66	0.04	0.02
3	3.47	3.52	3.53	3.51	0.03	0.01
4	4.38	4.10	4.11	4.20	0.16	0.04
5	4.97	4.82	4.82	4.87	0.08	0.02
6	5.16	5.21	5.23	5.20	0.03	0.01
7	6.43	6.49	6.55	6.49	0.06	0.01
8	6.12	5.76	6.31	6.07	0.28	0.05

SEMTECH-DS was used simultaneously with Axion PEMS to measure FID HC (known as THC), NDIR HC, NDUV NO and NDUV NO_2 exhaust concentrations. SEMTECH measurements were used to estimate notch average bias correction factors for Axion measurements of HC and NO. Bias correction factors for HC and NO are defined as ratio of SEMTECH measurements of THC/HC, and NO_x/NO, respectively. Axion measurements of HC and NO when multiplied by the bias correction factors, give an estimate of THC and NO_x, respectively. SEMTECH THC and HC concentrations measurements are given in Table A-10. SEMTECH NO, NO_2 and NO_x concentrations measurements are given in Table A-11.

TABLE A- 10. Notch average total hydrocarbon and hydrocarbon SEMTECH-DS measured concentrations during the November 2015 railyard test of locomotive NC 1859

Throttle Notch position	**SEMTECH-DS Measured Exhaust Concentrations**					
	THC (ppm)			HC (ppm)		
	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
Low Idle	44.0	45.0	43.2	9.9	9.7	9.7
High Idle	48.6	42.8	45.5	9.5	9.5	9.4
1	22.6	25.2	31.4	5.8	5.7	5.2
2	23.6	34.4	29.2	5.9	9.6	6.0
3	23.0	28.4	25.2	6.9	9.0	6.3
4	27.8	25.3	22.9	7.7	8.2	7.2
5	25.0	24.1	22.0	8.1	8.6	7.8
6	23.3	22.5	23.6	8.2	8.8	8.4
7	48.4	48.7	48.6	8.9	8.9	9.1
8	45.5	49.1	47.7	9.1	9.3	9.9

TABLE A- 11**.** Notch average nitrogen oxide, nitrogen dioxide and oxides of nitrogen SEMTECH-DS measured concentrations during the November 2015 railyard test of locomotive NC 1859

Throttle Notch position	**SEMTECH-DS Measured Exhaust Concentrations**								
	NO (ppm)			NO_2 (ppm)			NO_x (ppm)		
	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
Low Idle	135	149	88	5	0	0	140	149	88
High Idle	150	141	140	3	1	1	152	142	141
1	286	296	288	16	3	6	302	298	294
2	422	503	485	19	14	15	441	517	500
3	660	702	686	31	27	26	691	729	713
4	810	789	787	34	33	32	844	822	819
5	846	835	829	32	35	33	878	870	862
6	841	836	829	31	37	32	872	872	861
7	826	859	802	30	30	30	856	888	832
8	747	707	736	30	32	31	777	739	766

Appendix B. Detailed Results for Baseline Over-the-Rail Tests on NC 1859

The baseline OTR PME exhaust concentration measurements on locomotive NC 1859 were conducted during November, 2015 and April, 2016. The 2015 measurement was with NC 1859 operated in tandem with another locomotive, with each sharing 50 percent load. The train consist included two locomotives, four passenger cars and one baggage/café car. The 2016 measurement was with a single locomotive and typical Piedmont train consist of two passenger cars and one baggage/café car. The locomotive was operated on ULSD. Axion PEMS was used to measure CO_2, CO, HC, NO and PM. Six one-way trips between Raleigh and Charlotte were conducted for each train consist.

B.1 Tandem Locomotive Operation

Three days of over-the-rail measurements on the NC 1859 prime mover engine were conducted on November 25-27, 2015 on trains 75 and 76 running between Raleigh and Charlotte. Results for the over-the-rail measurements are presented and discussed in this section.

There was little variability between measured engine activity data during all three days of measurements. This indicates that the prime mover engine was operating consistently during over-the-rail measurements. Measured engine activity data during over-the-rail measurements were similar to the measured engine activity data during rail yard measurements.

Over-the-rail cycle average NO_x and PM emission rates are lower than during rail yard measurements. Cycle average HC and CO emission rates for OTR are similar to RY measurements. Differences in cycle average emission rates between rail yard and over-the-rail measurements can be attributed to various factors. RPM and MAP was essentially the same for rail yard and over-the-rail measurements. IAT differed on an absolute basis by less than 6 percent from run-to-run during over-the-rail measurements. At Notch 8, the engine output during rail yard measurements was 2700 horsepower, while engine output was 3000 horsepower during over-the-rail measurements. With Notch 8 accounting for 16 percent of the EPA line-haul duty cycle used to estimate cycle average emission rates, higher engine output decreases engine output-based emission rates and, therefore, cycle average emission rates. Finally, differences in measured exhaust concentrations between rail yard and over-the-rail measurements lead to differences in FUER.

Throttle notch position data was obtained from the locomotive data activity recorder to measure the duty cycles for the over-the-rail measurements. The prime mover engine operated in Notch 8 during the over-the-rail tests more than double the percentage of time, on average, the EPA estimates a line-haul locomotive is operating in Notch 8. The average percentage of time the prime mover engine operated in idle through Notch 7 during the over-the-rail tests was lower than the percentage of time the EPA estimates a line-haul locomotive is operating in those throttle notch settings, with the exception of dynamic brake, where the amount of time spent during the six one-way trips is similar to the percentage of time allocated in the line-haul duty cycle.

Table B-1 summarizes the average measured engine speed (RPM), intake air temperature (IAT), and manifold absolute pressure (MAP) for each throttle notch position and for each replicate of the rail yard (RY) test and for each one-way over-the-rail (OTR) trip. The volumetric efficiency and air to fuel ratios are summarized in Table B-2 Engine speed ranges from 238 to 904 RPM in both RY and OTR measurements. For the RY measurements, engine RPM is highly repeatable, with a standard deviation of less than 1 RPM for all notch positions. For the OTR measurements, the RPM is also repeatable, with a standard deviation of less than 1 RPM, except in dynamic braking, which is a transient mode of operation. The intake air temperature varies with ambient temperature and was generally in the range of 58 to 85 degrees C during all measurements. MAP was highly repeatable in the RY tests, ranging from 98 to 223 kPa with an inter-test standard deviation of less than 3 kPa for most notch settings. For OTR measurements, there is slightly more inter-trip variability. However, the ratio of the standard deviation to the mean of the run average MAP values for each notch position is typically 0.02 or less. Overall, the engine activity during the measurements was consistent from test to test for the three replicates in the rail yard, and from run to run for the five one-way trips observed between Raleigh and Charlotte.

Table B-3 summarizes the estimated notch average fuel use rates inferred from the engine data of Table B-1. For the RY tests, notch average fuel use rates range from 3.0 to 114 g/sec depending on notch position, and were highly repeatable, with a coefficient of variation (CV, which is standard deviation divided by the mean) of typically 0.04 or less at high engine load. There is more variability in run-to-run estimates of fuel use for the OTR measurements, in part because the amount of time spent in some notch positions was low. The OTR estimated fuel use ranged from 3 to 106 g/sec, with CV ranging from 0.02 to 0.14.

The cycle average over-the-rail emission rates are quantitatively similar to the cycle average rail yard emission rates measured in November 2015. There was less than one percent variability amongst the five one-way trips with regard to cycle average NO_x emission rates. The cycle average over-the-rail NO_x emission rate over five one-way trips was 13 percent lower than the cycle average rail yard NO_x emission rates. The cycle average rates of PM for five one-way trips were 25 percent lower than the railyard tests, while differences in CO and HC cycle average rates were not statistically significant as CO and HC exhaust concentrations were below the detection limit of instrument. Differences in notch average emission rates are attributable to differences in measured exhaust concentrations as the engine activity parameters (RPM, IAT, and MAP) were similar across all measurements. Detailed notch average measured concentrations and FUER are given in Table B-4 through Table B-8.

TABLE B- 1. Measured and Estimated Parameters of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements and operated in Tandem

Engine Speed (RPM)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	238	238	238	237	238	-	238	0.27	0.00
High Idle	370	370	371	370	370	-	370	0.42	0.00
DB[a]	398	372	397	367	387	-	384	13.98	0.04
1	370	370	370	370	370	-	370	0.20	0.00
2	369	368	369	370	370	-	369	0.87	0.00
3	493	492	492	495	492	-	493	1.12	0.00
4	564	564	565	565	565	-	565	0.15	0.00
5	652	652	652	652	651	-	652	0.30	0.00
6	730	729	729	730	729	-	730	0.38	0.00
7	821	820	-	820	820	-	820	0.63	0.00
8	903	902	902	902	903	-	902	0.35	0.00

Intake Air Temperature (°C)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	75	75	72	74	78	-	74	2.23	0.03
High Idle	75	75	78	76	80	-	77	2.03	0.03
DB[a]	74	75	76	76	80	-	76	2.27	0.03
1	75	74	77	71	80	-	75	3.23	0.04
2	75	74	75	74	79	-	75	1.84	0.02
3	72	76	73	71	77	-	74	2.69	0.04
4	75	75	77	78	79	-	77	1.96	0.03
5	74	75	77	75	78	-	76	1.65	0.02
6	76	75	75	76	80	-	77	2.10	0.03
7	78	75	-	75	82	-	78	3.31	0.04
8	75	74	77	75	78	-	76	1.66	0.02

Manifold Absolute Pressure (kPa)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	98	98	99	97	97	-	98	0.66	0.01
High Idle	107	107	107	106	105	-	106	0.84	0.01
DB[a]	108	107	109	106	107	-	108	1.31	0.01
1	107	107	107	106	105	-	106	0.91	0.01
2	107	107	108	107	106	-	107	0.75	0.01
3	120	120	119	118	117	-	119	1.13	0.01
4	129	129	131	129	127	-	129	1.50	0.01
5	144	145	144	143	140	-	143	1.61	0.01
6	160	162	158	158	155	-	159	2.58	0.02
7	189	189	-	195	178	-	188	7.19	0.04
8	222	223	210	211	208	-	215	6.96	0.03

Mass Air Flow (g/s)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	845	843	854	841	828	-	842	9.54	0.01
High Idle	1242	1243	1232	1234	1206	-	1231	14.89	0.01
DB[a]	1329	1246	1328	1229	1265	-	1279	46.64	0.04
1	1246	1247	1235	1249	1209	-	1237	16.69	0.01
2	1247	1244	1247	1248	1220	-	1241	12.04	0.01
3	1689	1668	1680	1683	1633	-	1671	22.27	0.01
4	1960	1966	1973	1939	1912	-	1950	24.70	0.01
5	2371	2380	2350	2359	2301	-	2352	30.96	0.01
6	2772	2817	2751	2760	2681	-	2756	49.15	0.02
7	3417	3446	-	3536	3231	-	3408	128.36	0.04
8	4175	4193	3980	4020	3940	-	4062	115.21	0.03

TABLE B- 2. Estimated Air/Fuel Ratio and Volumetric Efficiency of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements and operated in Tandem

Air to Fuel Ratio (g/g)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	288	289	291	281	297	-	289	5.82	0.02
High Idle	213	199	239	229	204	-	217	16.75	0.08
DB[a]	240	260	233	249	243	-	245	10.22	0.04
1	129	127	133	127	142	-	132	6.40	0.05
2	82	84	83	94	87	-	86	4.63	0.05
3	62	63	63	66	63	-	63	1.62	0.03
4	51	51	54	55	51	-	52	1.81	0.03
5	45	46	45	45	46	-	46	0.78	0.02
6	43	45	49	51	45	-	47	3.34	0.07
7	35	36	-	40	34	-	36	2.59	0.07
8	34	35	42	42	41	-	39	4.06	0.10

Volumetric Efficiency									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	1.66	1.66	1.66	1.66	1.66	-	1.66	0.00	0.00
High Idle	1.44	1.43	1.44	1.44	1.44	-	1.44	0.00	0.00
DB[a]	1.40	1.43	1.40	1.44	1.42	-	1.42	0.02	0.01
1	1.43	1.43	1.44	1.44	1.44	-	1.44	0.00	0.00
2	1.43	1.44	1.43	1.43	1.44	-	1.44	0.00	0.00
3	1.29	1.29	1.29	1.29	1.29	-	1.29	0.00	0.00
4	1.21	1.21	1.21	1.21	1.22	-	1.21	0.00	0.00
5	1.13	1.13	1.13	1.13	1.14	-	1.13	0.00	0.00
6	1.07	1.06	1.07	1.07	1.08	-	1.07	0.00	0.00
7	0.99	0.99	-	0.98	1.00	-	0.99	0.01	0.01
8	0.92	0.92	0.93	0.93	0.94	-	0.93	0.01	0.01

TABLE B- 3. Estimated Notch Average Fuel Use Rates of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements and operated in Tandem

Time based fuel use rate (g/s)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	3	3	3	3	3	-	3	0	0.03
High Idle	6	6	5	5	6	-	6	0	0.08
DB[a]	6	5	6	5	5	-	5	0	0.07
1	10	10	9	10	8	-	9	1	0.06
2	15	15	15	13	14	-	14	1	0.05
3	27	27	27	25	26	-	26	1	0.03
4	39	39	37	36	37	-	37	1	0.04
5	52	51	52	53	50	-	52	1	0.02
6	65	63	56	54	59	-	60	4	0.07
7	97	96	-	89	96	-	95	4	0.04
8	124	120	122	123	119	-	122	2	0.02

Engine output based fuel use rate (g/bhp-hr)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	2.8	2.8	2.8	2.7	2.9	-	2.8	0.1	0.03
High Idle	1.4	1.3	1.6	1.5	1.4	-	1.4	0.1	0.08
DB[a]	1.5	1.7	1.4	1.6	1.6	-	1.6	0.1	0.07
1	15.9	15.7	16.6	15.6	18.1	-	16.4	1.0	0.06
2	18.6	19.1	18.7	21.2	20.1	-	19.6	1.1	0.05
3	20.0	20.5	20.4	21.4	20.9	-	20.6	0.5	0.03
4	20.9	20.8	21.9	22.7	21.6	-	21.6	0.8	0.04
5	20.5	20.9	20.6	20.3	21.6	-	20.8	0.5	0.03
6	20.0	20.5	22.9	24.0	21.8	-	21.8	1.6	0.08
7	19.9	20.1	-	21.8	20.3	-	20.5	0.9	0.04
8	19.6	20.2	19.9	19.7	20.3	-	19.9	0.3	0.02

TABLE B- 4. Measured Notch Average NO_x Emission Rates of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements and operated in Tandem

Time based NO_x Emission rate (g/s)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	0.25	0.25	0.22	0.24	0.21	-	0.24	0.02	0.07
High Idle	0.40	0.44	0.32	0.34	0.37	-	0.38	0.05	0.12
DB[a]	0.35	0.32	0.33	0.30	0.31	-	0.32	0.02	0.07
1	0.68	0.69	0.58	0.63	0.54	-	0.62	0.07	0.10
2	1.17	1.14	1.04	0.93	0.99	-	1.05	0.10	0.10
3	2.19	2.21	1.97	1.31	1.97	-	1.93	0.37	0.19
4	3.08	3.20	2.75	2.70	2.78	-	2.90	0.22	0.08
5	3.92	3.92	3.64	3.80	3.35	-	3.73	0.24	0.06
6	4.65	4.69	3.58	3.62	3.82	-	4.07	0.55	0.14
7	5.67	5.68	-	5.92	5.01	-	5.57	0.39	0.07
8	6.09	6.20	4.31	4.57	4.30	-	5.09	0.97	0.19

Fuel based NO_x Emission rate (g/gal)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	272	277	246	256	247	-	260	14	0.05
High Idle	223	225	199	205	204	-	211	12	0.06
DB[a]	206	214	185	196	190	-	198	12	0.06
1	228	226	203	206	203	-	213	13	0.06
2	248	249	222	223	227	-	234	14	0.06
3	259	267	237	166	243	-	234	40	0.17
4	257	265	241	244	240	-	249	11	0.04
5	241	247	225	232	218	-	233	12	0.05
6	232	239	204	216	207	-	220	15	0.07
7	187	190	-	214	169	-	190	19	0.10
8	158	166	147	153	142	-	154	9	0.06

Engine output based NO_x Emission rate (g/bhp-hr)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	89.5	90.1	80.7	85.7	77.1	-	84.6	5.7	0.07
High Idle	145.3	157.1	114.6	123.7	134.7	-	135.0	16.9	0.12
DB[a]	127.7	114.5	117.9	108.1	110.3	-	115.7	7.7	0.07
1	12.9	13.1	11.1	11.9	10.2	-	11.8	1.2	0.10
2	12.0	11.8	10.7	9.5	10.2	-	10.8	1.0	0.10
3	11.7	11.8	10.5	7.0	10.5	-	10.3	2.0	0.19
4	11.1	11.5	9.9	9.7	10.0	-	10.5	0.8	0.08
5	10.6	10.7	9.9	10.3	9.1	-	10.1	0.7	0.06
6	10.5	10.5	8.1	8.1	8.6	-	9.2	1.2	0.14
7	8.5	8.5	-	8.9	7.5	-	8.4	0.6	0.07
8	7.3	7.4	5.7	6.1	5.2	-	6.3	1.0	0.16

Exhaust NO_x concentration (ppm)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	182	183	163	175	160	-	173	10	0.06
High Idle	200	216	160	172	192	-	188	22	0.12
DB[a]	164	157	153	150	150	-	155	6	0.04
1	340	342	296	314	277	-	314	28	0.09
2	586	574	524	466	513	-	533	49	0.09
3	818	830	747	520	761	-	735	125	0.17
4	991	1025	884	875	920	-	939	66	0.07
5	1045	1046	980	1022	928	-	1004	50	0.05
6	1063	1056	827	828	907	-	936	117	0.12
7	1066	1060	-	1021	1008	-	1039	29	0.03
8	950	961	911	933	987	-	948	29	0.03

TABLE B- 5. Measured CO Estimation rates of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements and operated in Tandem

*Time based CO Emission rate (g/s)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	0.004	0.008	0.007	*0.009*	*0.012*	-	0.008	0.003	0.35
High Idle	0.014	0.020	0.039	*0.032*	*0.016*	-	0.024	0.011	0.44
DB[a]	0.016	0.022	0.018	*0.021*	*0.011*	-	0.018	0.005	0.26
1	0.012	0.017	0.019	*0.009*	*0.020*	-	0.015	0.005	0.32
2	0.012	0.008	0.010	*0.014*	*0.012*	-	0.011	0.002	0.18
3	0.006	0.012	0.002	*0.011*	*0.014*	-	0.009	0.005	0.54
4	0.016	0.043	0.060	*0.030*	*0.020*	-	0.034	0.018	0.53
5	0.016	0.017	0.027	*0.136*	*0.025*	-	0.044	0.052	1.17
6	0.045	0.084	0.054	*0.045*	*0.038*	-	0.053	0.018	0.34
7	0.258	0.359	-	*0.218*	*0.145*	-	0.245	0.089	0.36
8	0.450	0.349	0.314	*0.285*	*0.378*	-	0.355	0.064	0.18

*Fuel based CO Emission rate (g/gal)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	4.8	9.2	8.2	9.4	14.2	-	9.1	3.4	0.37
High Idle	7.8	10.1	24.3	18.9	8.9	-	14.0	7.2	0.52
DB[a]	9.3	14.8	10.4	14.0	6.6	-	11.0	3.4	0.31
1	4.0	5.4	6.7	2.8	7.5	-	5.3	1.9	0.36
2	2.5	1.8	2.1	3.3	2.7	-	2.5	0.6	0.23
3	0.7	1.4	0.3	1.4	1.7	-	1.1	0.6	0.00
4	1.3	3.6	5.2	2.7	1.7	-	2.9	1.6	0.54
5	1.0	1.0	1.7	8.3	1.6	-	2.7	3.1	0.00
6	2.3	4.3	3.1	2.7	2.0	-	2.9	0.9	0.31
7	8.5	12.0	-	7.9	4.9	-	8.3	2.9	0.35
8	11.7	9.4	10.8	9.6	12.5	-	10.8	1.3	0.12

*Engine output based CO Emission rate (g/bhp-hr)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	1.57	2.98	2.68	3.15	4.43	-	2.96	1.03	0.35
High Idle	5.06	7.03	13.99	11.41	5.91	-	8.68	3.84	0.44
DB[a]	5.74	7.91	6.64	7.73	3.84	-	6.37	1.66	0.26
1	0.23	0.31	0.37	0.16	0.38	-	0.29	0.09	0.32
2	0.12	0.09	0.10	0.14	0.12	-	0.11	0.02	0.18
3	0.03	0.06	0.01	0.06	0.07	-	0.05	0.03	0.54
4	0.06	0.16	0.22	0.11	0.07	-	0.12	0.06	0.53
5	0.04	0.05	0.07	0.37	0.07	-	0.12	0.14	1.17
6	0.10	0.19	0.12	0.10	0.08	-	0.12	0.04	0.34
7	0.39	0.54	-	0.33	0.22	-	0.37	0.13	0.36
8	0.54	0.42	0.42	0.38	0.45	-	0.44	0.06	0.14

*Exhaust CO concentration (vol %)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	0.004	0.008	0.007	*0.009*	*0.012*	-	0.008	0.003	0.35
High Idle	0.014	0.020	0.039	*0.032*	*0.016*	-	0.024	0.011	0.44
DB[a]	0.016	0.022	0.018	*0.021*	*0.011*	-	0.018	0.005	0.26
1	0.012	0.017	0.019	*0.009*	*0.020*	-	0.015	0.005	0.32
2	0.012	0.008	0.010	*0.014*	*0.012*	-	0.011	0.002	0.18
3	0.006	0.012	0.002	*0.011*	*0.014*	-	0.009	0.005	0.00
4	0.016	0.043	0.060	*0.030*	*0.020*	-	0.034	0.018	0.53
5	0.016	0.017	0.027	*0.136*	*0.025*	-	0.044	0.052	0.00
6	0.045	0.084	0.054	*0.045*	*0.038*	-	0.053	0.018	0.34
7	0.258	0.359	-	*0.218*	*0.145*	-	0.245	0.089	0.36
8	0.450	0.349	0.314	*0.285*	*0.378*	-	0.355	0.064	0.18

*Values shown in italics correspond to notch average pollutant concentrations that were below the gas analyzer detection limit.

TABLE B- 6. Measured Notch Average HC Emission Rates of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements and operated in Tandem

*Time based HC Emission rate (g/s)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	0.034	0.035	0.049	*0.031*	*0.066*	-	0.043	0.014	0.33
High Idle	0.059	0.088	0.081	*0.051*	*0.073*	-	0.071	0.016	0.22
DB[a]	0.088	0.052	0.100	*0.067*	*0.085*	-	0.078	0.019	0.24
1	0.051	0.066	0.050	*0.039*	*0.066*	-	0.054	0.012	0.21
2	0.048	0.055	0.067	*0.035*	*0.043*	-	0.050	0.012	0.24
3	0.055	0.077	0.025	*0.080*	*0.081*	-	0.064	0.024	0.38
4	0.064	0.123	0.272	*0.060*	*0.095*	-	0.123	0.087	0.71
5	0.068	0.112	0.084	*0.069*	*0.079*	-	0.082	0.018	0.21
6	0.114	0.185	0.417	*0.079*	*0.097*	-	0.179	0.139	0.78
7	0.116	0.421	-	*0.077*	*0.051*	-	0.166	0.172	1.04
8	0.165	0.130	0.148	*0.104*	*0.113*	-	0.132	0.025	0.19

*Fuel based HC Emission rate (g/gal)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	37.6	38.8	53.5	33.3	75.7	-	47.8	17.4	0.4
High Idle	32.6	45.6	50.7	30.3	39.9	-	39.8	8.6	0.2
DB[a]	51.0	35.2	56.5	43.9	52.5	-	47.8	8.4	0.2
1	17.0	21.6	17.5	12.8	25.2	-	18.8	4.7	0.3
2	10.2	12.0	14.2	8.6	9.8	-	11.0	2.2	0.2
3	6.5	9.3	3.0	10.2	10.0	-	7.8	3.1	0.4
4	5.4	10.1	23.7	5.4	8.2	-	10.6	7.6	0.7
5	4.2	7.0	5.2	4.3	5.2	-	5.2	1.1	0.2
6	5.7	9.4	23.8	4.7	5.3	-	9.8	8.0	0.8
7	3.8	14.1	-	2.8	1.7	-	5.6	5.7	1.0
8	4.3	3.5	5.1	3.5	3.7	-	4.0	0.7	0.2

*Engine output based HC Emission rate (g/bhp-hr)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	12.36	12.63	17.54	11.12	23.59	-	15.45	5.17	0.33
High Idle	21.26	31.80	29.23	18.25	26.38	-	25.38	5.59	0.22
DB[a]	31.64	18.88	35.99	24.20	30.56	-	28.25	6.72	0.24
1	0.97	1.24	0.95	0.74	1.26	-	1.03	0.22	0.21
2	0.49	0.57	0.69	0.36	0.44	-	0.51	0.12	0.24
3	0.29	0.41	0.13	0.43	0.43	-	0.34	0.13	0.38
4	0.23	0.44	0.98	0.22	0.34	-	0.44	0.31	0.71
5	0.19	0.30	0.23	0.19	0.22	-	0.22	0.05	0.21
6	0.26	0.42	0.94	0.18	0.22	-	0.40	0.31	0.78
7	0.17	0.63	-	0.12	0.08	-	0.25	0.26	1.04
8	0.20	0.16	0.20	0.14	0.14	-	0.17	0.03	0.19

*Exhaust HC concentration (ppm)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	*6*	*6*	*8*	*5*	*11*	-	7	2	0.35
High Idle	*7*	*10*	*9*	*6*	*8*	-	8	2	0.22
DB[a]	*9*	*6*	*11*	*8*	*9*	-	8	2	0.21
1	*6*	*7*	*6*	*4*	*8*	-	6	1	0.22
2	*5*	*6*	*8*	*4*	*5*	-	6	1	0.24
3	*5*	*7*	*2*	*7*	*7*	-	5	2	0.39
4	*5*	*9*	20	*4*	*7*	-	9	6	0.70
5	*4*	*7*	*5*	*4*	*5*	-	5	1	0.21
6	*6*	*9*	22	*4*	*5*	-	9	7	0.78
7	*5*	18	-	*3*	*2*	-	7	7	1.04
8	*6*	*5*	*5*	*4*	*4*	-	5	1	0.18

*Values shown in italics correspond to notch average pollutant concentrations that were below the gas analyzer detection limit.

