RESEARCH & DEVELOPMENT

Managing Energy and Emissions for Rail Operations

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16. Abstract

The objectives of this work include: (1) benchmark baseline locomotive fuel use and emission rates (FUER) to EPA dynamometer measurements, other locomotives, and emission standards; (2) quantify the effect of transients on real-world trip fuel use and emissions (TFUE); (3) quantify the trade-offs in TFUE between double- and single-powered push/pull consists; and (4) calibrate, validate, and apply a locomotive power demand (LPD) model to predict 1 Hz FUER. Rail yard (RY) and over-the-rail (OTR) measurements of locomotive FUER using a portable emissions measurement system (PEMS) were conducted. Measurements were made for diesel locomotives owned by NCDOT and operated by Amtrak for the Piedmont rail service. The NCDOT locomotives are typically more fuel-efficient than the EPA benchmark fuel use rate. Measured steady-state RY and OTR emission rates were approximately similar to EPA dynamometer measurements. NCDOT locomotives with electronically-governed fuel injection had lower fuel use and CO_2 emission rates versus locomotives with mechanically-governed fuel injection. Several of the locomotives had real-world emission rates of selected pollutants higher than the level of the applicable Tier 0+ standard. Approaches to reduce such emissions are discussed. Accurate TFUE for real-world trips can be quantified based on incorporating transients. Approaches that incorporate transients include measuring 1 Hz FUER for the entire trip duration and estimating trip total emission rates based on modal average rates that are calibrated based on transient data. The double-powered push/pull consist is preferred in terms of fuel savings and emissions reductions of CO_2, CO, and NO_x with trade-offs of higher HC and PM emissions versus the single-powered consist based on measurements of two locomotives. However, the differences between consists with respect to TFUE would be estimated with more confidence based on a larger sample of locomotives. The LPD model is accurate for estimating average TFUE. The model can be used to demonstrate emission reduction benefits related to infrastructure improvements. The model was applied to case studies that illustrate potential ways to reduce TFUE via improvements to infrastructure and operations.

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Executive Summary

Introduction

Existing data on locomotive fuel use and emission rates (FUER) are typically based on static-load steady-state operation-based engine dynamometer and rail yard (RY) measurements. Locomotive regulatory emission certification tests are also based on static-load steady-state operation. However, real-world operation differs from steady-state measurements because it involves dynamic loads and transient operation. Therefore, steady-state operation-based FUER are not representative of actual locomotive operation. Real-world operation can also involve train consists with more than one locomotive operating a train. Locomotive FUER may differ for single locomotive operation versus multiple locomotives in a train consist due to differences in tractive power provided by each locomotive. To quantify FUER representative of actual operation, FUER should be measured during actual train operation, known as over-the-rail (OTR) measurements, including typical train consists.

RY measurements are conducted at steady-state in a controlled environment. Therefore, RY measurements provide a consistent basis for estimating FUER. Effects of changes such as alternate fuels, retrofits, and engine rebuilds can be quantified by comparing FUER after these changes to a baseline. Locomotive FUER can be benchmarked to other locomotives and to locomotive emission standards. Benchmarking to other locomotives in a fleet enables identification of the most fuel-efficient and least emitting locomotives. Benchmarking to emissions standards helps identify the needs for emission reduction interventions. However, RY measurements cannot be used to evaluate the effect of consists and transients. Therefore, to quantify FUER and trip fuel use and emissions (TFUE) representative of actual operation for actual consists, OTR measurements are required.

For OTR measurements, FUER and TFUE can be estimated based on steady-state and transient data. Transient data comprises all seconds of locomotive operation, including transitions between throttle notch positions. Therefore, transient data are more representative of OTR operation. The steady-state data are used to benchmark among locomotives, to emission standards, and to compare the effects of alternative fuels, retrofits, and engine rebuilds. FUER and TFUE may also vary based on the train consist. There may be trade-offs in TFUE among different train consists.