TABLE B- 7. Measured PM Estimation Rates of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements and operated in Tandem

Time based PM Emission rate (g/s)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	0.03	0.03	0.03	0.03	0.03	-	0.03	0.00	0.04
High Idle	0.03	0.03	0.03	0.03	0.03	-	0.03	0.00	0.02
DB[a]	0.03	0.03	0.03	0.03	0.03	-	0.03	0.00	0.02
1	0.04	0.04	0.04	0.04	0.04	-	0.04	0.00	0.04
2	0.04	0.04	0.04	0.04	0.04	-	0.04	0.00	0.04
3	0.05	0.05	0.04	0.04	0.05	-	0.05	0.00	0.10
4	0.07	0.07	0.07	0.06	0.07	-	0.07	0.00	0.05
5	0.08	0.07	0.07	0.07	0.07	-	0.08	0.00	0.06
6	0.09	0.08	0.09	0.07	0.08	-	0.08	0.01	0.10
7	0.20	0.16	-	0.14	0.15	-	0.16	0.03	0.16
8	0.28	0.23	0.16	0.16	0.18	-	0.20	0.05	0.25

Fuel based PM Emission rate (g/gal)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	39.9	42.6	43.5	43.5	44.6	-	42.8	1.8	0.04
High Idle	24.2	23.5	27.1	26.5	24.1	-	25.1	1.6	0.06
DB[a]	23.2	27.6	23.9	27.8	25.8	-	25.7	2.1	0.08
1	17.8	17.0	17.5	16.0	19.9	-	17.6	1.5	0.08
2	12.8	12.5	12.3	13.2	13.6	-	12.9	0.5	0.04
3	8.8	8.1	7.4	7.3	8.8	-	8.1	0.7	0.09
4	8.1	7.6	8.7	8.0	8.2	-	8.1	0.4	0.05
5	7.1	6.5	6.2	6.3	6.5	-	6.5	0.3	0.05
6	6.4	5.9	7.2	5.9	6.1	-	6.3	0.5	0.09
7	9.1	7.6	-	7.0	7.1	-	7.7	1.0	0.13
8	9.9	8.5	7.4	7.6	8.2	-	8.3	1.0	0.12

Engine output based PM Emission rate (g/bhp-hr)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	9.48	10.01	10.31	10.51	10.05	-	10.07	0.39	0.04
High Idle	11.41	11.86	11.28	11.56	11.53	-	11.53	0.21	0.02
DB[a]	10.41	10.67	11.00	11.07	10.83	-	10.80	0.26	0.02
1	0.73	0.71	0.69	0.67	0.72	-	0.70	0.02	0.04
2	0.45	0.43	0.43	0.41	0.44	-	0.43	0.02	0.04
3	0.29	0.26	0.24	0.22	0.27	-	0.26	0.03	0.10
4	0.25	0.24	0.26	0.23	0.25	-	0.25	0.01	0.05
5	0.23	0.20	0.20	0.20	0.20	-	0.20	0.01	0.06
6	0.21	0.19	0.21	0.16	0.18	-	0.19	0.02	0.10
7	0.30	0.25	-	0.22	0.23	-	0.25	0.04	0.14
8	0.33	0.27	0.21	0.22	0.21	-	0.25	0.05	0.21

Exhaust PM concentration (mg/m^3)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	7.5	7.9	8.1	8.3	8.1	-	8.0	0.3	0.04
High Idle	6.1	6.3	6.1	6.2	6.4	-	6.2	0.1	0.02
DB[a]	5.2	5.7	5.5	6.0	5.7	-	5.6	0.3	0.05
1	7.4	7.2	7.2	6.8	7.6	-	7.3	0.3	0.04
2	8.5	8.1	8.2	7.8	8.6	-	8.2	0.3	0.04
3	7.8	7.1	6.6	6.4	7.7	-	7.1	0.6	0.09
4	8.8	8.2	9.0	8.0	8.9	-	8.6	0.4	0.05
5	8.6	7.7	7.5	7.8	7.8	-	7.9	0.4	0.05
6	8.2	7.4	8.2	6.3	7.6	-	7.5	0.8	0.10
7	14.6	12.0	-	10.3	11.9	-	12.2	1.8	0.15
8	16.7	13.8	9.9	10.1	11.4	-	12.4	2.9	0.23

TABLE B- 8. Measured Notch Average CO_2 Emission Rates of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements and operated in Tandem

Time based CO_2 Emission rate (g/s)

Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	9	9	9	9	9	-	9	0	0.03
High Idle	18	19	16	17	18	-	18	1	0.08
DB[a]	17	15	18	15	16	-	16	1	0.07
1	30	31	29	31	27	-	29	2	0.06
2	47	46	47	42	44	-	45	2	0.05
3	85	83	84	80	82	-	83	2	0.03
4	121	122	115	111	117	-	117	4	0.04
5	164	160	163	164	155	-	161	4	0.02
6	202	197	176	169	186	-	186	14	0.07
7	304	301	-	278	299	-	295	12	0.04
8	387	375	294	299	304	-	332	45	0.14

Fuel based CO_2 Emission rate (g/gal)

Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	10044	10036	10029	10039	10005	-	10031	15	0.00
High Idle	10042	10030	10005	10026	10036	-	10028	14	0.00
DB[a]	10028	10029	10023	10025	10032	-	10028	3	0.00
1	10058	10052	10053	10062	10047	-	10054	6	0.00
2	10064	10064	10062	10064	10064	-	10064	1	0.00
3	10069	10066	10072	10066	10065	-	10068	3	0.00
4	10069	10062	10051	10067	10066	-	10063	7	0.00
5	10070	10068	10068	10059	10069	-	10067	5	0.00
6	10067	10062	10055	10067	10068	-	10064	6	0.00
7	10058	10047	-	10060	10066	-	10058	8	0.00
8	10053	10057	10054	10057	10052	-	10055	2	0.00

Engine output based CO_2 Emission rate (g/bhp-hr)

Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	3299	3267	3286	3358	3118	-	3266	89	0.03
High Idle	6542	6989	5765	6039	6634	-	6394	488	0.08
DB[a]	6217	5375	6386	5525	5836	-	5868	434	0.07
1	571	580	548	582	502	-	556	33	0.06
2	488	475	485	429	453	-	466	25	0.05
3	454	444	447	425	435	-	441	11	0.03
4	435	438	414	400	420	-	421	15	0.04
5	445	435	442	447	421	-	438	11	0.02
6	454	444	397	379	418	-	418	31	0.07
7	456	451	-	416	448	-	443	18	0.04
8	464	450	391	399	364	-	414	42	0.10

Exhaust CO_2 concentration (vol %)

Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6[b]	5 Trips Avg	5 Trips Std Dev	5 Trips CV
Low Idle	0.74	0.73	0.73	0.76	0.71	-	0.73	0.02	0.02
High Idle	0.99	1.06	0.89	0.92	1.04	-	0.98	0.07	0.08
DB[a]	0.88	0.81	0.91	0.85	0.87	-	0.86	0.04	0.04
1	1.65	1.67	1.61	1.69	1.51	-	1.63	0.07	0.04
2	2.62	2.55	2.62	2.31	2.51	-	2.52	0.13	0.05
3	3.50	3.44	3.49	3.48	3.47	-	3.47	0.02	0.01
4	4.28	4.29	4.06	3.97	4.25	-	4.17	0.15	0.03
5	4.81	4.70	4.82	4.87	4.72	-	4.78	0.07	0.02
6	5.08	4.89	4.48	4.25	4.85	-	4.71	0.34	0.07
7	6.30	6.18	-	5.27	6.62	-	6.09	0.58	0.09
8	6.64	6.39	6.80	6.33	6.22	-	6.48	0.24	0.04

B.2 Single Locomotive Operation

Several days of over-the-rail measurements on the NC 1859 prime mover engine were conducted in April 2016 on trains 75 and 76 running between Raleigh and Charlotte. The goal of the measurements was to get data for 6 one-way trips. Measurements had to be repeated several days because of instruments leakage once and then a minor accident with the locomotive that resulted in PEMS shutdown. On both occasions, data collection had to be stopped. Results for the over-the-rail measurements are presented and discussed in this section.

There was little variability between measured engine activity data during all three days of measurements. This indicates that the prime mover engine was operating consistently during over-the-rail measurements. Measured engine activity data during over-the-rail measurements were similar to the measured engine activity data during rail yard measurements.

Notch average engine parameters and measured exhaust has and PM concentrations were similar to that of the locomotive in tandem operation. Thus, the mass air flow, volumetric efficiency and estimated notch average fuel use and emission rates were also similar. The only key difference between tandem and single operation was the duty cycle.

The use of two locomotives to pull 4 passenger cars and one baggage/café car instead of the usual one locomotive to pull 2 passenger cars and one baggage/café car did not require much power. The two locomotives were able to provide more than enough power. Thus, in tandem operation, higher fraction of time was spent at lower notch positions compared to single operation. Conversely, a lower fraction of time was spent at higher notch positions in tandem operation. Since, FUER increase with notch positions, lower fraction of time at higher notch positions resulted in lower trip total fuel use and emissions per locomotive.

TABLE B- 9. Measured and Estimated Parameters of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements

Engine Speed (RPM)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	238	238	238	238	238	237	238	0.42	0.00
High Idle	370	370	371	370	370	370	370	0.43	0.00
DB[a]	367	372	367	362	366	393	371	11.15	0.03
1	370	370	369	370	370	370	370	0.33	0.00
2	370	369	368	368	369	369	369	0.65	0.00
3	492	492	492	492	492	491	492	0.35	0.00
4	565	565	564	565	565	565	565	0.23	0.00
5	654	652	653	653	653	653	653	0.54	0.00
6	731	730	730	732	731	730	731	0.88	0.00
7	822	821	821	-	820	-	821	0.58	0.00
8	904	903	904	904	904	903	904	0.24	0.00

Intake Air Temperature (^oC)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	52	52	67	53	66	50	57	7.78	0.14
High Idle	53	55	67	52	67	52	58	7.39	0.13
DB[a]	52	53	67	53	68	53	57	7.50	0.13
1	56	51	66	52	68	54	58	7.29	0.13
2	55	51	66	53	66	59	58	6.60	0.11
3	55	50	67	51	67	51	57	8.07	0.14
4	49	52	68	52	67	52	57	8.58	0.15
5	53	52	67	50	67	51	57	8.05	0.14
6	60	51	64	66	69	49	60	8.04	0.13
7	72	57	69	-	69	-	67	6.83	0.10
8	54	55	67	54	67	54	59	6.68	0.11

Manifold Absolute Pressure (kPa)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	104	98	100	100	100	98	100	2.00	0.02
High Idle	107	107	109	109	108	106	108	1.15	0.01
DB[a]	107	107	109	108	108	108	108	0.78	0.01
1	107	108	109	109	109	107	108	1.08	0.01
2	108	108	111	109	109	107	109	1.27	0.01
3	121	120	123	123	120	119	121	1.68	0.01
4	129	130	135	132	130	130	131	2.26	0.02
5	145	146	150	149	144	143	146	2.81	0.02
6	163	163	164	171	160	158	163	4.57	0.03
7	220	187	191	-	180	-	194	17.53	0.09
8	229	226	231	225	218	218	225	5.39	0.02

Mass Air Flow (g/s)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	1027	904	879	914	882	905	918	54.84	0.06
High Idle	1325	1324	1295	1348	1282	1322	1316	23.80	0.02
DB[a]	1321	1335	1286	1317	1269	1403	1322	46.54	0.04
1	1311	1343	1296	1348	1285	1319	1317	25.01	0.02
2	1333	1345	1310	1346	1286	1303	1321	24.46	0.02
3	1788	1809	1752	1828	1716	1781	1779	40.37	0.02
4	2119	2109	2074	2136	2016	2113	2095	43.35	0.02
5	2552	2561	2503	2625	2434	2528	2534	63.90	0.03
6	2955	3036	2931	3030	2839	2986	2963	73.09	0.02
7	3907	3607	3547	-	3382	-	3611	219.31	0.06
8	4557	4494	4401	4494	4216	4388	4425	120.39	0.03

TABLE B- 10. Estimated Air/Fuel Ratio and Volumetric Efficiency of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements

Air to Fuel Ratio (g/g)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	213	282	362	307	284	286	289	47.81	0.17
High Idle	235	208	241	239	230	240	232	12.50	0.05
DB[a]	235	242	245	248	242	225	240	8.23	0.03
1	134	124	127	127	138	115	128	7.95	0.06
2	108	85	85	94	89	78	90	10.25	0.11
3	60	63	62	66	65	68	64	2.75	0.04
4	53	51	58	56	52	51	53	2.73	0.05
5	46	47	48	47	48	45	47	1.19	0.03
6	45	46	47	45	43	46	45	1.24	0.03
7	37	35	47	-	38	-	39	5.11	0.13
8	36	36	37	36	35	36	36	0.76	0.02

Volumetric Efficiency									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	1.58	1.66	1.65	1.65	1.65	1.66	1.64	0.03	0.02
High Idle	1.44	1.43	1.43	1.43	1.43	1.44	1.43	0.00	0.00
DB[a]	1.44	1.43	1.43	1.44	1.44	1.41	1.43	0.01	0.01
1	1.44	1.43	1.43	1.43	1.43	1.44	1.43	0.00	0.00
2	1.43	1.43	1.42	1.43	1.43	1.43	1.43	0.00	0.00
3	1.28	1.28	1.28	1.28	1.28	1.29	1.28	0.01	0.00
4	1.21	1.21	1.20	1.21	1.21	1.21	1.21	0.01	0.00
5	1.13	1.13	1.12	1.12	1.13	1.13	1.13	0.01	0.01
6	1.06	1.06	1.06	1.05	1.07	1.07	1.06	0.01	0.01
7	0.95	0.99	0.98	-	1.00	-	0.98	0.02	0.02
8	0.91	0.92	0.91	0.92	0.92	0.92	0.92	0.01	0.01

TABLE B- 11. Estimated Notch Average Fuel Use Rates of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements

Time based fuel use rate (g/s)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	5	3	2	3	3	3	3	1	0.24
High Idle	6	6	5	6	6	6	6	0	0.06
DB[a]	6	6	5	5	5	6	6	0	0.07
1	10	11	10	11	9	11	10	1	0.07
2	12	16	15	14	14	17	15	2	0.10
3	30	29	28	28	27	26	28	1	0.05
4	40	41	36	38	39	41	39	2	0.05
5	55	55	52	56	51	57	54	2	0.04
6	65	66	63	67	66	65	66	1	0.02
7	106	102	76	-	90	-	93	13	0.14
8	125	123	120	123	122	121	122	2	0.02

Engine output based fuel use rate (g/bhp-hr)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	1.7	2.5	3.3	2.7	2.6	3	2.6	0.5	0.21
High Idle	1.4	1.3	1.5	1.4	1.5	1	1.4	0.1	0.06
DB[a]	1.4	1.5	1.5	1.5	1.5	1	1.5	0.1	0.06
1	15.7	14.2	15.0	14.4	16.5	13	14.9	1.1	0.07
2	22.9	17.9	18.3	19.7	19.6	17	19.2	2.1	0.11
3	18.3	18.9	19.2	19.7	20.5	21	19.6	0.9	0.05
4	20.0	19.6	22.5	21.0	20.8	20	20.6	1.1	0.05
5	19.5	19.5	20.5	19.1	20.9	19	19.7	0.8	0.04
6	19.8	19.5	20.5	19.2	19.5	20	19.7	0.4	0.02
7	18.3	19.0	25.5	-	21.6	-	21.1	3.3	0.15
8	17.4	17.7	18.2	17.7	17.9	18	17.8	0.3	0.02

TABLE B- 12. Measured Notch Average NO_x Emission Rates of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements

Time based NO_x Emission rate (g/s)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	0.37	0.27	0.20	0.25	0.23	0.27	0.26	0.06	0.21
High Idle	0.35	0.44	0.35	0.37	0.33	0.35	0.36	0.04	0.11
DB[a]	0.35	0.38	0.35	0.35	0.33	0.40	0.36	0.02	0.07
1	0.60	0.74	0.68	0.70	0.56	0.76	0.67	0.08	0.12
2	0.80	1.23	1.07	1.06	0.89	1.24	1.05	0.18	0.17
3	2.30	2.35	2.23	2.26	1.83	2.07	2.18	0.19	0.09
4	2.98	3.38	2.78	3.07	2.71	3.32	3.04	0.27	0.09
5	3.97	4.22	3.86	4.18	3.42	4.06	3.95	0.29	0.07
6	4.48	4.87	4.20	5.08	4.11	4.52	4.54	0.37	0.08
7	6.34	5.85	4.43	-	4.65	-	5.32	0.92	0.17
8	6.30	6.71	6.25	6.52	5.51	6.14	6.24	0.41	0.07

Fuel based NO_x Emission rate (g/gal)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	244	275	268	270	241	270	261	15	0.06
High Idle	198	223	208	211	191	207	206	11	0.05
DB[a]	201	221	216	210	203	205	209	8	0.04
1	198	220	214	212	193	214	208	11	0.05
2	208	250	222	236	198	238	225	20	0.09
3	249	263	253	263	222	253	251	15	0.06
4	238	264	250	257	225	260	249	15	0.06
5	232	247	239	240	215	230	234	11	0.05
6	221	236	215	243	200	223	223	15	0.07
7	193	185	188	-	167	-	183	11	0.06
8	162	176	168	170	146	164	164	10	0.06

Engine output based NO_x Emission rate (g/bhp-hr)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	131.6	98.5	72.7	90.0	83.6	95.5	95.3	20.0	0.21
High Idle	125.2	158.9	124.7	132.7	118.8	127.0	131.2	14.3	0.11
DB[a]	126.5	136.3	126.9	124.9	119.1	142.5	129.4	8.5	0.07
1	11.4	14.0	12.9	13.3	10.5	14.4	12.7	1.5	0.12
2	8.2	12.6	11.0	10.9	9.1	12.7	10.8	1.8	0.17
3	12.3	12.6	11.9	12.1	9.8	11.0	11.6	1.0	0.09
4	10.7	12.2	10.0	11.0	9.8	12.0	10.9	1.0	0.09
5	10.8	11.5	10.5	11.4	9.3	11.0	10.7	0.8	0.07
6	10.1	10.9	9.5	11.4	9.3	10.2	10.2	0.8	0.08
7	9.5	8.8	6.6	-	7.0	-	8.0	1.4	0.17
8	8.4	9.0	8.3	8.7	7.3	8.2	8.3	0.5	0.07

Exhaust NO_x concentration (ppm)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	221	187	143	169	164	180	177	26	0.15
High Idle	162	204	166	169	160	165	171	17	0.10
DB[a]	164	174	169	162	161	173	167	6	0.03
1	286	341	327	323	271	356	317	33	0.10
2	377	569	515	488	435	593	496	81	0.16
3	807	816	805	772	676	722	767	56	0.07
4	885	1010	842	892	852	985	911	70	0.08
5	978	1043	976	1007	890	1007	983	52	0.05
6	948	1018	913	1055	917	946	966	58	0.06
7	1049	1045	782	-	898	-	943	129	0.14
8	900	967	928	945	855	893	915	40	0.04

TABLE B- 13. Measured CO Estimation rates of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements

*Time based CO Emission rate (g/s)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	*0.018*	*0.009*	*0.009*	*0.009*	*0.007*	*0.015*	0.011	0.004	0.39
High Idle	*0.041*	*0.022*	*0.029*	*0.060*	*0.012*	*0.024*	0.031	0.017	0.55
DB[a]	*0.031*	*0.026*	*0.023*	*0.076*	*0.010*	*0.022*	0.031	0.023	0.73
1	*0.014*	*0.021*	*0.007*	*0.012*	*0.013*	*0.014*	0.014	0.005	0.34
2	*0.017*	*0.020*	*0.013*	*0.008*	*0.011*	*0.016*	0.014	0.004	0.30
3	*0.023*	*0.015*	*0.016*	*0.022*	*0.012*	*0.028*	0.019	0.006	0.30
4	*0.012*	*0.015*	*0.047*	*0.011*	*0.034*	*0.029*	0.025	0.015	0.60
5	*0.131*	*0.034*	*0.104*	*0.025*	*0.034*	*0.023*	0.058	0.047	0.80
6	*0.073*	*0.051*	*0.100*	*0.068*	*0.017*	*0.010*	0.053	0.035	0.65
7	*0.494*	*0.186*	*0.075*	-	*0.000*	-	0.189	0.217	1.15
8	*0.381*	*0.307*	*0.287*	*0.296*	*0.393*	*0.464*	0.355	0.070	0.20

*Fuel based CO Emission rate (g/gal)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	*12.2*	*9.4*	*11.6*	*9.6*	*7.5*	*15.7*	11.0	2.8	0.26
High Idle	*23.4*	*10.9*	*17.4*	*34.4*	*6.8*	*14.2*	17.8	9.9	0.55
DB[a]	*17.6*	*15.0*	*14.2*	*46.0*	*6.0*	*11.6*	18.4	14.1	0.77
1	*4.8*	*6.3*	*2.2*	*3.5*	*4.5*	*4.0*	4.2	1.4	0.32
2	*4.5*	*4.1*	*2.7*	*1.8*	*2.5*	*3.0*	3.1	1.0	0.32
3	*2.5*	*1.7*	*1.8*	*2.6*	*1.4*	*3.4*	2.2	0.7	0.00
4	*0.9*	*1.2*	*4.3*	*0.9*	*2.8*	*2.3*	2.1	1.3	0.65
5	*7.7*	*2.0*	*6.4*	*1.4*	*2.2*	*1.3*	3.5	2.8	0.00
6	*3.6*	*2.5*	*5.1*	*3.3*	*0.8*	*0.5*	2.6	1.7	0.67
7	*15.0*	*5.9*	*3.2*	-	*0.0*	-	6.0	6.5	1.07
8	*9.8*	*8.0*	*7.7*	*7.7*	*10.4*	*12.4*	9.3	1.9	0.20

*Engine output based CO Emission rate (g/bhp-hr)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	*6.54*	*3.38*	*3.15*	*3.20*	*2.59*	*5.55*	4.07	1.58	0.39
High Idle	*14.78*	*7.76*	*10.45*	*21.67*	*4.22*	*8.72*	11.26	6.16	0.55
DB[a]	*11.07*	*9.22*	*8.31*	*27.34*	*3.53*	*8.05*	11.25	8.27	0.73
1	*0.27*	*0.40*	*0.13*	*0.22*	*0.24*	*0.27*	0.26	0.09	0.34
2	*0.18*	*0.20*	*0.14*	*0.08*	*0.11*	*0.16*	0.15	0.04	0.30
3	*0.12*	*0.08*	*0.09*	*0.12*	*0.06*	*0.15*	0.10	0.03	0.30
4	*0.04*	*0.05*	*0.17*	*0.04*	*0.12*	*0.10*	0.09	0.05	0.60
5	*0.36*	*0.09*	*0.28*	*0.07*	*0.09*	*0.06*	0.16	0.13	0.80
6	*0.16*	*0.12*	*0.22*	*0.15*	*0.04*	*0.02*	0.12	0.08	0.65
7	*0.74*	*0.28*	*0.11*	-	*0.00*	-	0.28	0.33	1.15
8	*0.51*	*0.41*	*0.38*	*0.39*	*0.52*	*0.62*	0.47	0.09	0.20

*Exhaust CO concentration (vol %)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	*0.002*	*0.001*	*0.001*	*0.001*	*0.001*	*0.002*	0.001	0.000	0.34
High Idle	*0.003*	*0.002*	*0.002*	*0.005*	*0.001*	*0.002*	0.003	0.001	0.53
DB[a]	*0.002*	*0.002*	*0.002*	*0.006*	*0.001*	*0.002*	0.003	0.002	0.74
1	*0.001*	*0.002*	*0.001*	*0.001*	*0.001*	*0.001*	0.001	0.000	0.33
2	*0.001*	*0.002*	*0.001*	*0.001*	*0.001*	*0.001*	0.001	0.000	0.29
3	*0.001*	*0.001*	*0.001*	*0.001*	*0.001*	*0.002*	0.001	0.000	0.00
4	*0.001*	*0.001*	*0.002*	*0.001*	*0.002*	*0.001*	0.001	0.001	0.61
5	*0.006*	*0.001*	*0.005*	*0.001*	*0.002*	*0.001*	0.003	0.002	0.00
6	*0.003*	*0.002*	*0.004*	*0.002*	*0.001*	*0.000*	0.002	0.001	0.66
7	*0.014*	*0.006*	*0.002*	-	*0.000*	-	0.006	0.006	1.12
8	*0.009*	*0.008*	*0.007*	*0.007*	*0.011*	*0.012*	0.009	0.002	0.20

*Values shown in italics correspond to notch average pollutant concentrations that were below the gas analyzer detection limit.