Demonstration of emissions reductions associated with transportation is required to procure Federal funding. Transportation improvement projects may result in changes in train trajectories and track geometry. A train trajectory is quantified based on 1 Hz train speed and acceleration. Track geometry includes rail grade and curvature. Therefore, a model is developed and demonstrated to estimate FUER for a given train trajectory and track geometry. The model accounts for the train consists observed on the Piedmont passenger rail service and for fuels including ultra-low sulfur diesel (ULSD) and a blend of 20 percent biodiesel in diesel (B20). As an example of the application of the model, emission reduction benefits of replacing a hill with a flat track are estimated. Two train trajectories of similar average speed, similar duration and in the same travel direction for the same locomotive, consist, and fuel are compared.

Objectives

The objectives of this work include:

- Benchmark baseline fuel use and emission rates of locomotives to other locomotives and emission standards;
- Quantify the effect of transients on trip fuel use and emissions;
- Quantify the trade-offs in trip fuel use and emissions between double- and single-powered push/pull consists; and
- Calibration, validation, and application of a model to predict 1 Hz locomotive fuel use and emission rates.

Methods

Baseline RY and OTR measurements were conducted for the prime mover engines (PMEs) of two locomotives recently acquired by the North Carolina Department of Transportation (NCDOT). The two locomotives are NC 1871 and NC 1984 and were operated on 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 locomotive is slowed using the mechanical brake or dynamic brake. In a dynamic brake, the traction motors act as generators and electricity is dissipated as heat through an electric resistance grid.

RY measurements were used to quantify FUER based on steady-state data. Typically, one RY "measurement" was conducted for each locomotive to quantify FUER. Each "measurement" includes three replicates of a measurement schedule. The measurement schedule included running the locomotive at each of the PME throttle notch positions successively for a pre-defined time duration.

OTR measurements were conducted on the revenue-generating Amtrak Piedmont passenger rail service between Raleigh, NC and Charlotte, NC. A typical train included two locomotives in push/pull consist, 2-4 passenger cars, and one baggage/café car. In a push/pull consist, two locomotives are used at either end of a train. Typically, both locomotives provide equal tractive power and are referred to as double-powered push/pull (DP-P/P). In case of malfunction of one locomotive, the other locomotive provides full power and is referred to as single-powered push/pull (SP-P/P). Typically, three one-way trips on the double-powered consist and three one-way trips on the single-powered consist were conducted for a given locomotive. Each one-way trip had a different percentage of time spent in each throttle notch position, also known as a duty cycle, due to differences in driver behavior and due to differences in tractive power provided by each locomotive.

FUER depend on exhaust flow rate and exhaust concentrations. Exhaust flow rate depends on air flow rate and fuel/air ratio. Air flow rate depends on engine revolutions per minute (RPM), intake air temperature (IAT), and manifold absolute pressure (MAP). The fuel/air ratio can be inferred from exhaust composition.

Exhaust gas and particulate matter (PM) concentrations were measured using an Axion Portable Emissions Measurement System (PEMS) manufactured by Global MRV. Measured exhaust gases include carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxide (NO) and oxygen (O_2). RPM, IAT, and MAP were measured using an engine sensor array installed on the engine and connected to the Axion PEMS.

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 percentage of time at Notch 8, and a lower percentage of time at idle, compared to the line-haul cycle.

Benchmarking Locomotives

Benchmarking of NCDOT locomotives to EPA data, each other and levels of emission standards is useful in assessing the general performance of the locomotive fleet and in identifying opportunities to improve performance.

Variability in RPM, IAT, and MAP for a given notch position among locomotives can lead to inter-locomotive variability in air flow rate and, ultimately, in FUER. Therefore, the inter-locomotive variability in RPM, IAT, and MAP is quantified to help explain inter-locomotive variability in FUER.

FUER estimated for the PMEs of all NCDOT locomotives measured in this and prior projects were benchmarked to EPA reported data for the same model PME. Locomotives NC 1871 and NC 1984 were benchmarked to other NCDOT-owned locomotives operated on ULSD. The cycle-average emission rates (CAER) were benchmarked to the emission standards. CAER were estimated based on steady-state notch-average rates from OTR measurements weighted to the EPA line-haul duty cycle.