TABLE B- 14. Measured Notch Average HC Emission Rates of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements

*Time based HC Emission rate (g/s)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	*0.069*	*0.042*	*0.052*	*0.087*	*0.050*	0.092	0.065	0.021	0.32
High Idle	*0.090*	*0.114*	*0.111*	*0.097*	*0.078*	*0.122*	0.102	0.017	0.16
DB[a]	*0.108*	*0.105*	*0.080*	*0.127*	*0.090*	0.173	0.114	0.033	0.29
1	*0.070*	0.153	*0.092*	*0.093*	*0.077*	0.203	0.115	0.052	0.45
2	*0.057*	*0.091*	*0.111*	*0.093*	*0.074*	*0.091*	0.086	0.019	0.22
3	*0.071*	*0.132*	*0.067*	*0.095*	*0.077*	0.178	0.103	0.043	0.42
4	*0.198*	*0.130*	*0.077*	*0.083*	*0.096*	*0.172*	0.126	0.050	0.39
5	*0.184*	*0.151*	*0.220*	*0.109*	*0.101*	*0.173*	0.156	0.046	0.29
6	*0.222*	*0.143*	*0.189*	*0.145*	*0.145*	*0.177*	0.170	0.032	0.19
7	1.310	*0.080*	0.345	-	*0.222*	-	0.489	0.558	1.14
8	*0.309*	*0.306*	*0.186*	*0.226*	*0.126*	*0.267*	0.237	0.072	0.30

*Fuel based HC Emission rate (g/gal)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	*46.2*	*42.3*	*68.4*	*93.8*	*52.2*	93.6	66.1	23.2	0.4
High Idle	*51.2*	*57.6*	*66.4*	*55.4*	*45.0*	*71.4*	57.8	9.7	0.2
DB[a]	*61.5*	*61.2*	*48.9*	*76.6*	*55.1*	89.7	65.5	15.0	0.2
1	*23.1*	45.4	*28.9*	*28.0*	*26.8*	57.1	34.9	13.3	0.4
2	*14.7*	*18.5*	*23.1*	*20.8*	*16.4*	*17.5*	18.5	3.1	0.2
3	*7.6*	*14.8*	*7.6*	*11.0*	*9.4*	21.7	12.0	5.4	0.5
4	*15.8*	*10.2*	*6.9*	*6.9*	*8.0*	*13.4*	10.2	3.7	0.4
5	*10.8*	*8.9*	*13.6*	*6.3*	*6.3*	*9.8*	9.3	2.8	0.3
6	*10.9*	*6.9*	*9.7*	*6.9*	*7.0*	*8.7*	8.4	1.7	0.2
7	39.9	*2.5*	14.6	-	*8.0*	-	16.3	16.5	1.0
8	*7.9*	*8.0*	*5.0*	*5.9*	*3.3*	*7.1*	6.2	1.8	0.3

*Engine output based HC Emission rate (g/bhp-hr)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	*24.9*	*15.2*	*18.6*	*31.3*	*18.1*	33.1	23.51	7.45	0.32
High Idle	*32.3*	*41.0*	*39.9*	*34.9*	*28.0*	*43.9*	36.66	5.99	0.16
DB[a]	*38.7*	*37.8*	*28.7*	*45.6*	*32.3*	62.4	40.90	12.02	0.29
1	*1.3*	2.9	*1.7*	*1.8*	*1.5*	3.8	2.17	0.99	0.45
2	*0.6*	*0.9*	*1.1*	*1.0*	*0.8*	*0.9*	0.88	0.19	0.22
3	*0.4*	*0.7*	*0.4*	*0.5*	*0.4*	0.9	0.55	0.23	0.42
4	*0.7*	*0.5*	*0.3*	*0.3*	*0.3*	*0.6*	0.45	0.18	0.39
5	*0.5*	*0.4*	*0.6*	*0.3*	*0.3*	*0.5*	0.42	0.12	0.29
6	*0.5*	*0.3*	*0.4*	*0.3*	*0.3*	*0.4*	0.38	0.07	0.19
7	2.0	*0.1*	0.5	-	*0.3*	-	0.73	0.84	1.14
8	*0.4*	*0.4*	*0.2*	*0.3*	*0.2*	*0.4*	0.32	0.10	0.30

*Exhaust HC concentration (ppm)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	*9*	*6*	*8*	*13*	*8*	14	10	3	0.31
High Idle	*9*	*12*	*12*	*10*	*8*	*13*	11	2	0.16
DB[a]	*11*	*11*	*9*	*13*	*10*	17	12	3	0.26
1	*8*	16	*10*	*10*	*8*	21	12	5	0.44
2	*6*	*9*	*12*	*10*	*8*	*10*	9	2	0.22
3	*6*	*10*	*5*	*7*	*6*	14	8	3	0.41
4	*13*	*9*	*5*	*5*	*7*	*11*	8	3	0.39
5	*10*	*8*	*12*	*6*	*6*	*10*	9	3	0.29
6	*11*	*7*	*9*	*7*	*7*	*8*	8	2	0.19
7	49	*3*	14	-	*10*	-	19	20	1.08
8	*10*	*10*	*6*	*7*	*4*	*9*	8	2	0.28

*Values shown in italics correspond to notch average pollutant concentrations that were below the gas analyzer detection limit.

TABLE B- 15. Measured PM Estimation Rates of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements

Throttle Notch Position	Time based PM Emission rate (g/s)								
	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.00	0.04
High Idle	0.03	0.04	0.03	0.04	0.04	0.04	0.03	0.00	0.06
DB[a]	0.03	0.03	0.04	0.04	0.04	0.04	0.03	0.00	0.08
1	0.04	0.04	0.04	0.05	0.04	0.05	0.04	0.00	0.06
2	0.04	0.05	0.05	0.05	0.05	0.06	0.05	0.00	0.09
3	0.06	0.05	0.06	0.06	0.06	0.07	0.06	0.01	0.09
4	0.07	0.07	0.08	0.07	0.08	0.09	0.08	0.01	0.13
5	0.08	0.08	0.09	0.09	0.09	0.11	0.09	0.01	0.12
6	0.10	0.09	0.09	0.11	0.12	0.11	0.10	0.01	0.11
7	0.16	0.17	0.18	-	0.14	-	0.16	0.02	0.10
8	0.19	0.21	0.22	0.20	0.27	0.28	0.23	0.04	0.17

Throttle Notch Position	Fuel based PM Emission rate (g/gal)								
	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	31.2	42.1	59.4	47.5	48.6	47.5	46.0	9.2	0.20
High Idle	24.3	24.8	28.7	27.8	29.4	28.9	27.3	2.2	0.08
DB[a]	24.2	26.7	30.1	29.6	32.2	26.3	28.2	2.9	0.10
1	18.0	16.6	18.9	19.1	21.4	17.7	18.6	1.6	0.09
2	15.3	13.3	14.3	15.3	15.3	15.2	14.8	0.8	0.06
3	9.5	8.0	10.2	10.0	10.1	11.5	9.9	1.1	0.11
4	7.3	7.4	9.7	8.2	9.4	9.9	8.7	1.2	0.13
5	6.8	6.5	7.5	7.1	8.2	8.8	7.5	0.9	0.11
6	6.9	5.9	6.7	7.5	7.9	7.8	7.1	0.8	0.11
7	6.9	7.6	10.5	-	7.0	-	8.0	1.7	0.21
8	6.8	7.6	8.2	7.2	10.0	10.5	8.4	1.5	0.18

Throttle Notch Position	Engine output based PM Emission rate (g/bhp-hr)								
	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	12.15	10.88	11.65	11.44	12.18	12.14	11.74	0.52	0.04
High Idle	11.08	12.75	12.45	12.64	13.24	12.83	12.50	0.74	0.06
DB[a]	11.03	11.90	12.78	12.73	13.63	13.24	12.55	0.94	0.08
1	0.75	0.77	0.82	0.86	0.84	0.86	0.82	0.05	0.06
2	0.44	0.48	0.51	0.51	0.51	0.59	0.51	0.05	0.09
3	0.34	0.28	0.35	0.33	0.32	0.36	0.33	0.03	0.09
4	0.24	0.25	0.28	0.25	0.30	0.33	0.27	0.03	0.13
5	0.23	0.22	0.24	0.24	0.25	0.30	0.25	0.03	0.12
6	0.23	0.20	0.21	0.25	0.26	0.26	0.24	0.03	0.11
7	0.25	0.26	0.27	-	0.22	-	0.25	0.02	0.08
8	0.26	0.28	0.29	0.26	0.36	0.38	0.31	0.05	0.17

Throttle Notch Position	Exhaust PM concentration (mg/m^3)								
	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	7.9	8.0	8.9	8.3	9.3	8.9	8.6	0.6	0.06
High Idle	5.6	6.4	6.4	6.2	6.9	6.5	6.3	0.4	0.07
DB[a]	5.5	5.9	6.6	6.4	7.2	6.3	6.3	0.6	0.09
1	7.3	7.2	8.1	8.2	8.4	8.3	7.9	0.5	0.06
2	7.8	8.5	9.3	8.9	9.4	10.6	9.1	1.0	0.10
3	8.7	7.0	9.1	8.2	8.7	9.2	8.5	0.8	0.10
4	7.6	8.0	9.2	8.0	10.0	10.5	8.9	1.2	0.14
5	8.1	7.7	8.6	8.3	9.5	10.8	8.8	1.1	0.13
6	8.3	7.2	7.9	9.1	10.2	9.3	8.7	1.1	0.12
7	10.6	12.0	12.2	-	10.3	-	11.3	1.0	0.09
8	10.6	11.8	12.7	11.2	16.4	16.0	13.1	2.5	0.19

TABLE B- 16. Measured Notch Average CO_2 Emission Rates of the Prime Mover Engine of NC 1859 running on ULSD during Over-the-Rail measurements

Time based CO_2 Emission rate (g/s)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	15	10	8	9	10	10	10	3	0.25
High Idle	18	20	17	17	17	17	18	1	0.06
DB[a]	18	17	16	16	16	19	17	1	0.07
1	31	34	32	33	29	36	32	2	0.07
2	39	49	48	45	45	52	46	5	0.10
3	93	90	89	87	83	82	87	4	0.05
4	126	129	112	120	121	129	123	6	0.05
5	172	172	163	175	160	177	170	7	0.04
6	204	208	197	210	207	204	205	5	0.02
7	330	318	237	-	281	-	291	42	0.14
8	391	385	373	385	380	377	382	6	0.02

Fuel based CO_2 Emission rate (g/gal)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	10027	10033	10014	10002	10030	9992	10016	17	0.00
High Idle	10006	10022	10006	9986	10036	10008	10011	17	0.00
DB[a]	10009	10013	10022	9955	10031	10001	10005	27	0.00
1	10053	10037	10053	10052	10051	10033	10046	9	0.00
2	10058	10056	10056	10059	10060	10059	10058	2	0.00
3	10066	10062	10067	10063	10066	10056	10063	4	0.00
4	10063	10066	10063	10069	10065	10062	10065	2	0.00
5	10056	10066	10056	10068	10067	10066	10063	6	0.00
6	10062	10066	10060	10065	10069	10068	10065	3	0.00
7	10026	10063	10060	-	10069	-	10055	19	0.00
8	10054	10057	10059	10058	10056	10050	10056	3	0.00

Engine output based CO_2 Emission rate (g/bhp-hr)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	5397	3593	2719	3333	3478	3535	3676	901	0.25
High Idle	6316	7128	6009	6293	6246	6156	6358	394	0.06
DB[a]	6303	6175	5880	5916	5871	6960	6184	419	0.07
1	579	639	605	629	550	675	613	45	0.07
2	397	506	498	462	465	537	478	48	0.10
3	496	480	473	462	443	439	465	22	0.05
4	454	463	403	433	437	464	442	23	0.05
5	467	466	442	476	434	482	461	19	0.04
6	459	467	443	473	466	459	461	10	0.02
7	494	477	356	-	421	-	437	63	0.14
8	521	513	498	514	506	503	509	8	0.02

Exhaust CO_2 concentration (vol %)									
Throttle Notch Position	Over-theRail Tandem Operation Test (RY)								
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips Avg	6 Trips Std Dev	6 Trips CV
Low Idle	1.00	0.75	0.59	0.69	0.75	0.74	0.75	0.14	0.18
High Idle	0.90	1.01	0.88	0.88	0.93	0.88	0.91	0.05	0.06
DB[a]	0.90	0.87	0.86	0.85	0.88	0.93	0.88	0.03	0.03
1	1.60	1.71	1.69	1.69	1.55	1.84	1.68	0.10	0.06
2	2.01	2.52	2.57	2.29	2.44	2.76	2.43	0.26	0.11
3	3.59	3.44	3.52	3.25	3.38	3.16	3.39	0.16	0.05
4	4.12	4.23	3.73	3.85	4.20	4.21	4.06	0.21	0.05
5	4.66	4.67	4.53	4.65	4.59	4.84	4.66	0.11	0.02
6	4.75	4.79	4.71	4.81	5.08	4.70	4.80	0.14	0.03
7	6.00	6.26	4.61	-	5.96	-	5.71	0.75	0.13
8	6.15	6.10	6.10	6.14	6.48	6.03	6.17	0.16	0.03

Appendix C. Detailed Results of Rail Yard Tests on NC 1859 with BATS

After the BATS was retrofitted on the locomotive NC 1859, additional rail yard measurements were conducted between September 30, 2016 and October 2, 2016. These measurements were a part of zero-hour certification testing of a locomotive with LEMS. A total of four replicates were conducted on the specified dates. In the first three replicates, EF&EE did the tuning of the urea injection rate to obtain optimum NO_x control for each notch position. NCSU also conducted the measurements concurrently with each replicate with Axion PEMS. The concurrent measurements allow side-by-side comparison of two commercial PEMS.

For each of the four replicates, the sampling was done at the BATS exhaust outlet. The LEMS was used to measure the exhaust concentrations of CO_2, CO, THC and NO_x and filter based gravimetric PM. Only notch average mass emission rates of pollutant species are provided by EF&EE from LEMS analysis. The data of exhaust concentrations is not available. The Axion PEMS was used to record exhaust concentrations of CO_2, CO, HC, NO and PM, and PME activity parameters: RPM, IAT and MAP. The BATS data logger recorded the HEP and PME engine loads, the throttle notch position of the PME and the urea injection rate. The fuel use rate for each throttle notch position of a replicate were measured gravimetrically.

The notch average engine activity parameters, engine loads, exhaust concentrations, urea injection rate and the fuel use rate for each of the replicates are given in Tables C-1 through C-4. The HEP load was approximately constant at around 110-130 hp during the replicates. CO and HC were below the detection limit of the Axion PEMS for most of the measurements. The CO_2 concentrations typically increase with increasing notch position except for high idle. The NO concentrations were variable depending upon the urea injection rate. NO concentrations were typically high for mid notches and lower elsewhere.

TABLE C- 1. Engine load, BATS exhaust concentration, fuel use rate and urea injection rate from the rail yard tests conducted on September 30, 2016 (Replicate 1) at the BATS outlet of locomotive NC 1859 running on ULSD

Throttle Notch Position	PME Load [hp]	HEP Load [kW]	Engine Variables			Axion PEMS recorded Exhaust Concentrations						Gravimetric Fuel Use [gal/hr]	Total Engine Load [hp][b]	DEF Injection Rate [ml/min]
			RPM [rpm]	IAT [°C]	MAP [kPa]	CO_2 [%]	CO [%]	HC [ppm]	NO [ppm]	O_2 [%]	PM[a] [mg/m^3]			
Low Idle	9	145	238	59	100	1.95	0.000	0	175	20.68	0.227	13	240	30
High Idle	9	145	370	55	108	1.62	0.000	1	197	21.13	0.222	16	265	0
DB	9	127	370	60	108	1.48	0.000	3	144	20.17	0.207	23	241	0
1	190	122	370	67	108	2.51	0.000	2	261	19.81	0.207	23	425	0
2	350	132	370	69	109	3.26	0.000	1	331	18.14	0.229	30	595	45
3	675	122	492	71	120	3.91	0.000	0	441	16.60	0.196	47	928	55
4	1000	150	565	72	129	4.49	0.000	0	301	15.65	0.171	62	1228	137
5	1300	135	653	72	143	4.95	0.000	2	721	14.76	0.169	78	1569	0
6	1600	136	731	74	158	5.10	0.000	2	755	13.11	0.200	93	1920	0
7	2200	128	822	76	181	5.93	0.000	0	737	11.92	0.164	119	2403	0
8	2700	150	904	78	228	6.33	0.000	3	991	12.09	0.162	154	3071	0

[a]The PM measurements were quite low compared to the baseline measurements. It is anticipated that large number of bends in the sampling lines might have resulted in PM being deposited around the bends.

[b]The total engine load is estimated as the sum of tractive power of a prime mover engine (in hp), auxiliary load (approximated as proportional to main engine RPM), and the HEP engine load (in hp). The auxiliary load at 904 rpm of PME is 172 hp. The load in kW is divided by 0.7456 to obtain load in hp for a HEP engine.

TABLE C- 2. Engine load, BATS exhaust concentration, fuel use rate and urea injection rate from the rail yard tests conducted on October 1, 2016 (Replicate 2) at the BATS outlet of locomotive NC 1859 running on ULSD

Throttle Notch Position	**PME Load [hp]**	**HEP Load [kW]**	**Engine Variables**			**Axion PEMS recorded Exhaust Concentrations**						**Gravimetric Fuel Use [gal/hr]**	**Total Engine Load[b] [hp]**	**DEF Injection Rate [ml/min]**
			RPM [rpm]	**IAT [°C]**	**MAP [kPa]**	**CO_2 [%]**	**CO [%]**	**HC [ppm]**	**NO [ppm]**	**O_2 [%]**	**PM[a] [mg/m^3]**			
Low Idle	9	116	241	27	98	1.75	0.000	0	20	18.58	0.204	12	202	4.88
High Idle	9	109	373	36	107	1.45	0.000	1	90	18.92	0.199	14	217	0.00
DB	9	113	568	42	127	1.39	0.000	3	102	19.01	0.195	22	259	0.00
1	190	111	373	38	107	2.26	0.000	2	183	17.87	0.187	21	411	0.00
2	350	110	373	40	107	3.02	0.000	1	249	16.81	0.213	28	567	95.7
3	675	116	495	42	119	3.72	0.000	0	139	15.80	0.186	44	924	251
4	1000	109	568	43	129	4.31	0.000	0	82	15.02	0.164	59	1229	350
5	1300	115	656	46	143	4.81	0.000	1	85	14.34	0.164	75	1553	432
6	1600	109	734	50	159	5.25	0.000	2	99	13.48	0.206	95	1885	531
7	2200	127	824	52	182	6.10	0.000	0	96	12.26	0.168	122	2426	614
8	2700	117	906	56	228	6.30	0.000	3	93	12.03	0.161	153	3030	682

[a]The PM measurements were quite low compared to the baseline measurements. It is anticipated that large number of bends in the sampling lines might have resulted in PM being deposited around the bends.

[b]The total engine load is estimated as the sum of tractive power of a prime mover engine (in hp), auxiliary load (approximated as proportional to main engine RPM), and the HEP engine load (in hp). The auxiliary load at 904 rpm of PME is 172 hp. The load in kW is divided by 0.7456 to obtain load in hp for a HEP engine.

TABLE C- 3. Engine load, BATS exhaust concentration, fuel use rate and urea injection rate from the rail yard tests conducted on October 1, 2016 (Replicate 3) at the BATS outlet of locomotive NC 1859 running on Ultra-Low Sulfur Diesel

Throttle Notch Position	PME Load [hp]	HEP Load [kW]	Engine Variables			Axion PEMS recorded Exhaust Concentrations						Gravimetric Fuel Use [gal/hr]	Total Engine Load[b] [hp]	DEF Injection Rate [ml/min]
			RPM [rpm]	IAT [°C]	MAP [kPa]	CO_2 [%]	CO [%]	HC [ppm]	NO [ppm]	O_2 [%]	PM[a] [mg/m^3]			
Low Idle	9	116	238	36	98	1.94	0.000	7	13	17.61	0.132	12	200	17.2
High Idle	9	125	371	36	106	1.60	0.000	2	85	18.56	0.165	15	238	0.00
DB	9	121	566	48	125	1.44	0.000	0	114	18.98	0.133	20	270	0.00
1	190	126	371	45	106	2.38	0.000	2	203	17.53	0.134	23	431	46.0
2	350	119	371	42	106	3.13	0.000	7	186	16.42	0.132	30	579	152
3	675	113	494	40	118	3.75	0.000	11	48	15.63	0.126	44	919	301
4	1000	125	567	49	128	4.24	0.000	12	65	15.01	0.162	60	1250	353
5	1300	129	655	51	142	4.77	0.000	16	52	14.23	0.145	76	1572	483
6	1600	126	733	50	157	5.20	0.000	9	89	13.40	0.161	94	1908	554
7	2200	122	824	57	180	6.01	0.000	9	115	12.61	0.141	118	2420	613
8	2700	123	906	59	227	6.40	0.000	9	85	11.80	0.142	155	3037	684

[a]The PM measurements were quite low compared to the baseline measurements. It is anticipated that large number of bends in the sampling lines might have resulted in PM being deposited around the bends.

[b]The total engine load is estimated as the sum of tractive power of a prime mover engine (in hp), auxiliary load (approximated as proportional to main engine RPM), and the HEP engine load (in hp). The auxiliary load at 904 rpm of PME is 172 hp. The load in kW is divided by 0.7456 to obtain load in hp for a HEP engine.