FUER and CAER for other NCDOT-locomotives were measured in prior work for single-locomotive (*SLC*), and double-powered tandem (*DP-T*) consists operated on ULSD. A single-locomotive consist includes only one locomotive per train. In a double-powered tandem consist, two locomotives simultaneously propel the train and are placed next to each other. Data from prior work include single-locomotive consist measurements of NC 1797, NC 1810, NC 1859 and NC 1893 and double-powered tandem measurement of NC 1859.

Steady-State versus Transients

To quantify the effect of transients, FUER based on transient data and steady-state data were compared based on OTR measurements. Since real-world notch-average PME FUER and duty cycles may differ from steady-state based FUER and regulatory duty cycles, respectively, five approaches to estimate TFUE were compared. These approaches are based on steady-state rates, transient rates, or combinations of both. To quantify the accuracy of each approach, the estimated PME trip fuel consumption was benchmarked to the actual PME trip fuel consumption. The locomotive activity recorder displays the volume of the fuel left in the tank. The fuel tank provides fuel to the PME and the Head End Power (HEP) engine of the locomotive. The trip combined PME and HEP engine fuel consumption was inferred based on the difference of the fuel tank display at the beginning and the end of each one-way trip. The actual PME trip fuel consumption was inferred from the difference of the total fuel consumed and the estimated HEP engine fuel consumption.

Double- versus Single-powered Consists

For push/pull consists, TFUE for the entire train was estimated based on the sum of TFUE of both locomotives. During OTR measurements, more time delays were typically encountered for the double- versus single-powered push/pull consists. However, these delays were not due to the consist. These delays were because of rail maintenance or heavy rail traffic. Therefore, to have a consistent comparison of the double-versus single-powered consists, the comparisons were made for equal duration trips. Idling time was added to the shorter time duration trip of the single-powered consist so that it equaled the trip duration of the double-powered consist.

Model to Predict Locomotive FUER

A model to predict locomotive FUER based on train trajectory, track geometry, train consist, and fuel was developed and demonstrated. Based on literature review, FUER for engine load above idle is directly related to locomotive power demand (LPD). LPD is based on the physics of resistive forces that must be overcome by the tractive effort of the locomotive(s). LPD for a given train consist is a function of train trajectory and track geometry.

The data used to calibrate and validate the model includes OTR measurements conducted during this project period and OTR measurements from prior work. Data from prior work includes single-locomotive consist measurements of NC 1797, NC 1810 and NC 1859 operated on B20 biodiesel in addition to locomotives and consists operated on ULSD. One-Hz engine activity, exhaust concentration, locomotive activity, and GPS data were time-aligned and screened for errors from which 1 Hz FUER were quantified. The rail grade and curvature for every second of data were quantified based on GPS receiver data.

The change in RPM, IAT, and MAP during the transition period from one notch setting to another is gradual over a period of typically 5 to 30 seconds depending on the difference of engine output between the two levels. Therefore, FUER were hypothesized to vary linearly with an n-second backward moving average LPD, where n is the backward moving average period. To identify a suitable averaging period for model specification, the number of seconds in the moving average period, n, was varied from 1 to 100. The Pearson correlation coefficient was estimated between non-idle fuel use rate and moving average LPD. The averaging period that led to the highest correlation between the moving average LPD and 1 Hz fuel use rate was selected as the basis for model calibration.

For each combination of locomotive, consist, and fuel, proportionality constants were estimated as the slope of linear regression of 1 Hz FUER versus 12 second backward moving average LPD based on leave-one-out (LOO) cross-validation. In LOO cross-validation, all but one of the available one-way trips were used to calibrate the model. The left out one-way trip was used to validate the model. LOO model calibration was repeated for all possible combinations of selected and left-out trips. The accuracy of model predictions for each LOO case for each species (i.e., fuel, pollutant) was evaluated based on the slope of the parity plot of predicted versus empirical FUER. The accuracy of the models was evaluated based on calibration data and based on the left-out trip used for validation. The precision of the parity slope is indicated by the confidence interval of the slope. Model precision was also inferred based on the coefficient of determination (R^2). For models with similar proportionality constants among all LOO cross-validation cases, a final model calibrated to all one-way trips was used.

Model Applications

The model was applied to evaluate the effect of infrastructure changes and variations in train trajectories on FUER for a single consist locomotive NC 1859 operated on ULSD with three passenger cars and one baggage/café car. To evaluate the impact of infrastructure changes, a hypothetical case of replacing a mile of track with ascent followed by descent with a mile of flat track (zero grade) is demonstrated. To quantify the effect of trajectory changes on TFUE, the empirical and predicted fuel use and emissions for two trajectories are compared.

Results

Benchmark comparisons of recently acquired locomotives to other NCDOT locomotives and emission standards based on OTR measurements are presented. Differences in TFUE for steady-state versus transient operation are quantified. Trade-offs between TFUE for the double- versus single-powered consists are quantified. The calibration, validation and application of a model to predict 1 Hz FUER are demonstrated.

Benchmarking Locomotives

Benchmarking of NCDOT locomotives based on OTR measurements to a typical EPA reported line-haul duty cycle-average fuel-specific engine output (FSEO) is presented in Figure ES-1. The EPA reported typical FSEO is 20.8 bhp-hr/gal for PMEs manufactured in the mid-1990s. The NCDOT locomotives are typically more fuel-efficient than the EPA benchmark.

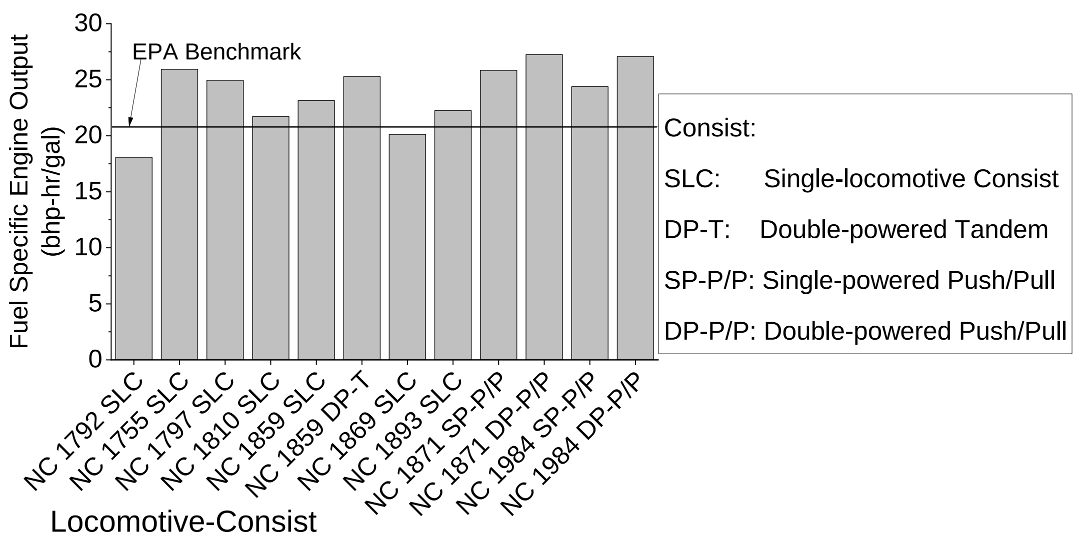


FIGURE ES-1. The EPA Line-haul Duty Cycle based Fuel Specific Engine Output Estimated based on Steady-State Fuel Use Rates for the Most Recent Over-the-Rail Measurement of the Prime Mover Engines of all NCDOT Locomotives Operated on Ultra-low Sulfur Diesel.

The measured OTR notch-average CO, NO_x and PM emission rates were approximately similar to those reported by the EPA for the same model PME based on engine dynamometer measurement. Notch-average HC emission rates were approximately 3 to 4 times higher. For most NCDOT locomotives and PME notch positions, the measured exhaust concentrations were below the gas analyzer detection limit. Therefore, the differences in HC emission rates compared to the EPA reported rates are not significant.