TABLE C- 4. Engine load, BATS exhaust concentration, fuel use rate and urea injection rate from the rail yard tests conducted on October 2, 2016 (Replicate 4) at the BATS outlet of locomotive NC 1859 running on Ultra-Low Sulfur Diesel

Throttle Notch Position	**PME Load [hp]**	**HEP Load [kW]**	**Engine Variables**			**Axion PEMS recorded Exhaust Concentrations**						**Gravimetric Fuel Use [gal/hr]**	**Total Engine Load [b] [hp]**	**DEF Injection Rate [ml/min]**
			RPM [rpm]	**IAT [°C]**	**MAP [kPa]**	**CO_2 [%]**	**CO [%]**	**HC [ppm]**	**NO [ppm]**	**O_2 [%]**	**PM[a] [mg/m^3]**			
Low Idle	9	118	241	29	99	1.82	0.000	0	18	18.44	0.786	12	204	58.1
High Idle	9	118	372	33	107	1.54	0.000	0	78	18.80	0.773	14	230	73.0
DB	9	127	589	43	133	2.01	0.000	0	21	18.06	0.768	21	282	131
1	190	120	372	37	107	2.33	0.000	2	143	17.70	0.737	20	423	10.5
2	350	127	373	37	107	3.23	0.000	0	108	16.47	0.500	30	589	166
3	675	120	495	36	119	3.81	0.000	0	37	15.67	0.774	47	929	307
4	1000	120	568	36	129	4.39	0.000	0	22	14.81	0.835	61	1244	353
5	1300	126	655	41	144	4.92	0.000	0	45	13.98	0.881	78	1568	454
6	1600	112	733	44	159	5.32	0.000	0	124	13.47	0.991	93	1890	522
7	2200	126	824	46	182	6.14	0.000	0	68	12.30	0.965	121	2426	604
8	2700	120	907	50	229	6.40	0.000	0	79	11.90	0.825	153	3033	683

[a]The PM measurements were quite low compared to the baseline measurements. It is anticipated that large number of bends in the sampling lines might have resulted in PM being deposited around the bends.

[b]The total engine load is estimated as the sum of tractive power of a prime mover engine (in hp), auxiliary load (approximated as proportional to main engine RPM), and the HEP engine load (in hp). The auxiliary load at 904 rpm of PME is 172 hp. The load in kW is divided by 0.7456 to obtain load in hp for a HEP engine.

Based on the methods described in Chapter 6, the exhaust flow rate, fuel use rate and bias corrected mass per time-based notch average emission rates of CO_2, CO, HC, NO and PM were estimated for the Axion measured exhaust concentrations using the 'engine load' and 'fuel use' methods. The baseline measurements were not done for the dynamic braking; hence no results are available for the engine load method with dynamic braking. The fuel use method does not require any baseline measurements on HEP and PME engines, hence results are available for dynamic braking also.

After the estimation of notch average molar exhaust flow rates and fuel use rates, notch average emission rates of CO_2, CO, HC, NO and PM were estimated using the two methods and compared with the LEMS results to determine the accuracy and precision of Axion PEMS in estimating emission rates. The CO_2, CO, HC, NO and PM emission rates estimating using the engine load and fuel use methods for each replicate are given in Tables C-5 through C-10. The emissions rates estimated through each method were compared to the LEMS results. The results of the comparison are shown in Figures C-1 through C-10.

TABLE C- 5. CO_2 emission rates estimated from engine load and fuel use methods with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

Throttle Notch Position	CO_2 Emission Rate at BATS Outlet (g/sec)														
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Average		
	Engine Activity Method	Fuel Use Method	LEMS	Engine Activity Method	Fuel Use Method	LEMS	Engine Activity Method	Fuel Use Method	LEMS	Engine Activity Method	Fuel Use Method	LEMS	Engine Activity Method	Fuel Use Method	LEMS
Low Idle	33.9	36.6	37.4	33.9	32.7	32.8	33.9	34.3	33.2	33.9	34.3	34.8	33.9	34.5	34.6
High Idle	38.4	45.5	46.6	38.4	40.6	40.2	38.4	41.0	41.6	38.4	40.5	42.9	38.4	41.9	42.9
DB	-	64.6	64.6	-	60.6	61.3	-	57.0	61.1	-	58.6	61.6	-	60.2	62.1
1	60.5	64.6	66.3	60.5	58.0	58.9	60.5	64.4	64.6	60.6	55.4	64.9	60.5	60.6	63.6
2	79.1	85.3	86.7	79.1	78.6	83.2	79.2	84.9	86.6	79.3	83.9	83.2	79.2	83.2	84.9
3	119	131	131	119	125	129	120	124	127	120	131	130	119	128	129
4	152	173	171	152	165	162	152	168	170	152	172	170	152	169	168
5	196	219	221	196	212	212	196	213	220	196	220	223	196	216	219
6	250	262	263	250	268	241	250	263	263	250	262	263	250	264	258
7	326	334	336	326	343	348	326	333	335	326	340	339	326	338	339
8	409	432	437	409	429	429	409	436	429	409	431	435	409	432	433

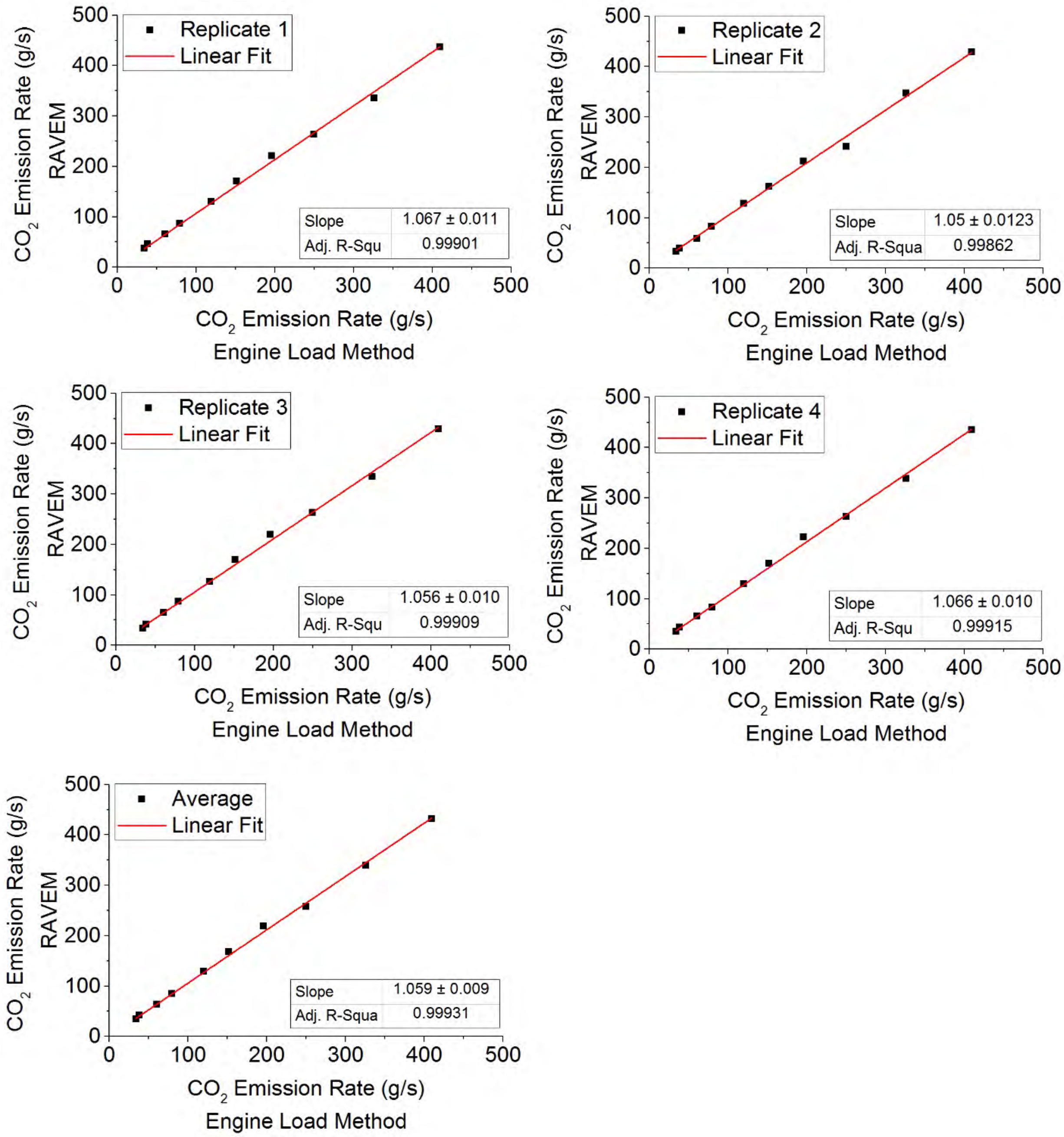

FIGURE C- 1. Comparison of CO_2 emission rates estimated from engine Activity method with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

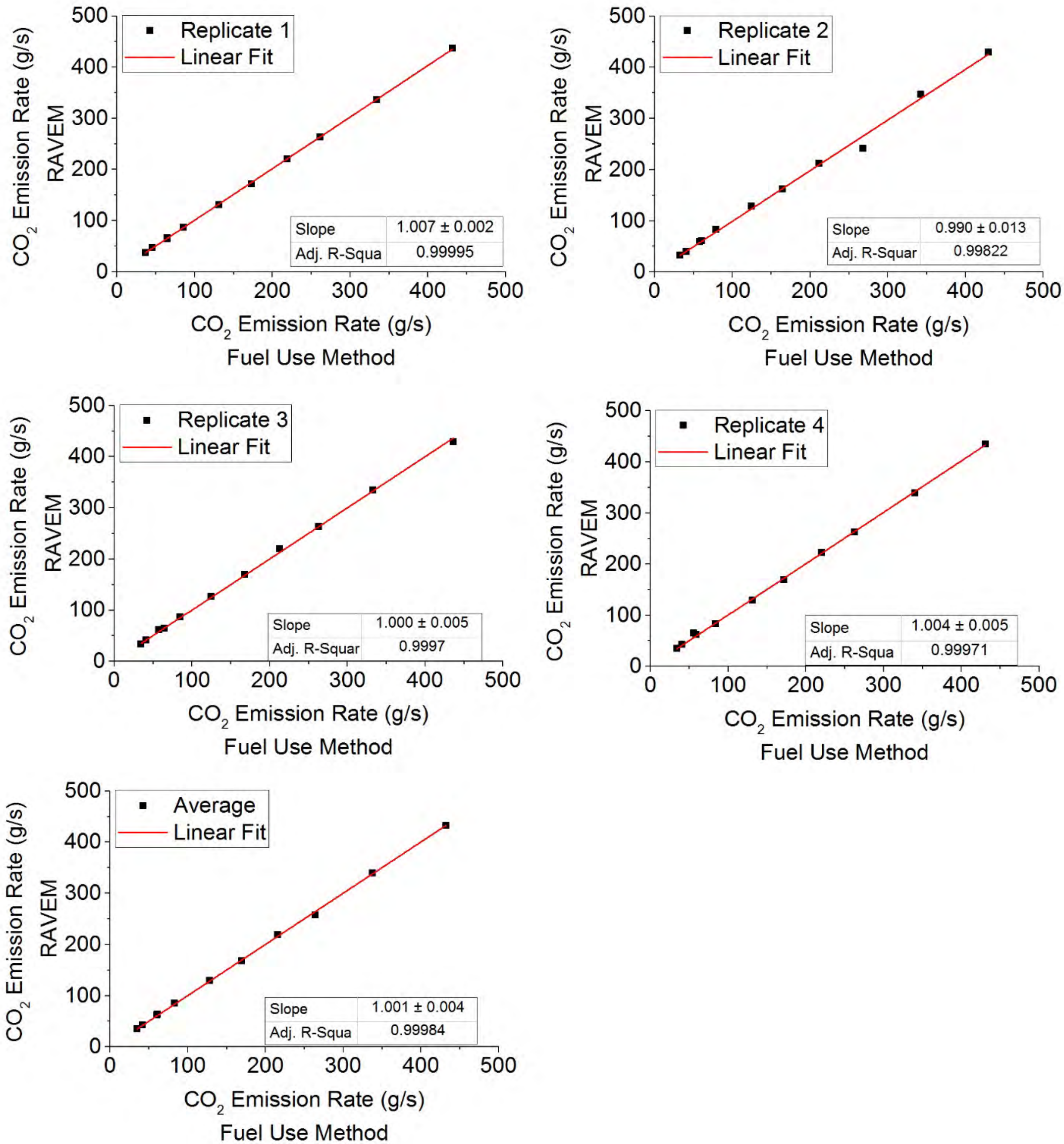

FIGURE C- 2.Comparison of CO_2 emission rates estimated from fuel use method with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

TABLE C- 6. NO_x emission rates estimated from engine Activity and fuel use methods with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

Throttle Notch Position	**NO_x Emission Rate at BATS Outlet (g/sec)**														
	Replicate 1			**Replicate 2**			**Replicate 3**			**Replicate 4**			**Average**		
	Engine Activity Method	**Fuel Use Method**	**LEMS**	**Engine Activity Method**	**Fuel Use Method**	**LEMS**	**Engine Activity Method**	**Fuel Use Method**	**LEMS**	**Engine Activity Method**	**Fuel Use Method**	**LEMS**	**Engine Activity Method**	**Fuel Use Method**	**LEMS**
Low Idle	0.02	0.04	0.04	0.04	0.04	0.06	0.03	0.03	0.03	0.04	0.04	0.04	0.03	0.04	0.04
High Idle	0.20	0.25	0.22	0.26	0.28	0.27	0.23	0.24	0.23	0.21	0.22	0.23	0.22	0.25	0.24
DB	-	0.27	0.49	-	0.49	0.48	-	0.49	0.50	-	0.07	0.46	-	0.33	0.49
1	0.29	0.31	0.29	0.54	0.52	0.51	0.57	0.60	0.58	0.41	0.37	0.47	0.45	0.45	0.46
2	0.24	0.22	0.27	0.72	0.71	0.74	0.52	0.55	0.61	0.29	0.31	0.36	0.44	0.45	0.49
3	0.12	0.13	0.13	0.49	0.51	0.85	0.17	0.17	0.28	0.13	0.14	0.17	0.23	0.24	0.36
4	0.11	0.27	0.14	0.32	0.34	0.48	0.26	0.28	0.32	0.08	0.10	0.11	0.19	0.25	0.26
5	0.28	0.30	0.30	0.38	0.41	0.59	0.24	0.26	0.28	0.20	0.22	0.25	0.27	0.30	0.36
6	0.61	0.59	0.64	0.52	0.56	0.62	0.47	0.49	0.49	0.64	0.68	0.72	0.56	0.58	0.62
7	1.38	1.32	1.38	0.56	0.59	0.85	0.69	0.70	0.79	0.40	0.42	0.47	0.76	0.76	0.87
8	2.36	2.39	2.39	0.67	0.70	0.88	0.60	0.64	0.64	0.56	0.59	0.64	1.04	1.08	1.14

Note: NO_x includes NO and NO_2. The Axion PEMS records only NO whereas LEMS records total NO_x. Typically, NO_x is comprised of 95 vol-% NO. NO_x is always reported as equivalent mass of NO_2. Engine Activity and fuel use method results include a multiplicative correction factor of 1.053 to approximate total NO_x from the measured NO concentrations.

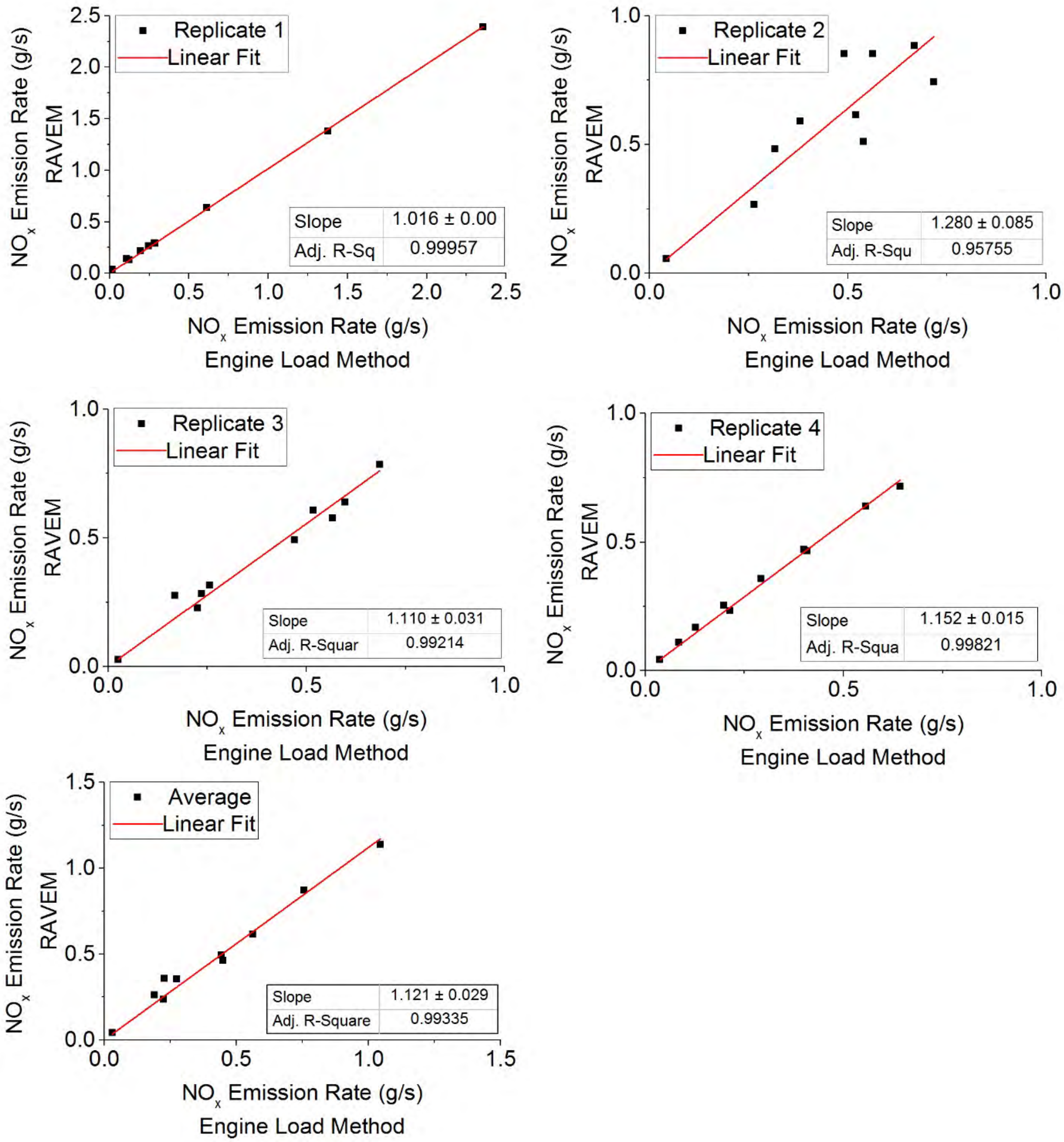

FIGURE C- 3.Comparison of NO_x emission rates estimated from engine Activity method with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

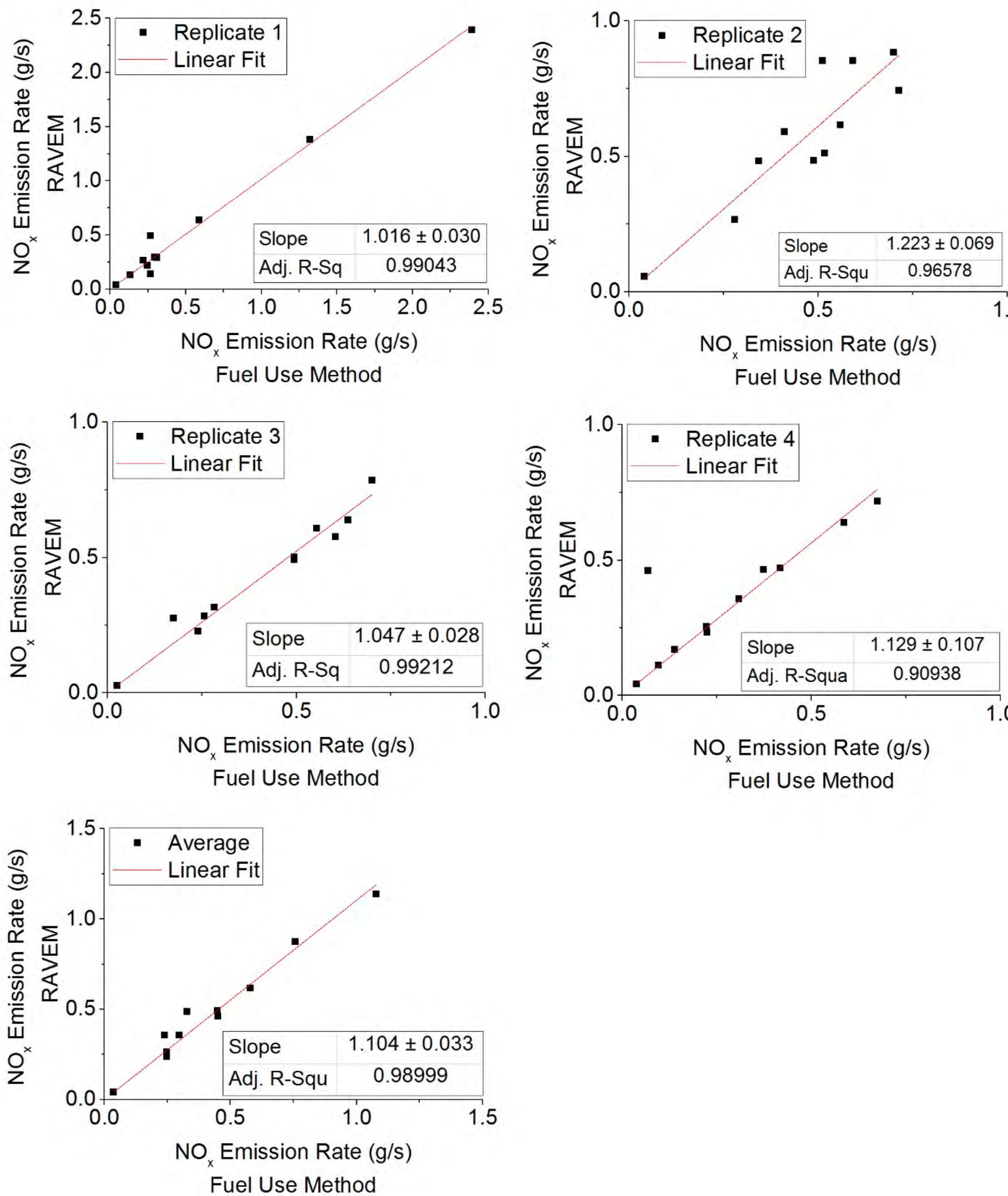

FIGURE C- 4.Comparison of NO_x emission rates estimated from fuel use method with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

TABLE C- 7. PM emission rates estimated from engine Activity and fuel use methods with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

Throttle Notch Position	PM Emission Rate at BATS Outlet (mg/sec)														
	Replicate 1			**Replicate 2**			**Replicate 3**			**Replicate 4**			**Average**		
	Engine Activity Method	**Fuel Use Method**	**LEMS**	**Engine Activity Method**	**Fuel Use Method**	**LEMS**	**Engine Activity Method**	**Fuel Use Method**	**LEMS**	**Engine Activity Method**	**Fuel Use Method**	**LEMS**	**Engine Activity Method**	**Fuel Use Method**	**LEMS**
Low Idle	1.02	1.19	6.60	1.12	1.06	4.17	0.66	0.65	7.71	4.15	4.12	8.74	1.74	1.75	6.80
High Idle	1.09	1.74	10.22	1.49	1.55	6.17	1.12	1.17	7.73	5.46	5.65	10.20	2.29	2.53	8.58
DB	-	2.52	5.28	-	2.37	6.49	-	1.45	9.56	-	6.22	17.92	-	3.14	9.81
1	1.22	1.49	1.50	1.42	1.34	7.47	0.96	1.00	8.75	5.42	4.87	-	2.26	2.17	5.91
2	2.08	1.67	7.67	1.58	1.54	7.77	0.95	0.99	9.75	3.47	3.61	-	2.02	1.95	8.39
3	1.19	1.83	14.15	1.69	1.73	9.94	1.14	1.16	8.18	6.87	7.41	1.59	2.72	3.03	8.46
4	1.93	1.83	15.71	1.63	1.74	9.70	1.64	1.78	14.51	8.18	9.10	5.42	3.35	3.61	11.34
5	2.09	2.07	18.10	1.89	2.01	13.63	1.69	1.80	18.32	9.92	10.95	-	3.90	4.21	16.68
6	3.17	2.85	20.08	2.77	2.92	9.70	2.19	2.26	20.71	13.18	13.58	3.78	5.33	5.40	13.57
7	3.05	2.57	35.68	2.55	2.63	23.40	2.16	2.16	33.05	14.52	14.88	30.41	5.57	5.56	30.63
8	2.56	3.07	64.34	2.96	3.05	50.39	2.58	2.69	-	14.96	15.46	53.15	5.77	6.07	55.96

Note: PM in Axion PEMS is measured using a light scattering technique, which provides useful relative comparisons of particle levels in the exhaust. Hence, engine Activity and fuel use method results include multiplicative correction factor of 5 to approximate total PM. The LEMS measures filter based gravimetric PM, hence no correction is needed.