The notch-average RPM, IAT, and MAP for a given notch position of a locomotive were typically different versus all locomotives measured here and in prior work. Among these locomotives, fuel injection was governed either mechanically or electronically. For a given locomotive, notch-average MAP differed between the double- and single-powered consists at notches 7 and 8. Therefore, notch-average FUER varied among locomotives and consists. These results imply that comparisons between consists must account for variations in engine operation. Locomotives NC 1871 and NC 1984 typically have the highest cycle-average FSEOs among all of the NCDOT locomotives based on single- and double-powered push/pull consists. In contrast, locomotives NC 1810, NC 1869, and NC 1893 have lower FSEO based on single-locomotive consists. Although, these numbers are not directly comparable, because the consists differ, and because a given locomotive is typically more efficient fuel-efficient in a double-locomotive consist, the results are indicative that some locomotives are more fuel efficient than others.

The EPA has set emission standards for CO, HC, $NO_{x,}$ and PM. Although the EPA has not set emission standards for CO_2 emissions from locomotive engines, a typical CO_2 emission rate can be inferred from the EPA benchmark fuel specific engine output of 20.8 bhp-hr/gal. A CO_2 emission rate benchmark corresponding the EPA benchmark FSEO was inferred to be 480 g/bhp-hr by assuming 100% conversion of C in fuel to CO_2, and 87 wt% carbon content in the fuel. Cycle average CO_2 emission rates for the NCDOT locomotives are compared to this inferred benchmark value. CAER are given in Figure ES-2. The PME of each locomotive is certified to the Tier 0+ standard. Each of the locomotives and consists had cycle-average CO emission rates below the level of the Tier 0+ standard. However, cycle-average HC, $NO_{x,}$ and PM emission rates were higher than the level of the Tier 0+ standard for at least 7 of the 12 measured locomotives and consists.

Steady-State versus Transients

On average, OTR operation is mostly comprised of transient operation. Steady-state operation only accounts for an average of 35 percent of the trip duration. Steady-state operation contributes 38 percent to 60 percent to TFUE. Therefore, it is not possible to estimate trip total fuel use or emissions simply by summing observed second-by-second steady state operation. Steady-state notch average emission rates tend to be higher, on average, than transient emission rates. Therefore, using notch average rates based on steady-state data extrapolated to the total amount of time in each notch position for real-world trips will lead to overestimation of trip total fuel use and emissions. Accurate TFUE can be quantified based on incorporating transients. Approaches that incorporate transients include measuring 1 Hz FUER for the entire trip duration, estimating trip total emission rates based on modal average rates that are calibrated based on transient data, or estimating average rates using an LPD-based modeling approach.