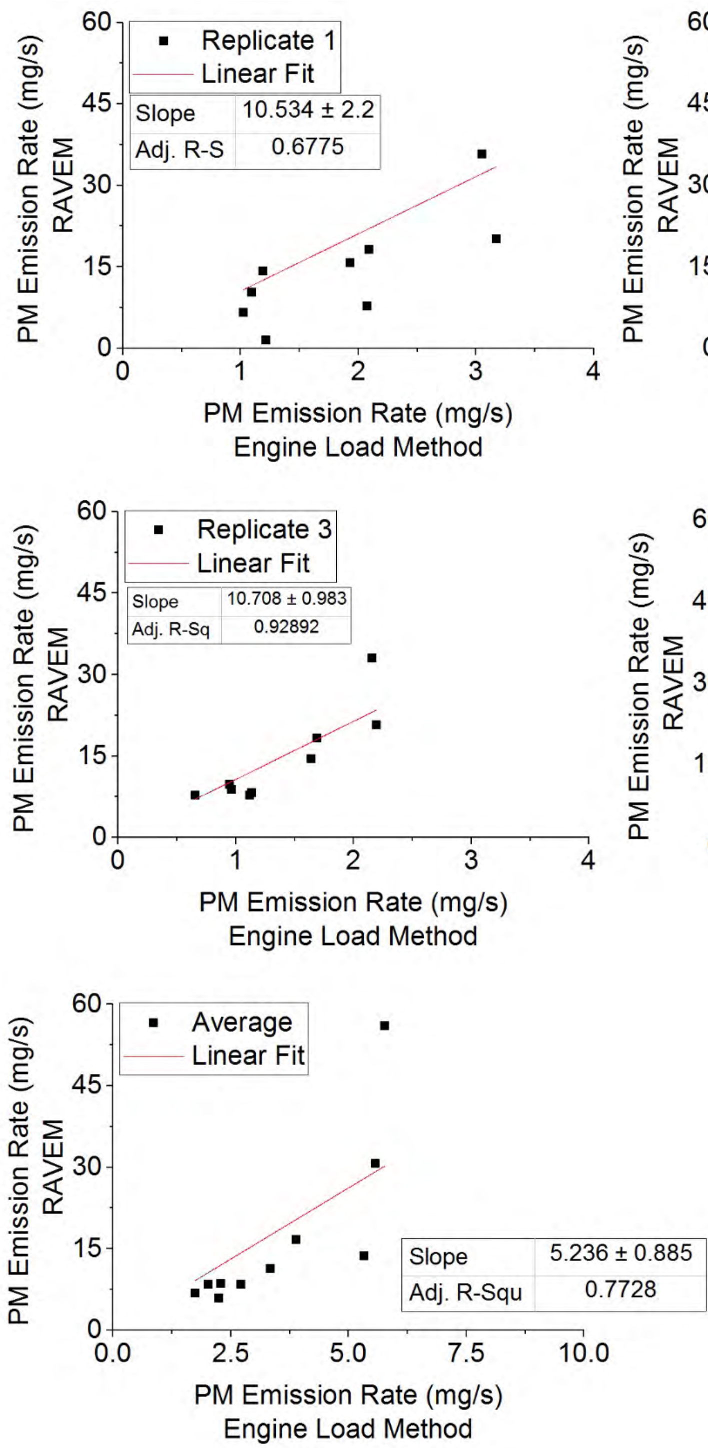

FIGURE C- 5.Comparison of PM emission rates estimated from engine Activity method with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

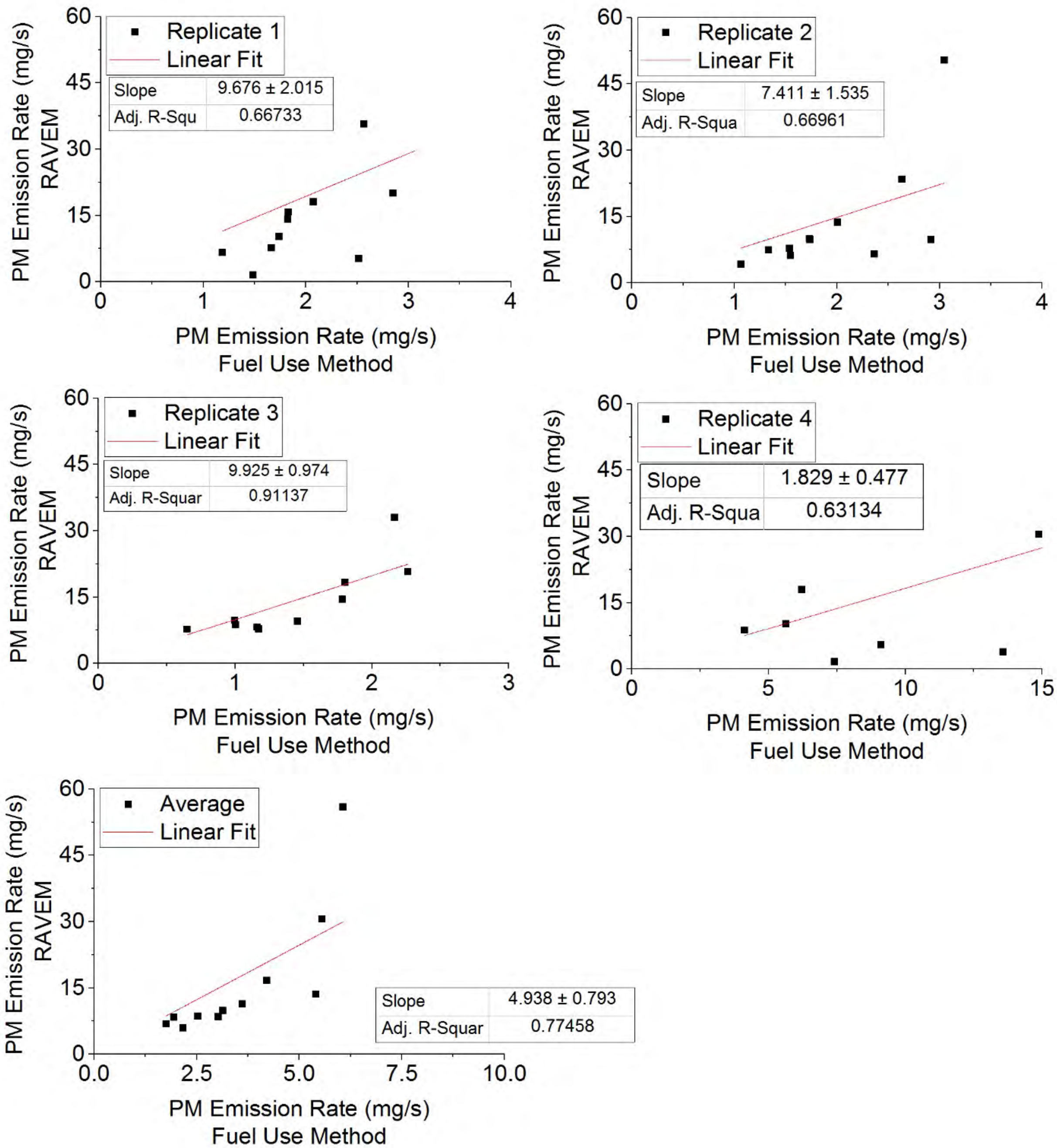

FIGURE C- 6.Comparison of PM emission rates estimated from fuel use method with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

TABLE C- 8. HC emission rates estimated from engine Activity and fuel use methods with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

Throttle Notch Position	HC Emission Rate at BATS Outlet (g/sec)														
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Average		
	Engine Activity Method	Fuel Use Method	LEMS	Engine Activity Method	Fuel Use Method	LEMS	Engine Activity Method	Fuel Use Method	LEMS	Engine Activity Method	Fuel Use Method	LEMS	Engine Activity Method	Fuel Use Method	LEMS
Low Idle	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.06	0.01	0.00	0.00	0.01	0.02	0.02	0.00
High Idle	0.01	0.02	0.00	0.01	0.02	0.01	0.02	0.02	0.01	0.00	0.00	0.01	0.01	0.01	0.01
DB	-	0.07	0.01	-	0.06	0.01	-	0.00	0.01	-	0.01	0.02	-	0.03	0.01
1	0.02	0.02	0.01	0.02	0.02	0.01	0.03	0.03	0.01	0.02	0.02	0.01	0.02	0.02	0.01
2	0.01	0.02	0.01	0.01	0.01	0.00	0.09	0.10	0.01	0.00	0.00	0.01	0.03	0.03	0.01
3	0.00	0.00	0.00	0.00	0.00	0.01	0.18	0.18	0.01	0.00	0.00	0.01	0.04	0.05	0.01
4	0.00	0.00	0.00	0.00	0.00	0.01	0.21	0.23	0.01	0.00	0.00	0.01	0.05	0.06	0.01
5	0.03	0.03	0.00	0.03	0.03	0.01	0.31	0.34	0.01	0.00	0.00	0.01	0.09	0.10	0.01
6	0.04	0.04	0.00	0.04	0.04	0.00	0.20	0.21	0.01	0.00	0.00	0.01	0.07	0.08	0.01
7	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.24	0.02	0.00	0.00	0.01	0.06	0.06	0.01
8	0.09	0.09	0.02	0.09	0.09	0.00	0.27	0.29	0.02	0.00	0.00	0.01	0.11	0.12	0.01

Note: HC in Axion PEMS is measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Hence, engine Activity and fuel use method results include multiplicative correction factor of 2.5 to approximate total HC. The LEMS measures total hydrocarbons. Hence, no correction factor is required for LEMS measurements.

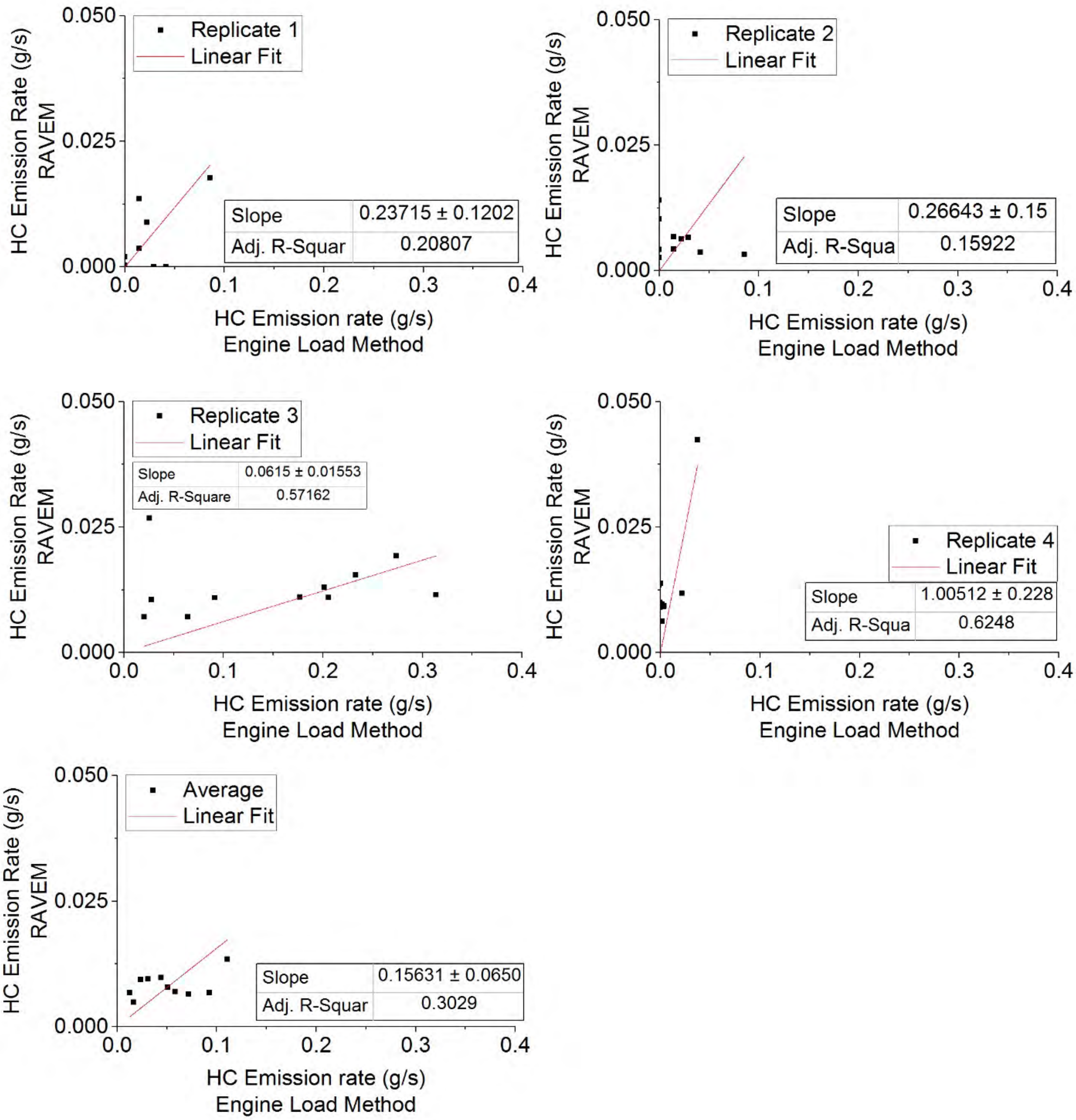

FIGURE C- 7.Comparison of HC emission rates estimated from engine Activity method with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

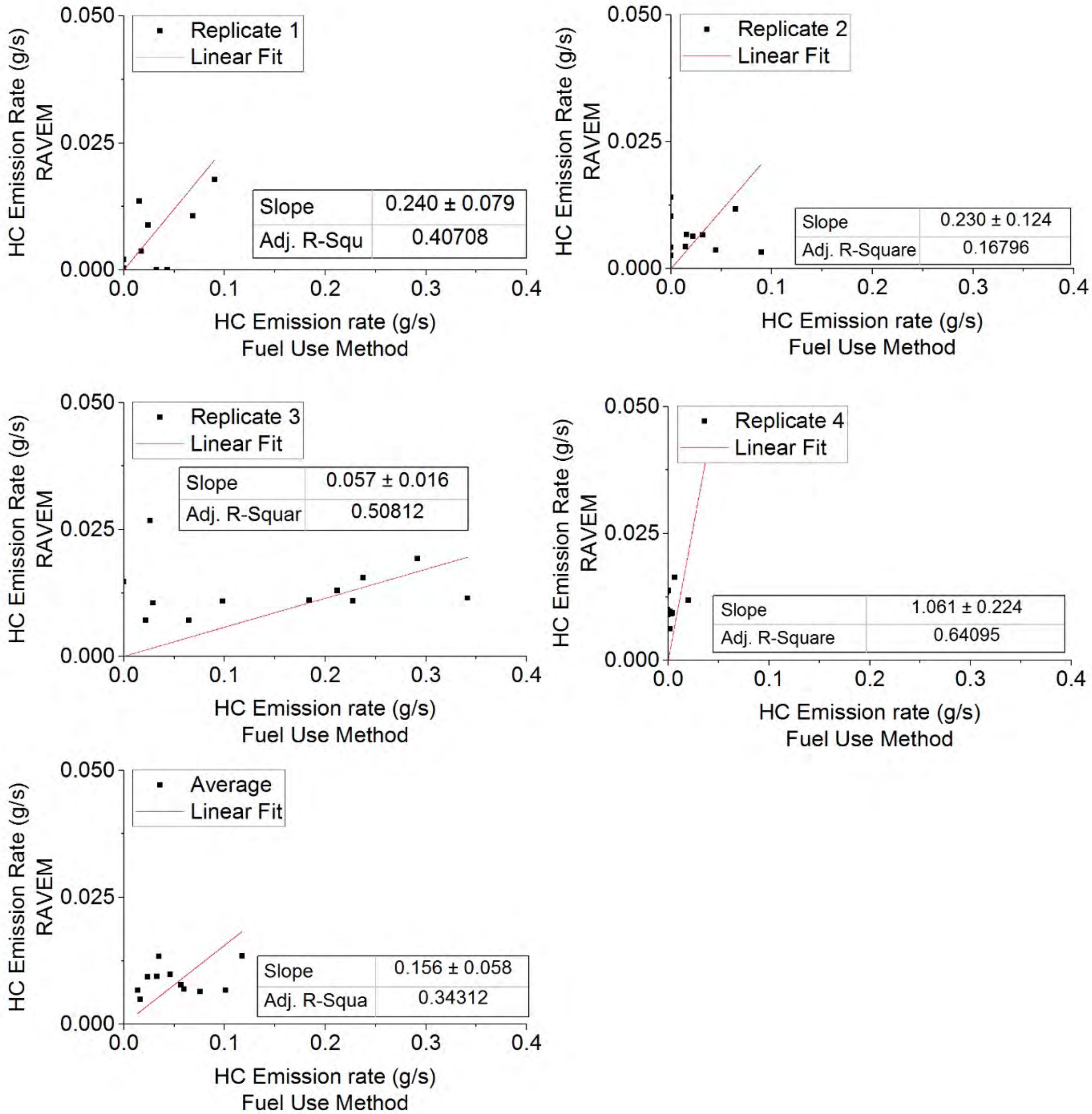

FIGURE C- 8.Comparison of HC emission rates estimated from fuel use method with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

TABLE C- 9. CO emission rates estimated from engine Activity and fuel use methods with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

Throttle Notch Position	CO Emission Rate at BATS Outlet (mg/sec)														
	Replicate 1			Replicate 2			Replicate 3			Replicate 4			Average		
	Engine Activity Method	Fuel Use Method	LEMS	Engine Activity Method	Fuel Use Method	LEMS	Engine Activity Method	Fuel Use Method	LEMS	Engine Activity Method	Fuel Use Method	LEMS	Engine Activity Method	Fuel Use Method	LEMS
Low Idle	0.00	0.00	38.3	0.00	0.00	10.3	1.18	1.20	22.8	0.00	0.00	25.5	0.30	0.30	24.2
High Idle	0.51	0.55	36.0	0.41	0.49	28.5	2.06	2.17	22.6	0.00	0.00	46.8	0.52	0.80	33.5
DB	-	3.57	53.3	-	3.36	55.9	-	0.00	42.2	-	0.00	66.7	-	1.73	54.5
1	0.00	0.00	23.1	0.00	0.00	35.1	0.00	0.00	26.7	0.00	0.00	62.6	0.00	0.00	36.9
2	0.00	0.00	49.4	0.00	0.00	15.9	0.00	0.00	10.8	0.00	0.00	27.1	0.00	0.00	25.8
3	0.00	0.00	48.6	0.00	0.00	22.0	0.00	0.00	13.6	0.00	0.00	35.8	0.00	0.00	30.0
4	0.00	0.00	34.6	0.00	0.00	22.1	0.00	0.00	14.5	0.00	0.00	26.1	0.00	0.00	24.3
5	0.00	0.00	24.0	0.00	0.00	23.6	0.00	0.00	16.7	0.00	0.00	20.4	0.00	0.00	21.2
6	0.00	0.00	28.4	0.00	0.00	22.8	0.00	0.00	16.9	0.00	0.00	23.3	0.00	0.00	22.9
7	0.00	0.00	50.8	0.00	0.00	48.4	0.00	0.00	40.6	0.00	0.00	45.1	0.00	0.00	46.2
8	0.00	0.00	108	0.00	0.00	104	0.00	0.00	94	0.00	0.00	102	0.00	0.00	102

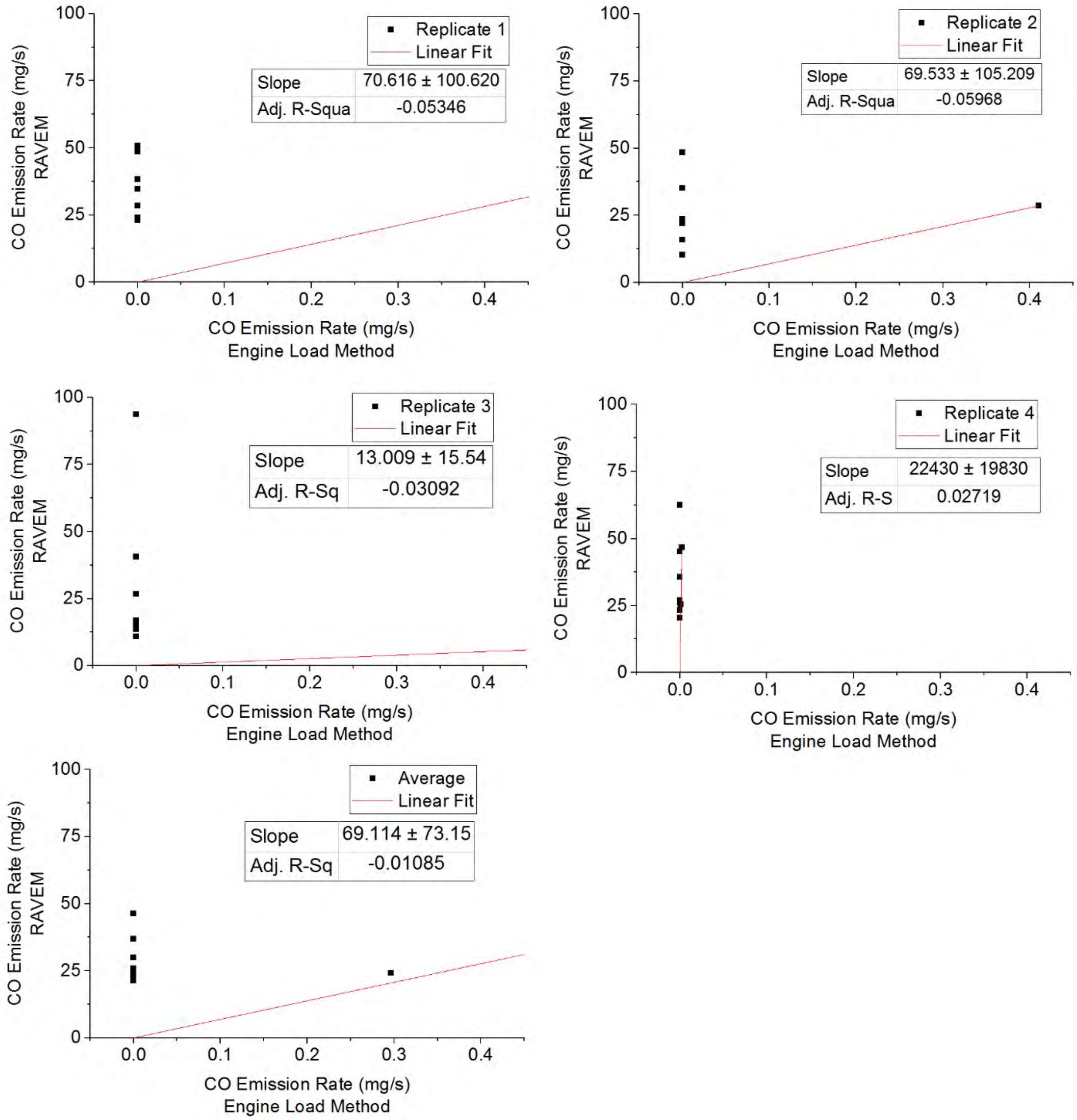

FIGURE C- 9.Comparison of CO emission rates estimated from engine Activity method with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

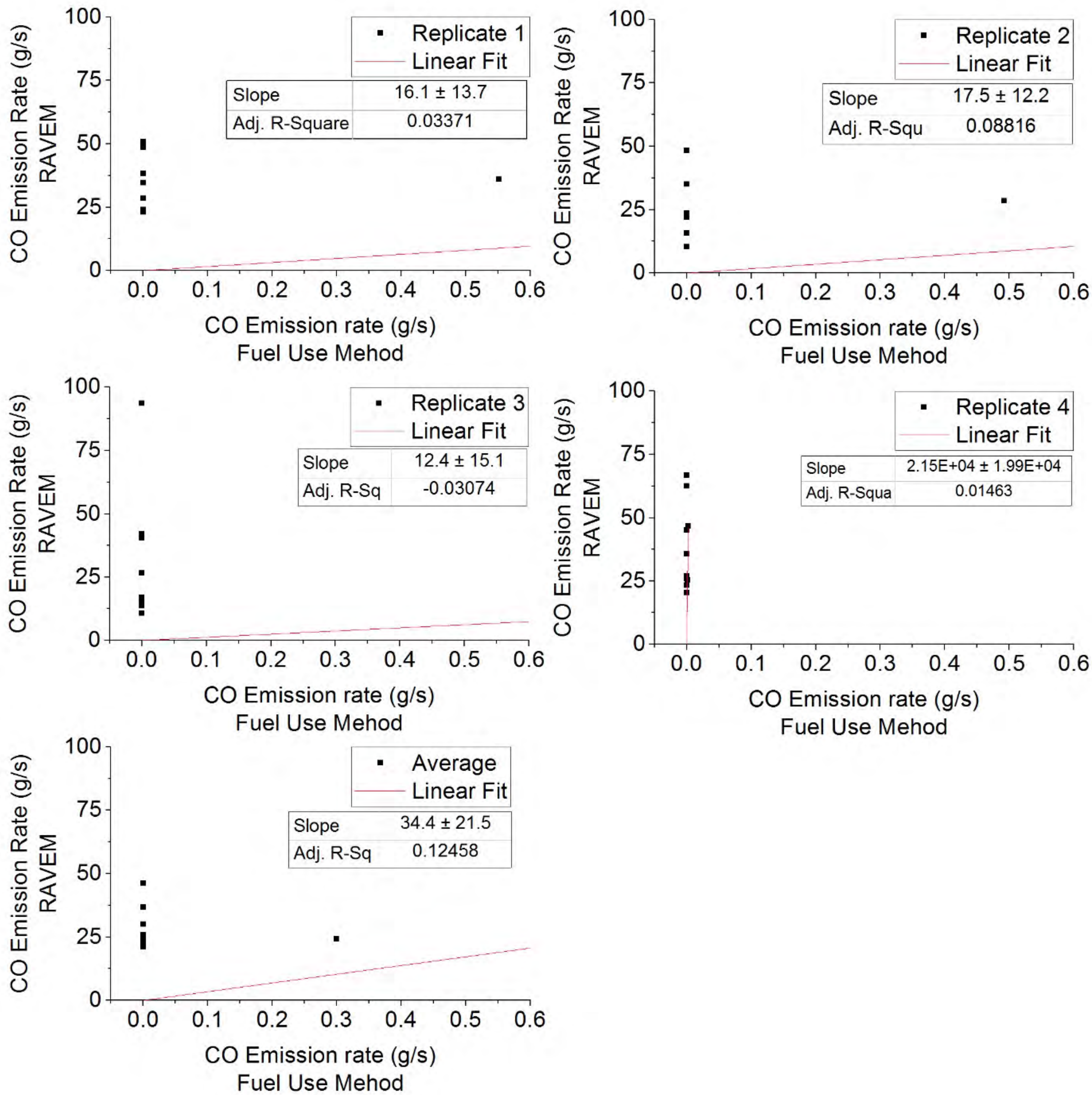

FIGURE C- 10.Comparison of CO emission rates estimated from fuel use method with LEMS estimates at BATS outlet of locomotive NC 1859 running on ULSD

TABLE C- 10. The effect of DEF injection rate on the NO_x control efficiency at BATS outlet

Throttle Notch Position	Effect of DEF Injection Rate on NO_x Control Efficiency at BATS Outlet											
	Replicate 1			Replicate 2			Replicate 3			Replicate 4		
	Engine Activity Method	Fuel Use Method	DEF Injection Rate	Engine Activity Method	Fuel Use Method	DEF Injection Rate	Engine Activity Method	Fuel Use Method	DEF Injection Rate	Engine Activity Method	Fuel Use Method	DEF Injection Rate
	[%]	[%]	(ml/min)	[%]	[%]	(ml/min)	[%]	[%]	(ml/min)	[%]	[%]	(ml/min)
Low Idle	28.9	24.5	30	91.0	91.5	4.9	94.5	94.2	17.2	92.1	92.2	58.1
High Idle	-1.30	-18.2	0	47.9	45.7	0.0	55.6	48.8	0.0	58.0	53.3	73.0
DB	-	-	0	-	-	0.0	-	-	0.0	-	-	130.6
1	13.5	9.28	0	32.7	36.4	0.0	29.3	29.5	46.0	49.0	50.4	10.5
2	27.6	23.4	45	41.2	42.4	95.7	57.6	57.0	151.6	76.0	74.9	166.2
3	25.0	18.7	55	75.1	74.4	251	91.5	91.2	301	93.6	93.3	307
4	54.8	49.2	137	87.2	86.2	350	89.7	89.1	353	96.6	96.3	353
5	-6.09	-17.1	0	87.0	86.2	432	92.0	91.5	483	93.2	92.6	454
6	-13.9	-17.9	0	85.3	84.5	531	86.7	86.1	554	81.9	80.6	522
7	-10.2	-11.6	0	86.0	85.5	614	83.0	82.6	613	90.1	89.6	604
8	-54.3	-60.9	0	85.3	84.8	682	86.8	86.2	684	87.7	87.2	683

Appendix D. BATS Mapping

The BATS outlet consists of two long channels on each side of the SCR reactor that release the exhaust to atmosphere. The two long channels are spread out longitudinally in the direction of motion of the train. The BATS channel receives exhaust from several circular filters installed in the channel. Thus, the exhaust may not be uniformly distributed across the BATS channel. A sampling rake (Shown in Figure D-1) was used to draw the composite exhaust gas and PM sample from the two channels at the BATS outlet. The sampling intake on the rake used by NCSU resulted in a significant loss of PM as the sampling lines had too many sharp bends. Compared to the baseline PM emission rates, the PM was significantly lower, thus indicating substantial loss of PM.

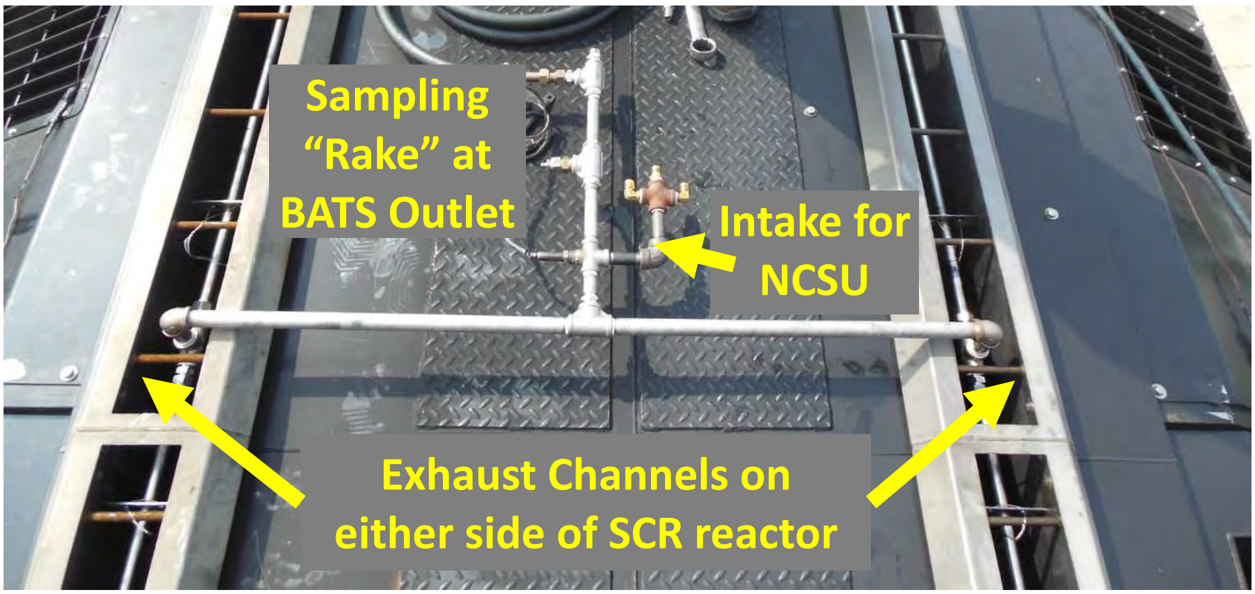

FIGURE D- 1. The BATS exhaust outlet on the locomotive NC 1859.

In future, NCSU plans to conduct the same rail yard test at the BATS outlet using a re-designed sampling configuration to minimize PM loss. The re-designed sampling rake consists of multiple tubes inserted into the exhaust channel at a single point which would be the most representative sampling location. The purpose of this study is to determine the most representative sampling location in the BATS channel, which would be the location that has the least amount of dilution of the exhaust. NCSU also plans to conduct over-the-rail measurements to determine the in-use efficiency of the BATS using the re-designed sampling configuration. The same sampling configuration between the rail yard and over-the-rail measurements will result in similar loss of PM. It is anticipated that wind turbulence in over-the-rail operation might disperse the exhaust in the rear end of the BATS channels. Thus, the most representative location should have negligible wind turbulence.

D.1 Methods

A sampling rake (shown in Figure D-2) was designed by NCDOT to draw multiple exhaust sample lines from a single location inside the BATS channel. Multiple sample lines can be connected to several emissions measurement systems to conduct parallel measurements. The sampling rake can be moved across the two channels and its height could be adjusted to collect samples at different depths of the BATS channel.

The sample lines were routed into the locomotive cab from across the roof of the locomotive through the cab window, where the Axion PEMS was placed. Since the planned over-the-rail measurement will be conducted using two Axion PEMS (one each for the exhaust from BATS outlet and PME), a rack (Figure D-3) was designed by NCDOT to secure the PEMS while the locomotive is in-use. The sampling lines and PEMS setup was used in this study and will be used in future rail yard and over-the-rail measurements.

FIGURE D- 2. Sampling rake re-designed by NCDOT to collect exhaust sample from a single location

FIGURE D- 3. Rack designed by NCDOT to secure two Axion PEMS inside the locomotive cab

For the purpose of identification of the sampling locations, the channels were classified as left channel (L) and right channel (R) based on their location in the direction of travel of locomotive. For each BATS channel, measurements were conducted at three different locations along the length of the channel: front (F); mid (M), and end (E). At each of the front, mid and end sections of the BATS channel, two depths were explored: top (T), and bottom (B). Hence, measurements were conducted at 6 points in each channel, making a total of 12 points. The sampling locations are shown in Figure D-4 and the legend for sampling locations is given in Table D-1. The layout of the BATS channel with identification of sampling locations is given in Figure D-4.

TABLE D- 1. Definition of Abbreviations for BATS Channel Sample Locations.

Horizontal Location	Vertical Location	Left Channel (L)	Right Channel (R)
Front (F)	**Top (T)**	LFT: Left Front Top	RFT: Right Front Top
	Bottom (B)	LFB: Left Front Bottom	RFB: Right Front Bottom
Mid (M)	**Top (T)**	LMT: Left Middle Top	RMT: Right Middle Top
	Bottom (B)	LMB: Left Middle Bottom	RMB: Right Middle Bottom
End (E)	**Top (T)**	LET: Left End Top	RET: Right End Top
	Bottom (B)	LEB: Left End Bottom	REB: Right End Bottom

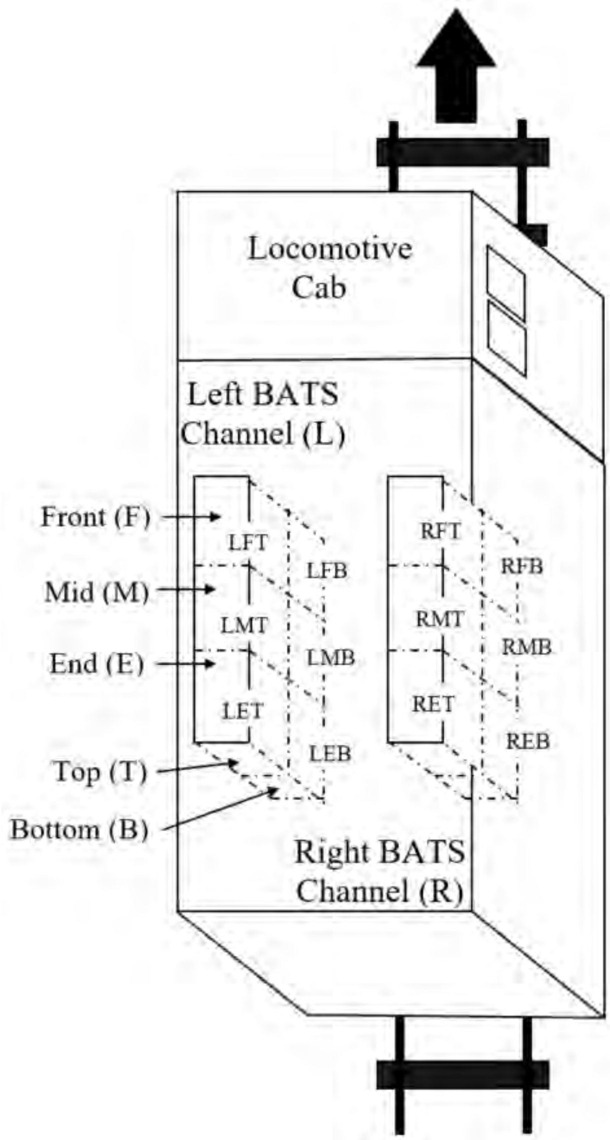

FIGURE D- 4. Sampling Locations for BATS Mapping

The PME of the test locomotive was run according to test schedule given in Table D-2 at each of the sampling locations. The load on the HEP engine during the test varied between 40 kW and 60 kW. Urea Injection was turned off for the entire test. The locomotive was run at selected notch positions only due to limited available time for testing and to allow for time to measure 12 sampling locations during one day of measurement. Each test replicate required 30 minutes. Thus, the total amount of sampling time was more than 6 hours. The selected notch positions provided sufficient variability in emission rates and covered the entire range of engine power demand.

TABLE D- 2. Test Schedule for BATS Mapping

Throttle Notch Position	Time
Low Idle (Warmup)	1 hr
Notch 8 (Warmup)	10 min
Low Idle	5 min
Notch 2	5 min
Notch 6	5 min
Notch 8	5 min

D.2 Results

The BATS mapping study was performed on January 20, 2017. CO_2, CO, HC, NO and PM emissions were measured at the 12 sampling locations. CO and HC were mostly below the detection limit of the PEMS. The measured PM emission rates were comparable to the baseline emission rates. This indicates that PM sampling losses were comparable to those of previous studies and, given this consistency, that PM measurements with the current sampling configuration can be compared with previous measurements. CO_2 and NO exhaust concentrations were used to determine the most representative sampling location for future rail yard and over-the-rail measurements. The most representative location is the one that has the least amount of dilution and the highest concentrations. The notch average measured concentrations of CO_2 and NO are given in Table D-3 and Table D-4, respectively.

TABLE D- 3. CO_2 concentrations at selected locations in the BATS exhaust channels

Notch average vol % CO_2 in Left Channel (L) of BATS Exhaust of locomotive NC 1859 on ULSD									
Position	Front (F)			Middle (M)			End (E)		
Notch	2	6	8	2	6	8	2	6	8
Top (T)	2.58	4.48	5.74	2.55	4.46	5.64	2.56	4.41	5.68
Bottom (B)	2.52	4.27	5.44	2.52	4.31	5.48	2.47	4.17	5.53

Notch average vol % CO_2 in Right Channel (R) of BATS Exhaust of locomotive NC 1859 on ULSD									
Position	Front (F)			Middle (M)			End (E)		
Notch	2	6	8	2	6	8	2	6	8
Top (T)	2.73	4.64	5.89	2.67	4.56	5.62	2.46	4.36	5.47
Bottom (B)	1.94	3.16	4.19	2.44	4.16	5.30	2.41	4.16	5.24

TABLE D- 4. NO concentrations at selected locations in the BATS exhaust channels

Notch average ppm NO in Left Channel (L) of BATS Exhaust of locomotive NC 1859 on ULSD									
Position	Front (F)			Middle (M)			End (E)		
Notch	2	6	8	Notch	2	6	8	Notch	2
Top (T)	375	713	639	424	748	669	422	728	669
Bottom (B)	383	651	617	387	673	630	385	652	632

Notch average ppm NO in Right Channel (R) of BATS Exhaust of locomotive NC 1859 on ULSD									
Position	Front (F)			Middle (M)			End (E)		
Notch	2	6	8	Notch	2	6	8	Notch	2
Top (T)	457	788	743	450	774	700	408	736	677
Bottom (B)	271	455	458	329	618	595	362	633	598

The notch average measured concentrations of CO_2 and NO are shown in Figure D-5 and Figure D-6, respectively.

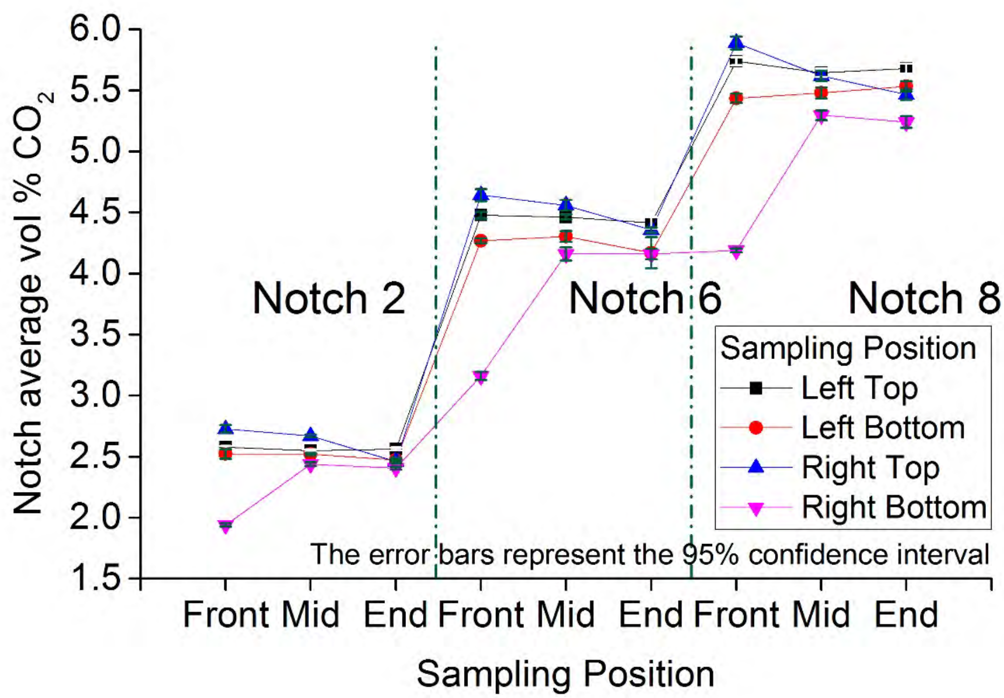

FIGURE D- 5. Variation of CO_2 Concentration with Sampling Location

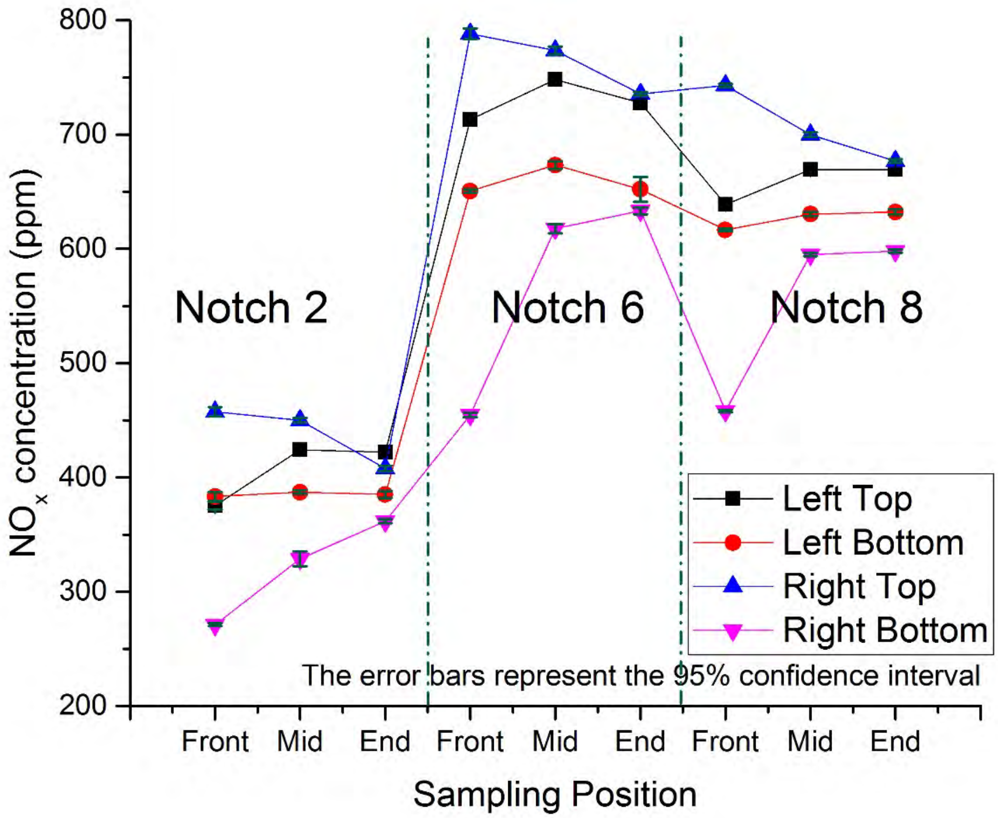

FIGURE D- 6. Variation of NO Concentration with Sampling Location

For CO_2, the overall highest measured concentration was 5.89 volume percent at Notch 8 in the right channel. The CO_2 concentrations at all engine loads were consistently higher at the top of the channel than the bottom of the channel for both right and left channels. The CO_2 concentrations at all engine loads were consistently higher for the front of the channel versus the middle or end of the channel. The CO_2 concentration varied with engine load, as expected, since the air/fuel ratio varies with engine load.

At Notch 8, the measured CO_2 concentrations varied from 5.4 vol-% to 5.7 vol-% in the left channel and from 4.2 vol-% to 5.9 vol-% in the right channel. The difference in CO_2 concentration between top and bottom was typically 0.2 vol-% with one exception which was in the front channel. The right channel top front location has CO_2 concentration approximately 0.1 vol-% to 0.4 vol-% higher than at the top in the middle and end locations. Thus, the right channel, front and top, is the location with the highest CO_2 concentration. This location also has the highest CO_2 volume percent for Notches 2 and 6.

The right and left channels have similar CO_2 concentrations, within 0.1 vol-%, at a given horizontal and vertical position for a given load with a few exceptions. The right front top positions have higher concentrations than the left top positions. However, the right front bottom positions have substantially lower concentrations. The right channel also has lower concentrations than the left channel at Notch 8 at the middle bottom and the end top and bottom. The variability in CO_2 concentration in the front right channel between top and bottom may indicate a flow obstruction and possibly channeling of exhaust gas toward the top of the channel.

The top part of the channel typically has concentrations that average 0.15 vol-% higher on the left side and 0.60 vol-% higher on the right side. The larger average difference on the right side is mostly influenced by differences of 0.8 vol-% to 1.7 vol% from Notch 2 to Notch 8 in the front location.

The CO_2 concentrations in the left channel were less sensitive to location than those in the right channel. For example, for Notch 8, the average concentration for all six sampled locations was 5.6 vol-% with a coefficient of variation of 0.02. However, in the right channel, the average was 5.3 vol-% with a coefficient of variation of 0.11. Thus, even though the right channel has the location with the overall highest CO_2 concentration at the front top, the left channel has a more uniform distribution of exhaust gas.

After the mapping measurements were completed, it was discovered later that some of the catalyst material had been damaged as a result of crankcase oil accumulation in the right channel during extended idling. The accumulated oil may have subsequently "lit off" leading to physical damage to portions of the catalyst. Thus, it is possible that the mapping measurements were affected by flow blockage in parts of the catalyst. As such, it appears that the left channel mapping measurements were less affected by blockage than the right channel measurements.

The NO concentrations reported in Table D-3 have patterns similar to those for CO_2. The highest NO concentration is at the right front top during Notch 6, at 788 ppm, which is substantially higher than any other measured location. However, the NO concentration at the right front bottom is substantially lower than at any other location. Thus, there may have been some flow channeling that could have affected the results. Although the right channel has the individual location with the highest NO concentration, the mean NO concentration of 690 ppm at Notch 8 in the left channel is higher than the mean concentration of 670 ppm in the right channel, when averaged over all six sampling locations. The left channel has less variability in concentration among the six locations, with a coefficient of variation of 0.06 at Notch 6 compared to a coefficient of variation of 0.96 in the right channel. The difference in NO concentration between the right and left channels is less than 60 ppm for the middle and end locations.