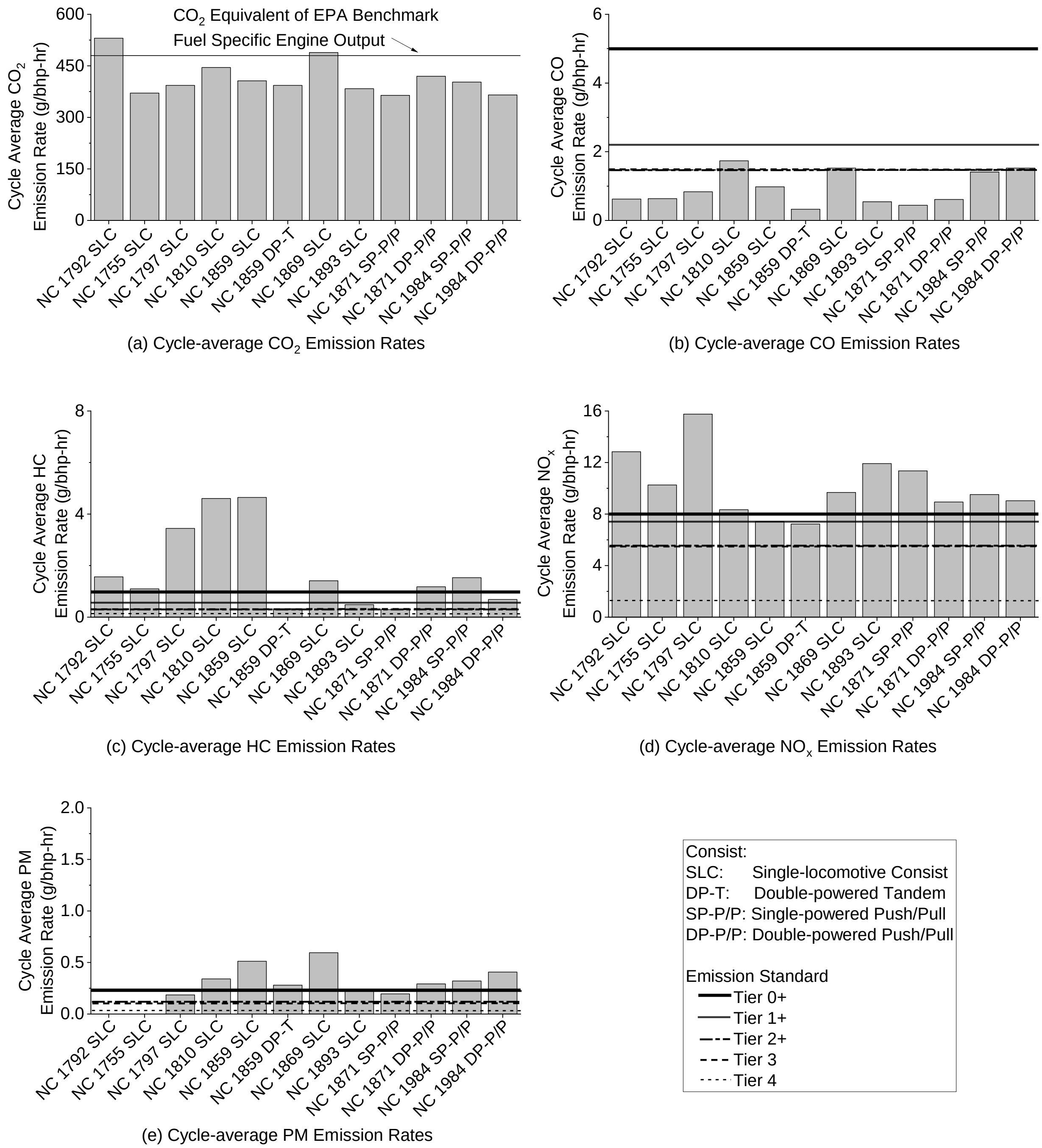


FIGURE ES-2. The EPA Line-haul and Piedmont Duty Cycle based Average Emission Rates Estimated based on Steady-State Emission Rates for the Most Recent Over-the-rail Measurement of the Prime Mover Engines of all NCDOT Locomotives Operated on Ultra-low Sulfur Diesel: (a) CO_2 Emission Rate; (b) CO Emission Rate; (c) HC Emission Rate; (d) NO_x Emission Rate; and (e) PM Emission Rate. CO_2 emission rate corresponding the EPA benchmark FSEO of 20.8 bhp-hr/gal was inferred by assuming 100% conversion of C in fuel to CO_2, and 87 wt% carbon content in the fuel.

Trade-offs of Double- versus Single-powered Consists

To compare double- versus single-power consists on a consistent basis, TFUE for double- and single-powered consists were estimated taking transients into account. Based on measurements of NC 1871 and NC 1984 in single and double powered consists, inferences are made regarding the TFUE of push/pull consist trains with two locomotives. The double-powered configuration has lower fuel use and lower emissions of CO_2, CO and NO_x. These findings are consistent based on measurements of both of the locomotives. However, the findings are inconsistent for HC and PM emissions. The TFUE for a push/pull consistent for HC and PM emission rates was higher for the single-powered configuration based on NC 1984 but lower based on NC 1871.

Model to Predict 1 Hz Locomotive Fuel Use and Emission Rates

A model to predict locomotive FUER for a given locomotive, consist, and fuel at 1 Hz is demonstrated. Locomotive FUER were most strongly correlated to 12-second backward moving average LPD. Thus, FUER in the current second depends on the average of the LPD in the current second and past 11 seconds.