The variation of the HEP engine load between 40 kW to 60 kW during the test could also lead to slight variation in the measured exhaust concentrations in either channels. Based on the baseline measurements of the PME and HEP engine of the same locomotive, the predicted CO_2 and NO concentrations for the PME operating at Notches 2, 6 and 8, and the HEP engine operating at 40 kW and 60 kW loads are given in Table D-5.

At Notch 2 of the PME, and HEP load between 40 kW and 60 kW only leads to a difference of about 4 percent in the predicted CO_2 and NO concentrations in the blended exhaust. At higher notch positions, the contribution of the HEP engine to the blended exhaust becomes even lower and the variability in CO_2 and NO concentrations due to variable HEP load reduces to approximately 2.5 percent and 1.8 percent at Notch 6 and Notch 8, respectively. Thus, the variation of 40 kW to 60 kW HEP load during the test has a very little impact on the measured exhaust concentrations in the blended exhaust, affecting the measured exhaust concentrations of CO_2 and NO by less than 4 percent.

TABLE D- 5. Variation of the predicted CO_2 and NO concentrations in the blended exhaust at different HEP engine loads for a given PME throttle notch position estimated from baseline measurements

Notch	CO_2 (vol %) HEP Load		Percentage Difference (%)	NO (ppm) HEP Load		Percentage Difference (%)
	40 kW	60 kW		40 kW	60 kW	
2	2.19	2.27	3.56	347	362	4.27
6	4.46	4.56	2.37	852	874	2.60
8	5.81	5.91	1.80	848	864	1.88

D.3 Conclusions

There was more uniformity of CO_2 and NO exhaust concentrations in the left channel versus the right channel. It is possible that there was an obstruction to exhaust gas flow because of crankcase oil deposition that later was found to lead to physical damage to the catalyst. The variation in the measured exhaust concentrations due to varying HEP engine load during the test was found to be less than 4 percent. Thus, the variations in measured exhaust concentrations across the sampling locations were mainly due to non-uniform distribution of the blended exhaust.

Based on the mapping study, the top part of the front section on the right channel was found to be most representative sampling location with highest NO and CO_2 concentrations for each notch position. Thus, although the highest measured concentrations were found in the right front top sampling position, the left channel results may be more representative of proper flow distribution. In the left channel, the front top position typically had the highest CO_2 concentrations. The top locations at the front, middle, and end horizontal locations typically had higher CO_2 concentrations than the bottom locations. The highest NO concentrations in the left channel were at the middle top location. The CO_2 concentrations at the middle top location were within 0.1 vol-% of those at the front top location.

During these measurements, DEF was not injected. Given the potential impact of flow channeling as a result of crankcase oil deposition and catalyst damage, which was not diagnosed until after these measurements were made, it is advisable to repeat the mapping measurement after the catalyst is repaired. It would also be advisable to repeat the measurement under more representative conditions in which the HEP is running and DEF is being injected.

The PM emission rates in this study were comparable to the baseline measurements. Thus, the sampling line configuration used in these measurements is suitable for use in future measurements.

Appendix E. Effect of Fuels

RY and OTR measurements on three locomotives of NCDOT fleet were conducted in prior study. The three locomotives include an F59PHI locomotive NC 1797, and two F59PH locomotive NC 1810 and NC 1859. Each of the locomotive was operated on ULSD and biodiesel blends B10, B20 and B40. Additional blends such as B60, B80 and B100 were also tested on one locomotive. Measurements were conducted on ULSD to obtain baseline FUER of each locomotive. Prior to each test, locomotive was run for at least two weeks on the alternative fuel to be tested. This ensured that the locomotive was purged with the new fuel. B20 biodiesel was found to be the best fuel since B20 lead to reduced fuel consumption, and reduced PM emissions and a minimal increase in NO_x emissions. Other blends resulted in significant increase in one or more of these.

RY and OTR measurements were conducted as explained in Chapter 3. FUER for all three locomotives on all fuel blends were estimated. Significant differences were found between RY and OTR estimates for some of the throttle notch positions. Thus, for this study, only OTR measurements are being evaluated to quantify the effect of fuels. Only B10, B20 and B40 biodiesel blends are considered in this study for comparison as measurements on multiple locomotives were done using these blends. The three locomotives at the time of study represented 50 percent of the NCDOT locomotive fleet of two F59PHIs and four F59PHs. Effect of each fuel are being evaluated for an average NCDOT locomotive based on measurement on three locomotives.

The notch average FUER based on OTR trips for three locomotives on ULSD, B10, B20 and B40 are given in Table E-1 through E-4.

TABLE E- 1. Notch average Fuel Use and Emission Rates based on Over-the-Rail Measurements on Three Locomotives Operated on ULSD: (a) Fuel Use Rate; (b) CO_2 Emission Rate; (c) CO Emission Rate; (d) HC Emission Rate; (e) NO_x Emission Rate; and, (f) PM Emission Rate.

(a) Notch Average Fuel Use Rate on ULSD (g/s)

Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	4	4	3	6	5	5	3	5	3	3	3	4	3	3	3	2	4	3
DB[a]	4	4	5	5	5	4	6	5	5	5	5	7	6	5	4	5	5	6
1	8	7	11	10	8	7	9	11	10	9	9	11	10	10	7	8	12	9
2	13	10	18	18	16	13	14	16	13	13	14	16	14	14	12	12	14	14
3	22	24	30	30	34	20	25	28	23	26	26	28	25	26	24	25	29	29
4	38	37	44	43	40	41	36	39	37	37	38	40	34	35	32	36	40	35
5	49	49	57	58	56	58	48	55	53	53	46	58	48	53	51	51	55	55
6	57	54	65	68	69	61	63	68	70	67	58	74	65	67	57	59	69	70
7	45	78	66	92	96	78	-[b]	103	95	92	70	70	86	74	-[b]	89	90	-[b]
8	104	104	120	119	121	110	126	132	128	133	127	131	117	117	118	117	119	116

[a]DB = Dynamic Braking
[b] = No steady state data for the given notch position

(b) Notch Average CO_2 Emission Rate on ULSD (g/s)

Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	13	12	9	19	16	14	11	15	9	10	10	12	10	9	8	7	11	10
DB[a]	12	10	15	15	14	12	18	16	15	15	17	20	17	15	12	14	17	18
1	25	22	35	30	25	23	26	33	30	27	29	33	29	28	22	24	36	26
2	42	30	56	55	50	41	45	49	40	41	42	48	44	44	36	38	43	45
3	69	74	93	92	105	62	79	88	72	79	82	85	78	79	75	77	91	89
4	117	114	137	135	126	127	114	121	117	115	118	124	106	106	101	111	124	109
5	151	150	179	179	174	180	148	172	165	165	144	178	149	166	158	157	171	171
6	177	167	203	211	216	191	196	212	217	209	182	227	202	207	179	183	213	219
7	140	241	208	287	299	244	-[b]	319	297	284	217	217	268	228	-[b]	277	280	-[b]
8	324	323	373	371	378	341	392	410	398	413	395	405	365	362	368	364	371	360

[a]DB = Dynamic Braking
[b] = No steady state data for the given notch position

Table E-1 Continued on next page.

Table E-1 Continued from previous page.

(c) Notch Average CO Emission Rate on ULSD (g/s)																		
Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.07	0.05	0.02	0.17	0.04	0.11	0.07	0.05	0.06	0.08	0.07	0.11	0.05	0.01	0.01	0.01	0.08	0.06
DB[a]	0.02	0.20	0.05	0.34	0.02	0.12	0.09	0.09	0.07	0.10	0.08	0.22	0.09	0.03	0.00	0.00	0.14	0.19
1	0.06	0.09	0.01	0.11	0.04	0.08	0.17	0.05	0.06	0.13	0.12	0.12	0.10	0.06	0.03	0.05	0.14	0.17
2	0.11	0.08	0.04	0.09	0.03	0.09	0.07	0.10	0.08	0.09	0.10	0.11	0.11	0.02	0.09	0.09	0.08	0.21
3	0.17	0.09	0.06	0.11	0.09	0.09	0.11	0.14	0.07	0.12	0.11	0.18	0.10	0.04	0.00	0.10	0.13	0.94
4	0.19	0.23	0.08	0.16	0.06	0.24	0.10	0.17	0.09	0.23	0.14	0.23	0.14	0.10	0.14	0.09	0.00	0.28
5	0.10	0.19	0.14	0.24	0.13	0.18	0.15	0.20	0.18	0.35	0.17	0.51	0.21	0.08	0.01	0.00	0.37	0.19
6	0.21	0.46	0.12	0.21	0.04	0.10	0.28	0.27	0.24	0.34	0.17	0.65	0.08	0.18	0.28	0.00	0.33	0.27
7	0.04	0.65	0.00	0.15	0.33	0.33	-[b]	1.28	0.51	0.72	0.29	0.80	0.43	0.16	-[b]	0.00	0.15	-[b]
8	0.37	0.56	0.43	0.63	0.52	0.65	1.07	1.52	0.86	1.52	1.09	1.68	0.65	0.58	0.60	0.61	0.73	0.76

[a]DB = Dynamic Braking

[b] = No steady state data for the given notch position

(d) Notch Average HC Emission Rate on ULSD (g/s)[c]																		
Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.44	0.31	0.08	0.90	0.29	0.94	0.39	0.35	0.38	0.74	0.45	0.58	0.22	1.16	0.33	0.41	0.21	0.06
DB[a]	0.31	0.64	0.26	1.30	0.14	1.03	0.62	0.68	0.52	0.98	0.56	0.89	0.80	1.65	0.30	0.36	0.24	0.42
1	0.48	0.62	0.01	0.74	0.30	0.80	0.47	0.65	0.49	1.25	0.48	0.83	0.81	1.97	0.35	0.96	0.24	0.03
2	0.72	0.80	0.37	0.69	0.26	0.81	0.43	0.72	0.59	0.64	0.42	0.77	0.46	0.49	0.03	0.75	0.03	0.51
3	0.88	0.89	0.27	0.99	0.38	1.13	0.45	1.34	0.66	1.38	0.73	1.05	0.87	2.47	0.38	1.36	0.22	0.71
4	1.20	1.82	0.76	1.35	0.67	1.74	0.56	1.36	0.61	1.21	0.57	1.10	0.93	2.64	0.81	1.29	0.57	0.15
5	0.86	2.05	1.02	1.83	0.96	1.35	0.54	0.97	1.25	1.55	0.63	1.54	0.62	2.69	0.56	3.09	1.27	0.38
6	1.23	1.28	1.10	1.81	0.31	0.62	0.93	1.43	1.21	1.56	1.08	2.45	0.92	3.25	0.00	2.68	1.58	1.19
7	0.40	1.93	0.07	1.68	0.71	1.40	-[b]	2.19	1.47	1.88	1.01	2.12	2.06	3.80	-[b]	0.00	0.44	-[b]
8	0.83	1.58	0.60	1.34	0.73	1.32	0.81	1.71	0.86	1.51	0.94	1.94	2.13	3.78	1.09	2.14	1.08	1.57

[a]DB = Dynamic Braking

[b] = No steady state data for the given notch position

[c] = HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factor of 2.5 to approximate total HC.

Table E-1 Continued on next page.

Table E-1 Continued from previous page.

(e) Notch Average NO_x Emission Rate on ULSD (g/s)[c]																		
Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.64	0.53	0.35	0.79	0.66	0.63	0.23	0.30	0.20	0.22	0.23	0.27	0.20	0.20	0.22	0.17	0.21	0.21
DB[a]	0.56	0.41	0.54	0.61	0.61	0.56	0.31	0.30	0.28	0.29	0.31	0.35	0.28	0.29	0.23	0.28	0.27	0.29
1	1.28	0.95	1.30	1.22	1.04	1.10	0.52	0.58	0.52	0.53	0.55	0.62	0.51	0.54	0.45	0.51	0.59	0.46
2	2.13	1.46	2.23	2.44	2.13	2.06	0.86	1.01	0.78	0.80	0.88	1.01	0.77	0.81	0.83	0.85	0.84	0.80
3	4.04	4.48	3.85	4.01	4.67	3.98	1.58	1.79	1.40	1.64	1.59	1.79	1.42	1.46	1.52	1.58	1.54	1.46
4	6.01	5.87	5.40	5.94	5.97	6.60	2.19	2.28	2.17	2.17	2.32	2.39	1.93	1.92	2.11	2.25	2.13	2.19
5	6.38	6.84	6.96	7.21	7.49	8.08	3.00	2.93	2.83	2.91	2.65	3.08	2.45	2.67	2.72	2.65	2.69	2.61
6	6.55	5.77	7.10	6.98	6.84	6.21	3.38	3.54	3.67	3.40	2.91	3.65	3.17	3.29	2.72	3.40	3.11	3.25
7	5.97	6.46	8.21	8.93	7.12	7.19	-[b]	4.26	4.53	3.15	3.35	3.67	3.50	2.96	-[b]	3.42	3.51	-[b]
8	8.41	8.57	8.01	8.38	8.16	8.23	4.64	4.77	4.98	4.71	4.75	4.60	4.29	4.30	4.21	4.16	4.05	4.05

[a]DB = Dynamic Braking
[b] = No steady state data for the given notch position
[c] = NO is measured using electrochemical cell which does not measure NO_2. Results include multiplicative correction factor of 1.053 to approximate total NO_x based on NO measurements.

(f) Notch Average PM Emission Rate on ULSD (g/s)[d]																		
Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
DB[a]	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.02	0.02	0.02	0.02	0.02
1	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.03	0.03	0.03	0.03	0.03
2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.04	0.05	0.05	0.04	0.04
3	0.02	0.02	0.02	0.02	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.03	0.06	0.06	0.07	0.07	0.05	0.07
4	0.03	0.03	0.03	0.02	0.02	0.02	0.05	0.06	0.06	0.05	0.06	0.07	0.09	0.08	0.12	0.11	0.08	0.09
5	0.04	0.03	0.04	0.02	0.03	0.03	0.05	0.08	0.06	0.07	0.05	0.09	0.12	0.11	0.13	0.15	0.11	0.11
6	0.04	0.04	0.03	0.03	0.04	0.03	0.07	0.09	0.08	0.08	0.07	0.11	0.17	0.14	0.15	0.27	0.14	0.15
7	0.06	0.07	0.03	0.07	0.12	0.09	-[b]	0.25	0.23	0.18	0.14	0.13	0.25	0.14	-[b]	0.26	0.23	-[b]
8	0.14	0.11	0.11	0.10	0.11	0.11	0.26	0.29	0.21	0.23	0.24	0.26	0.36	0.31	0.32	0.40	0.29	0.29

[a]DB = Dynamic Braking
[b] = No steady state data for the given notch position
[c] = PM is measured using laser light scattering which does not measure total PM. Results include multiplicative correction factor of 5 to approximate total PM mass.

TABLE E- 2. Notch average Fuel Use and Emission Rates based on Over-the-Rail Measurements on Three Locomotives Operated on B10: (a) Fuel Use Rate; (b) CO_2 Emission Rate; (c) CO Emission Rate; (d) HC Emission Rate; (e) NO_x Emission Rate; and, (f) PM Emission Rate.

(a) Notch Average Fuel Use Rate on B10 (g/s)

Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	6	4	4	4	4	5	3	4	3	3	4	3	4	4	3	4	3	4
DB[a]	5	5	5	5	5	4	3	5	4	5	5	5	13	5	7	5	5	5
1	12	12	12	11	10	9	8	6	10	9	11	8	11	9	10	11	11	10
2	21	18	12	16	16	13	13	9	15	12	15	12	15	14	16	16	13	15
3	30	31	28	30	26	24	24	18	21	26	29	23	28	27	29	29	27	27
4	45	48	46	46	46	40	36	28	31	36	41	31	39	39	39	39	39	39
5	50	60	56	59	60	55	51	46	39	49	57	52	50	51	53	53	51	52
6	45	70	66	67	59	65	62	65	63	64	71	65	61	65	65	67	66	63
7	70	105	88	102	72	98	-[b]	92	81	90	102	95	91	90	-[b]	92	-[b]	91
8	119	128	121	122	118	121	126	126	121	119	133	125	102	115	114	119	115	113

[a]DB = Dynamic Braking
[b] = No steady state data for the given notch position

(b) Notch Average CO_2 Emission Rate on B10 (g/s)

Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	17	13	11	12	11	15	8	12	9	9	13	10	12	13	10	11	10	10
DB[a]	16	16	16	14	14	13	11	15	13	15	15	14	41	16	20	17	16	16
1	37	38	36	34	31	28	25	18	31	28	33	24	34	29	33	33	32	31
2	64	55	36	50	49	41	40	28	46	38	48	36	47	44	49	49	42	45
3	92	96	88	93	81	76	75	56	66	80	89	71	86	84	90	90	83	83
4	140	148	143	142	143	124	112	88	96	112	127	96	122	120	121	122	121	119
5	156	186	175	185	187	171	159	142	120	152	177	163	155	159	166	164	158	162
6	140	218	206	208	184	201	192	202	196	200	219	202	190	201	204	208	205	196
7	219	327	272	318	224	306	-[b]	285	250	279	316	294	282	281	-[b]	286	-[b]	282
8	371	397	376	381	369	377	391	389	374	368	413	389	319	358	354	369	358	350

[a]DB = Dynamic Braking
[b] = No steady state data for the given notch position

Table E-2 Continued on next page.

Table E-2 Continued from previous page.

(c) Notch Average CO Emission Rate on B10 (g/s)																		
Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.06	0.06	0.05	0.02	0.03	0.06	0.01	0.04	0.02	0.02	0.01	0.03	0.03	91.00	0.04	0.09	0.07	0.13
DB[a]	0.08	0.10	0.07	0.08	0.05	0.07	0.03	0.06	0.02	0.02	0.03	0.02	0.05	0.09	0.08	0.11	0.15	0.13
1	0.04	0.09	0.03	0.07	0.03	0.03	0.02	0.04	0.05	0.05	0.06	0.09	0.03	0.06	0.02	0.10	0.13	0.13
2	0.03	0.08	0.09	0.07	0.02	0.02	0.06	0.02	0.05	0.05	0.06	0.09	0.03	0.06	0.02	0.08	0.10	0.17
3	0.05	0.07	0.05	0.07	0.02	0.02	0.05	0.05	0.10	0.11	0.09	0.10	0.03	0.10	0.05	0.10	0.11	0.16
4	0.07	0.15	0.05	0.09	0.02	0.03	0.12	0.17	0.09	0.12	0.14	0.22	0.02	0.08	0.04	0.13	0.15	0.19
5	0.05	0.18	0.10	0.14	0.00	0.07	0.11	0.26	0.22	0.19	0.22	0.40	0.05	0.14	0.02	0.18	0.18	0.23
6	0.05	0.15	0.11	0.08	0.01	0.02	0.34	0.30	0.25	0.34	0.40	0.28	0.05	0.19	0.03	0.18	0.16	0.19
7	0.11	0.47	0.10	0.26	0.15	0.06	-[b]	0.88	0.20	1.15	1.38	1.19	0.07	0.20	-[b]	0.23	-[b]	0.25
8	0.22	0.44	0.36	0.36	0.07	0.10	2.22	2.58	1.86	1.91	2.13	2.84	0.11	0.21	0.08	0.28	0.34	0.35

[a]DB = Dynamic Braking

[b] = No steady state data for the given notch position

(d) Notch Average HC Emission Rate on B10 (g/s)[c]																		
Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.38	0.45	0.34	0.21	0.23	0.32	0.07	0.04	0.03	0.04	0.06	0.07	0.21	0.41	0.22	0.54	0.48	0.68
DB[a]	0.30	0.73	0.58	0.60	0.32	0.60	0.18	0.17	0.13	0.21	0.12	0.48	0.26	0.69	0.66	0.75	0.88	0.82
1	0.26	0.68	0.42	0.55	0.27	0.35	0.11	0.29	0.02	0.13	0.09	2.42	0.29	0.37	0.24	0.63	0.73	0.82
2	0.42	0.68	0.56	0.68	0.27	0.29	0.13	0.20	0.06	0.11	0.09	0.08	0.26	0.33	0.37	0.56	0.48	0.92
3	0.55	0.77	0.89	0.61	0.34	0.47	0.11	0.54	0.10	0.17	0.07	1.38	0.26	0.56	0.45	0.61	0.74	0.98
4	0.47	1.32	0.72	1.03	0.27	0.70	0.12	0.43	0.08	0.19	0.07	0.24	0.30	0.74	0.34	0.86	0.91	1.04
5	0.59	1.63	0.99	1.20	0.55	1.15	0.10	0.40	0.06	0.12	0.01	5.69	0.38	0.94	0.52	1.31	0.93	1.21
6	0.64	1.33	1.27	0.86	0.40	0.69	0.12	0.25	0.05	0.22	0.02	0.09	0.54	1.43	0.37	1.27	0.90	1.04
7	1.18	2.25	1.50	1.16	1.58	0.72	-[b]	0.33	0.08	0.56	0.03	0.14	0.40	1.47	-[b]	1.38	-[b]	1.11
8	0.54	1.24	0.92	0.68	0.44	0.52	0.09	0.12	0.03	0.12	0.02	1.79	0.65	1.20	1.42	1.27	1.04	1.61

[a]DB = Dynamic Braking

[b] = No steady state data for the given notch position

[c] = HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factor of 2.5 to approximate total HC.

Table E-2 Continued on next page.

Table E-2 Continued from previous page.

(e) Notch Average NO_x Emission Rate on B10 (g/s)[c]

Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.63	0.56	0.43	0.46	0.67	0.58	0.17	0.26	0.20	0.26	0.32	0.19	0.53	0.21	0.36	0.25	0.25	0.26
DB[a]	0.64	0.63	0.59	0.51	0.59	0.55	0.25	0.20	0.25	0.27	0.26	0.24	0.51	0.25	0.37	0.33	0.33	0.34
1	1.42	1.58	1.39	1.24	1.23	1.15	0.47	0.28	0.49	0.46	0.49	0.38	0.63	0.53	0.66	0.73	0.67	0.64
2	2.41	2.44	1.45	1.90	2.08	1.96	0.87	0.48	0.81	0.68	0.83	0.60	0.83	0.85	1.16	1.16	0.90	1.02
3	4.37	4.72	3.80	4.05	4.13	3.79	1.50	1.08	1.19	1.38	1.51	1.21	1.77	1.64	2.18	2.22	2.04	2.06
4	6.25	7.48	4.96	5.65	6.55	5.65	2.07	1.49	1.70	1.85	1.98	1.37	2.39	2.29	2.76	2.85	2.89	2.86
5	7.69	6.84	7.22	6.28	7.54	7.53	2.55	2.13	2.10	2.30	2.35	2.24	2.98	2.93	3.79	3.63	3.57	3.74
6	7.11	7.24	6.98	7.92	7.86	7.42	2.97	2.65	2.86	2.69	2.81	2.71	3.92	3.67	4.38	4.55	4.46	4.41
7	8.34	8.01	7.57	7.96	8.94	8.54	-[b]	3.18	3.08	3.27	3.20	3.04	4.91	4.78	-[b]	5.70	-[b]	5.16
8	8.88	9.34	8.63	8.59	9.22	9.52	3.81	3.36	3.61	3.48	3.72	3.31	5.51	5.01	6.06	6.32	5.77	5.85

[a]DB = Dynamic Braking

[b] = No steady state data for the given notch position

[c] = NO is measured using electrochemical cell which does not measure NO_2. Results include multiplicative correction factor of 1.053 to approximate total NO_x based on NO measurements.

(f) Notch Average PM Emission Rate on B10 (g/s)[d]

Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
DB[a]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01
1	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.02	0.03	0.01	0.02	0.01	0.01	0.01	0.01
2	0.02	0.02	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.04	0.02	0.02	0.01	0.01	0.02	0.01
3	0.02	0.02	0.02	0.02	0.02	0.02	0.05	0.06	0.05	0.06	0.05	0.07	0.03	0.03	0.02	0.02	0.02	0.02
4	0.03	0.03	0.03	0.02	0.03	0.03	0.09	0.09	0.07	0.09	0.08	0.12	0.04	0.04	0.03	0.03	0.03	0.03
5	0.04	0.03	0.03	0.03	0.03	0.03	0.13	0.15	0.11	0.17	0.12	0.16	0.04	0.05	0.04	0.03	0.04	0.03
6	0.03	0.04	0.03	0.03	0.04	0.03	0.17	0.21	0.15	0.19	0.17	0.20	0.05	0.06	0.04	0.04	0.06	0.06
7	0.06	0.14	0.10	0.11	0.06	0.10	-[b]	0.35	0.13	0.41	0.29	0.31	0.10	0.14	-[b]	0.10	-[b]	0.13
8	0.13	0.17	0.14	0.14	0.11	0.12	0.41	0.40	0.37	0.39	0.36	0.37	0.16	0.21	0.14	0.16	0.22	0.24

[a]DB = Dynamic Braking

[b] = No steady state data for the given notch position

[c] = PM is measured using laser light scattering which does not measure total PM. Results include multiplicative correction factor of 5 to approximate total PM mass.

TABLE E- 3. Notch average Fuel Use and Emission Rates based on Over-the-Rail Measurements on Three Locomotives Operated on B20: (a) Fuel Use Rate; (b) CO_2 Emission Rate; (c) CO Emission Rate; (d) HC Emission Rate; (e) NO_x Emission Rate; and, (f) PM Emission Rate.

(a) Notch Average Fuel Use Rate on B20 (g/s)

Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	4	6	5	5	5	6	7	5	6	7	6	6	3	4	4	3	3	3
DB[a]	4	4	5	5	5	4	5	6	6	4	5	5	5	5	6	5	5	5
1	8	7	11	10	8	7	8	11	10	8	9	8	9	9	11	11	11	10
2	13	10	18	18	16	13	13	15	14	10	10	10	14	13	15	16	15	13
3	22	24	30	30	34	20	27	28	21	20	21	14	26	27	27	29	28	25
4	38	37	44	43	40	41	36	38	35	27	29	24	36	39	36	40	38	35
5	49	49	57	58	56	58	53	51	49	42	45	42	49	50	50	54	54	51
6	57	54	65	68	69	61	61	67	55	56	56	54	61	66	61	67	63	65
7	45	78	66	92	96	78	93	97	97	89	-[b]	79	89	94	-[b]	96	83	90
8	104	104	120	119	121	110	127	127	125	117	112	111	111	118	109	123	117	115

[a]DB = Dynamic Braking

[b] = No steady state data for the given notch position

(b) Notch Average CO_2 Emission Rate on B20 (g/s)

Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	11	18	15	15	16	17	22	16	18	21	17	17	9	13	12	9	10	9
DB[a]	12	11	15	14	12	10	16	19	18	12	16	14	14	16	18	15	16	14
1	18	28	35	30	30	25	25	35	31	26	27	24	27	29	33	32	33	31
2	41	41	56	48	49	34	41	45	44	31	32	30	43	40	48	49	47	41
3	81	73	93	83	85	62	82	87	65	62	64	44	81	82	83	88	88	77
4	110	114	137	130	118	100	111	117	107	84	90	74	112	122	112	123	118	109
5	126	151	179	171	167	150	163	157	153	131	139	130	152	154	156	168	168	159
6	143	180	203	195	189	169	189	207	172	174	173	168	188	204	188	207	196	202
7	140	279	207	333	189	254	287	300	302	274	-[b]	245	278	290	-[b]	298	256	278
8	309	343	372	350	359	341	392	393	389	364	346	343	345	365	339	382	363	356

[a]DB = Dynamic Braking

[b] = No steady state data for the given notch position

Table E-3 Continued on next page.

Table E-3 Continued from previous page.

(c) Notch Average CO Emission Rate on B20 (g/s)																		
Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.02	0.01	0.01	0.05	0.01	0.01	0.03	0.02	0.04	0.02	0.03	0.04	0.08	0.10	0.08	0.12	0.05	0.04
DB[a]	0.01	0.00	0.01	0.09	0.01	0.00	0.03	0.02	0.04	0.02	0.03	0.04	0.08	0.10	0.08	0.13	0.06	0.05
1	0.00	0.00	0.00	0.01	0.05	0.01	0.05	0.05	0.02	0.03	0.04	0.04	0.08	0.08	0.07	0.12	0.04	0.06
2	0.00	0.00	0.01	0.02	0.03	0.00	0.04	0.04	0.05	0.04	0.03	0.04	0.04	0.08	0.06	0.14	0.04	0.05
3	0.00	0.00	0.00	0.04	0.01	0.00	0.06	0.09	0.12	0.04	0.07	0.07	0.05	0.10	0.08	0.21	0.05	0.07
4	0.00	0.01	0.01	0.06	0.02	0.00	0.08	0.08	0.20	0.06	0.04	0.06	0.08	0.13	0.04	0.19	0.06	0.08
5	0.00	0.01	0.00	0.03	0.01	0.00	0.14	0.16	0.30	0.10	0.12	0.16	0.07	0.18	0.07	0.40	0.09	0.09
6	0.00	0.01	0.03	0.06	0.00	0.00	0.15	0.33	0.60	0.16	0.17	0.24	0.11	0.13	0.03	0.24	0.06	0.14
7	0.00	0.04	0.03	0.01	0.42	0.02	0.39	0.61	0.51	0.56	-[b]	0.49	0.11	0.23	-[b]	0.45	0.13	0.13
8	0.14	0.15	0.13	0.15	0.11	0.07	1.43	1.38	1.41	1.19	0.74	1.20	0.17	0.35	0.20	0.47	0.21	0.24

[a]DB = Dynamic Braking
[b] = No steady state data for the given notch position

(d) Notch Average HC Emission Rate on B20 (g/s)[c]																		
Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.34	0.39	0.33	0.39	0.32	0.45	0.22	0.25	0.35	0.22	0.23	0.34	0.34	0.43	0.53	0.63	0.30	0.34
DB[a]	0.34	0.58	0.37	0.37	0.30	0.05	0.27	0.26	0.19	0.13	0.04	0.15	0.14	0.56	0.30	0.84	0.34	0.42
1	0.24	0.36	0.29	0.29	0.43	0.21	0.13	0.17	0.17	0.30	0.02	0.10	0.15	0.32	0.15	0.63	0.85	0.34
2	0.19	0.47	0.48	0.08	0.37	0.17	0.23	0.17	0.20	0.17	0.04	0.07	0.09	0.45	0.19	0.72	0.31	0.48
3	0.18	0.63	0.71	0.33	0.53	0.26	0.22	0.14	0.18	0.18	0.04	0.08	0.08	0.60	0.39	0.83	0.27	0.69
4	0.47	0.86	0.25	0.51	0.48	0.33	0.26	0.24	0.13	0.18	0.05	0.14	0.09	0.78	0.50	1.11	0.47	0.57
5	0.06	1.15	0.63	0.64	0.71	0.27	0.33	0.22	0.15	0.25	0.04	0.11	0.15	0.88	0.28	1.57	1.38	0.63
6	1.16	0.72	0.86	0.87	0.25	0.44	0.17	0.22	0.07	0.41	0.03	0.12	0.15	0.99	0.65	1.61	0.77	0.83
7	0.00	1.16	0.13	0.20	2.44	0.13	0.12	0.13	0.11	0.48	-[b]	0.33	0.33	1.19	-[b]	1.70	0.85	1.19
8	0.83	1.22	0.55	0.95	0.94	0.55	0.33	0.11	0.77	0.29	0.34	0.75	0.10	0.96	0.43	1.70	0.45	1.31

[a]DB = Dynamic Braking
[b] = No steady state data for the given notch position
[c] = HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factor of 2.5 to approximate total HC.

Table E-3 Continued on next page.

Table E-3 Continued from previous page.

(e) Notch Average NO_x Emission Rate on B20 (g/s)[c]

Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.48	0.74	0.67	0.59	0.56	0.64	0.22	0.34	0.24	0.35	0.23	0.22	0.23	0.35	0.23	0.21	0.23	0.20
DB[a]	0.49	0.48	0.47	0.54	0.46	0.36	0.26	0.32	0.27	0.25	0.25	0.23	0.30	0.29	0.33	0.28	0.32	0.28
1	0.92	1.17	1.10	1.12	1.19	1.09	0.49	0.59	0.62	0.59	0.47	0.61	0.57	0.58	0.61	0.61	0.65	0.58
2	1.87	1.86	1.91	2.00	2.09	1.73	0.71	0.83	0.93	0.72	0.71	0.64	1.03	0.80	0.97	1.07	1.01	0.74
3	3.44	4.09	3.70	3.92	3.51	3.55	1.43	1.58	1.38	1.36	1.20	0.98	1.89	1.74	1.75	1.97	1.95	1.57
4	5.52	5.70	5.53	6.02	5.23	5.17	1.92	2.05	2.12	1.75	1.91	1.56	2.61	2.53	2.18	2.66	2.50	2.13
5	6.60	6.23	6.94	6.93	7.68	7.25	2.51	2.49	2.76	2.64	2.58	2.36	3.27	2.94	3.03	3.34	3.50	3.18
6	7.37	6.67	7.09	7.46	7.18	6.79	2.83	3.01	3.18	3.37	3.09	2.99	4.07	3.89	3.75	4.06	3.90	3.82
7	0.00	7.54	6.44	8.81	6.84	9.01	3.53	3.71	4.70	4.20	-[b]	3.89	5.37	5.03	-[b]	5.06	4.79	4.96
8	8.21	8.38	8.69	9.17	8.72	8.95	3.98	3.90	4.56	4.68	4.46	4.27	5.65	5.17	5.13	5.54	5.67	5.30

[a]DB = Dynamic Braking

[b] = No steady state data for the given notch position

[c] = NO is measured using electrochemical cell which does not measure NO_2. Results include multiplicative correction factor of 1.053 to approximate total NO_x based on NO measurements.

(f) Notch Average PM Emission Rate on B20 (g/s)[d]

Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
DB[a]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.01
1	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.00	0.00	0.02	0.02
2	0.01	0.01	0.01	0.01	0.02	0.01	0.04	0.03	0.03	0.03	0.03	0.03	0.01	0.01	0.00	0.00	0.02	0.02
3	0.02	0.02	0.02	0.02	0.02	0.02	0.05	0.04	0.04	0.04	0.04	0.04	0.01	0.01	0.00	0.00	0.03	0.03
4	0.02	0.02	0.02	0.02	0.02	0.02	0.08	0.07	0.07	0.06	0.07	0.06	0.02	0.02	0.00	0.00	0.04	0.04
5	0.02	0.02	0.02	0.02	0.02	0.02	0.10	0.10	0.09	0.08	0.09	0.10	0.02	0.02	0.00	0.00	0.05	0.04
6	0.03	0.02	0.02	0.02	0.03	0.03	0.10	0.14	0.08	0.11	0.12	0.10	0.02	0.03	0.00	0.00	0.04	0.05
7	0.00	0.10	0.10	0.08	0.05	0.07	0.18	0.22	0.11	0.19	-[b]	0.18	0.08	0.06	-[b]	0.00	0.07	0.12
8	0.11	0.12	0.13	0.08	0.08	0.10	0.25	0.28	0.20	0.19	0.16	0.20	0.12	0.11	0.00	0.00	0.14	0.16

[a]DB = Dynamic Braking

[b] = No steady state data for the given notch position

[c] = PM is measured using laser light scattering which does not measure total PM. Results include multiplicative correction factor of 5 to approximate total PM mass.

TABLE E- 4. Notch average Fuel Use and Emission Rates based on Over-the-Rail Measurements on Three Locomotives Operated on B40: (a) Fuel Use Rate; (b) CO_2 Emission Rate; (c) CO Emission Rate; (d) HC Emission Rate; (e) NO_x Emission Rate; and, (f) PM Emission Rate.

(a) Notch Average Fuel Use Rate on B40 (g/s)

Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	6	5	6	6	5	6	6	5	6	5	5	-[c]	3	4	4	3	3	3
DB[a]	5	6	5	6	5	5	5	5	6	7	8	-[c]	6	5	5	4	5	4
1	12	13	11	13	11	10	7	8	8	11	12	-[c]	8	9	9	7	9	9
2	16	15	18	19	15	14	13	10	11	13	13	-[c]	11	11	13	10	14	11
3	31	30	31	32	31	29	22	19	21	23	21	-[c]	28	24	25	24	24	25
4	46	45	47	47	45	40	31	29	35	25	26	-[c]	35	36	38	36	35	33
5	61	55	63	62	57	58	45	40	49	34	48	-[c]	48	47	53	53	47	46
6	74	65	66	73	64	64	60	57	61	34	56	-[c]	63	64	66	65	58	62
7	-[b]	86	-[b]	-[b]	79	-[b]	77	94	82	-[b]	79	-[c]	91	86	97	92	83	80
8	125	127	128	129	125	122	120	115	121	111	123	-[c]	118	120	124	118	113	112

[a]DB = Dynamic Braking
[b] = No steady state data for the given notch position
[c] = Data unavailable

(b) Notch Average CO_2 Emission Rate on B40 (g/s)

Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	17	16	16	17	16	19	19	16	19	16	16	-[c]	9	12	12	8	9	8
DB[a]	16	17	15	17	16	15	16	14	18	21	24	-[c]	17	15	15	13	15	13
1	38	39	34	39	32	30	22	26	24	35	38	-[c]	24	27	27	21	28	26
2	50	46	55	57	45	42	39	31	34	40	41	-[c]	33	34	40	29	43	33
3	94	92	95	97	95	88	68	58	67	70	64	-[c]	87	75	78	73	75	78
4	142	137	142	144	136	121	95	89	108	77	82	-[c]	109	110	118	111	108	102
5	187	169	195	191	174	179	141	124	153	105	148	-[c]	148	146	164	164	146	143
6	228	199	203	225	198	196	187	175	189	106	173	-[c]	195	197	203	202	179	192
7	-[b]	264	-[b]	-[b]	243	-[b]	239	290	254	-[b]	246	-[c]	280	264	299	283	254	247
8	387	391	394	398	386	376	373	355	374	346	383	-[c]	364	369	384	364	348	345

[a]DB = Dynamic Braking
[b] = No steady state data for the given notch position
[c] = Data unavailable

Table E-4 Continued on next page.

Table E-4 Continued from previous page.

(c) Notch Average CO Emission Rate on B40 (g/s)																		
Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.04	0.08	0.23	0.33	0.12	0.11	0.03	0.03	0.03	0.03	0.03	-[c]	0.02	0.01	0.05	0.04	0.06	0.05
DB[a]	0.16	0.18	0.18	0.51	0.14	0.37	0.03	0.02	0.04	0.01	0.01	-[c]	0.12	0.10	0.06	0.07	0.08	0.06
1	0.15	0.07	0.03	0.15	0.11	0.03	0.03	0.02	0.04	0.07	0.03	-[c]	0.09	0.10	0.04	0.06	0.10	0.04
2	0.19	0.06	0.11	0.17	0.07	0.03	0.03	0.04	0.04	0.04	0.03	-[c]	0.05	0.09	0.02	0.05	0.06	0.05
3	0.28	0.07	0.07	0.13	0.18	0.03	0.11	0.06	0.07	0.05	0.03	-[c]	0.05	0.15	0.07	0.07	0.08	0.05
4	0.04	0.13	0.26	0.25	0.28	0.00	0.09	0.11	0.05	0.07	0.06	-[c]	0.10	0.10	0.06	0.11	0.10	0.06
5	0.02	0.20	0.08	0.28	0.20	0.08	0.14	0.12	0.16	0.08	0.14	-[c]	0.07	0.14	0.07	0.21	0.07	0.09
6	0.00	0.13	0.01	0.27	0.22	0.04	0.07	0.10	0.21	0.12	0.14	-[c]	0.19	0.05	0.14	0.11	0.11	0.08
7	-[b]	0.20	-[b]	-[b]	0.08	-[b]	0.01	0.32	0.23	-[b]	0.22	-[c]	0.23	0.19	0.13	0.39	0.23	0.20
8	0.31	0.39	0.50	0.62	0.54	0.40	0.74	0.61	0.70	0.84	0.91	-[c]	0.33	0.48	0.29	0.32	0.28	0.24

[a]DB = Dynamic Braking
[b] = No steady state data for the given notch position
[c] = Data unavailable

(d) Notch Average HC Emission Rate on B40 (g/s)[c]																		
Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.44	0.58	1.24	1.16	0.77	0.89	0.03	0.04	0.02	0.03	0.02	-[d]	0.22	0.33	0.16	0.19	0.25	0.20
DB[a]	0.75	1.05	1.06	1.48	0.87	0.57	0.04	0.04	0.03	0.04	0.05	-[d]	0.61	0.41	0.21	0.30	0.34	0.27
1	0.74	0.64	0.23	0.94	0.64	0.15	0.03	0.02	0.04	0.02	0.04	-[d]	0.44	0.49	0.17	0.30	0.38	0.15
2	0.77	0.82	0.95	0.99	0.57	0.30	0.04	0.05	0.03	0.02	0.03	-[d]	0.38	0.28	0.22	0.33	0.25	0.26
3	1.25	0.84	0.50	1.24	0.88	0.79	0.04	0.07	0.03	0.05	0.01	-[d]	0.28	0.59	0.37	0.39	0.28	0.23
4	0.64	0.99	1.99	1.66	1.73	1.66	0.07	0.08	0.03	0.05	0.04	-[d]	0.68	0.43	0.25	0.47	0.30	0.39
5	1.64	1.37	1.57	1.80	1.34	0.72	0.00	0.06	0.06	0.10	0.01	-[d]	0.39	0.77	0.47	0.78	0.22	0.38
6	1.33	0.91	0.33	1.89	1.44	1.24	0.05	0.05	0.01	0.00	0.00	-[d]	0.51	0.72	0.38	0.48	0.40	0.46
7	-[b]	1.79	-[b]	-[b]	0.87	-[b]	0.12	0.08	0.02	-[b]	0.00	-[d]	0.60	0.59	0.28	0.89	0.70	0.94
8	1.11	0.72	1.73	1.49	1.24	0.57	0.04	0.07	0.03	0.04	0.00	-[d]	0.84	1.10	0.25	0.61	0.31	0.49

[a]DB = Dynamic Braking
[b] = No steady state data for the given notch position
[c] = HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factor of 2.5 to approximate total HC.
[d] = Data unavailable

Table E-4 Continued on next page.

Table E-4 Continued from previous page.

(e) Notch Average NO_x Emission Rate on B40 (g/s)[c]																		
Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.67	0.64	0.67	0.70	0.62	0.43	0.22	0.32	0.38	0.43	0.33	-[d]	0.23	0.23	0.23	0.19	0.25	0.21
DB[a]	0.66	0.68	0.65	0.66	0.68	0.54	0.32	0.27	0.38	0.34	0.35	-[d]	0.34	0.31	0.29	0.26	0.34	0.30
1	1.59	1.69	1.54	1.65	1.37	1.13	0.51	0.51	0.52	0.57	0.58	-[d]	0.57	0.58	0.54	0.43	0.65	0.61
2	2.20	2.12	2.59	2.65	2.10	1.82	0.64	0.83	0.63	0.71	0.58	-[d]	0.70	0.80	0.85	0.63	1.02	0.73
3	4.66	4.75	4.89	4.72	4.79	4.33	1.18	1.38	1.38	1.30	1.47	-[d]	2.01	1.76	1.72	1.65	1.89	1.78
4	6.78	6.07	7.03	5.59	7.37	5.82	1.87	1.65	2.32	1.68	2.25	-[d]	2.51	2.54	2.53	2.32	2.57	2.31
5	8.72	8.22	6.79	8.53	7.01	7.85	2.55	2.59	3.01	2.75	3.06	-[d]	3.21	3.17	3.37	3.36	3.51	3.12
6	6.80	9.13	9.21	8.46	9.30	6.96	3.40	3.21	3.69	3.34	3.59	-[d]	3.98	4.10	3.97	3.85	3.93	3.99
7	-[b]	8.98	-[b]	-[b]	9.63	-[b]	4.57	4.34	4.30	-[b]	4.08	-[d]	5.02	4.83	5.19	5.40	4.72	4.55
8	9.14	9.23	9.39	9.45	9.30	8.50	4.32	4.62	4.82	3.79	4.57	-[d]	5.79	6.00	5.72	5.37	5.70	5.43

[a]DB = Dynamic Braking

[b] = No steady state data for the given notch position

[c] = NO is measured using electrochemical cell which does not measure NO_2. Results include multiplicative correction factor of 1.053 to approximate total NO_x based on NO measurements.

[d] = Data unavailable

(f) Notch Average PM Emission Rate on B40 (g/s)[d]																		
Throttle Notch Position	NC 1797						NC 1810						NC 1859					
	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6
Idle	0.01	0.02	0.01	0.01	0.01	0.02	0.03	0.03	0.03	0.02	0.02	-[d]	0.01	0.01	0.01	0.01	0.02	0.02
DB[a]	0.01	0.02	0.01	0.01	0.01	0.01	0.03	0.03	0.03	0.02	0.02	-[d]	0.01	0.01	0.01	0.01	0.01	0.01
1	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.02	0.03	0.03	0.02	-[d]	0.02	0.02	0.02	0.02	0.02	0.02
2	0.02	0.02	0.02	0.01	0.01	0.01	0.03	0.02	0.02	0.03	0.02	-[d]	0.02	0.02	0.03	0.02	0.03	0.02
3	0.03	0.02	0.02	0.02	0.02	0.01	0.06	0.04	0.04	0.04	0.03	-[d]	0.03	0.03	0.03	0.03	0.03	0.03
4	0.04	0.06	0.03	0.03	0.03	0.02	0.05	0.05	0.04	0.05	0.04	-[d]	0.04	0.04	0.05	0.05	0.04	0.04
5	0.06	0.09	0.06	0.03	0.03	0.03	0.09	0.07	0.09	0.08	0.07	-[d]	0.05	0.05	0.06	0.06	0.05	0.05
6	0.06	0.10	0.04	0.04	0.04	0.03	0.10	0.10	0.11	0.11	0.08	-[d]	0.06	0.06	0.07	0.07	0.06	0.06
7	-[b]	0.43	-[b]	-[b]	0.06	-[b]	0.07	0.14	0.13	-[b]	0.11	-[d]	0.12	0.09	0.11	0.10	0.10	0.08
8	0.28	0.25	0.24	0.20	0.18	0.15	0.23	0.23	0.24	0.22	0.20	-[d]	0.12	0.13	0.16	0.16	0.14	0.16

[a]DB = Dynamic Braking

[b] = No steady state data for the given notch position

[c] = PM is measured using laser light scattering which does not measure total PM. Results include multiplicative correction factor of 5 to approximate total PM mass.

[d] = Data unavailable

Appendix F. Abbreviations and Acronyms

AREMA	American Railway Engineering and Maintenance-of-way Association
ASTM	American Society for Testing and Materials
B10	Blend of 90 percent, by volume, ULSD and 10% biofuel blend stock
B100	100% biofuel blend stock, no ULSD.
B20	Blend of 80 percent, by volume, ULSD and 20% biofuel blend stock
B40	Blend of 60 percent, by volume, ULSD and 40% biofuel blend stock
B60	Blend of 40 percent, by volume, ULSD and 60% biofuel blend stock
B80	Blend of 20 percent, by volume, ULSD and 80% biofuel blend stock
BAR	California Bureau of Automotive Repair
BATS	Blended exhaust After-Treatment System
CAER	Cycle Average Emission Rate
CAT ACERT	Caterpillar Advanced Combustion Emissions Reduction Technology
CAT-ET	Caterpillar Electronic Technician
CFR	Code of Federal Regulations
CN	Cetane Number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CV	Coefficient of Variation (Standard deviation divided by mean)
DB	Dynamic Brake
DEF	Diesel Exhaust Fluid
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECU	Electronic Control Unit
EF&EE	Engine Fuels and Emissions Engineering
EMD	Electro Motive Division
EMD	Electromotive Diesel
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification program of the US EPA
FUER	Fuel Use and Emission Rate
GPS	Global Position System
H_2O	Water Vapor
HC	Hydrocarbons
HEP	Head End Power engine
HFID	Heated Flame Ionization Detection
IAT	Intake Air Temperature
ISO	International Organization for Standardization
LEMS	Locomotive Emissions Measurement System
LHV	Lower Heating Value
LHV	Lower Heating Value
LPD	Locomotive Power Demand
MAD	Maximum Allowable Difference
MAP	Manifold Absolute Pressure
NAAQS	National Ambient Air Quality Standards

NC	North Carolina
NCDOT	North Carolina Department of Transportation
NCSU	North Carolina State University
NDIR	Non-Dispersive Infrared
NDUV	Non-Dispersive Ultra Violet
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
OTR	Over-the-Rail
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter less than 2.5 micro-meters in aerodynamic diameter
PME	Prime Mover Engine
RPM	Revolutions per Minute
RY	Railyard
SCR	Selective Catalytic Reduction
SWRI	South West Research Institute
THC	Total Hydro Carbons
U.S. EPA	United States Environmental Protection Agency
ULSD	Ultra-Low Sulfur Diesel
VOC	Volatile Organic Compounds
WHO	World Health Organization