Since the model is based on physics of overcoming resistances opposing train motion, the model formulation is robust. In general, the models were more precise for fuel use and emission rates of CO_2, $NO_{x,}$ and PM than for CO and HC emissions. The imprecision of CO and HC emission rates because measured notch average concentrations for multiple notch positions for all locomotives were below the detection limit of the analyzers. Nonetheless, the calibrated proportionality constant for each locomotive, consist, fuel, and species (i.e. fuel, pollutant) was robust to choice of trips for model calibration. Although, modeled CO and HC emission rates were imprecise, proportionality constants were estimated with high precision for these pollutants, and for other species, because of large sample sizes.

On average over all available trips, the models were accurate for each combination of locomotives, consists, and fuels. The rates estimated by the LPD models are able to appropriately respond to changes in model inputs such as speed, acceleration, grade, and curvature. The random errors at 1 Hz compensate to a large extent when averaged over a larger period of time such as trip duration. Overall, the model performed well for pollutants of greatest concern, including CO_2, NO_x and PM. The model is calibrated based on real-world data for the Piedmont rail operation, including typical train consists. Therefore, the model is representative of real-world Piedmont rail operation. Models were calibrated for 12 combinations of locomotives, consists, and fuels. Not all locomotives were measured for all consists and fuels. This suite of models can be used to compare TFUE among combinations of locomotives, consists, and fuels based on real-world operation.

Model Applications

The model case study 1 quantifies the difference in fuel use and emission rates over the 1 mile of track for the hill described above compared to a level flat track. This type of regrading might occur, for example, in a real project for which a grade crossing is separated. To focus the comparison only on the effect of grade, the train is assumed to run at a constant speed of 35 mph over the level track. The predicted fuel use and emissions for the one mile of track for the hilly and flat alternatives are given in Table ES-1. Leveling the track is estimated to result in a localized 65 percent reduction in fuel use and emissions of CO_2 and reductions of 18 percent, 58 percent, and 39 percent in CO. HC, NO_x and PM emissions, respectively.

The model case study 2 quantifies the difference in fuel use and emission rates for two train trajectories. The trips had similar average speeds at 49 mph for Trip 1 and 48 mph for Trip 2. However, because of differences in the frequency and magnitude of accelerations, the average power demand for Trip 1 was 5 percent higher versus Trip 2. The percentage difference in the fuel use and emissions is affected not just be differences in trip average power demand, but also by differences in episodes of high-power demand at various locations throughout the trip. The predicted fuel use and emissions for each trajectory are given in Table ES-1. Trip 1 had 24 percent, 15 percent, and 17 percent higher fuel use, NO_x emissions and PM emissions, respectively, versus Trip 2. The modeled results were similar to the measured values. Thus, the model is useful for comparing trajectories and evaluating the impact of trajectory changes of fuel use and emissions.

Conclusions

Fuel Use and Emission Rates (FUER) measured for the Prime Mover Engines (PMEs) of each of the NCDOT locomotives were typically consistent with EPA reported data for the same models of PMEs. The NCDOT locomotives are typically more fuel efficient than indicated by EPA's benchmark fuel specific engine output. Within the NCDOT locomotive fleet, locomotives with electronically-governed fuel injection were typically more fuel-efficient versus locomotives with mechanically-governed fuel injection. Consequently, CO_2 emission rates were lower for locomotives with electronically-governed fuel injection. However, no particular trend in emissions rates were observed based on whether fuel injection is electronically or mechanically governed.

Based on RY and OTR measurements, the EPA line-haul duty-cycle based CO emission rates were lower than the level of the Tier 0+ emission standard for each locomotive. However, the EPA line-haul duty-cycle based HC, NO_x, and PM emission rates were higher than the corresponding levels of the Tier 0+ standards for most locomotives.

Most of the time spent in real-world over-the-rail operations involves transients. Steady state operation accounts for only approximately one-third of average operational time. Therefore, it is not possible to estimate trip total fuel use or emissions simply by summing observed second-by-second steady state operation. Steady-state notch average emission rates tend to be higher, on average, than transient emission rates. Therefore, using notch average rates based on steady-state data extrapolated to the total amount of time in each notch position for real-world trips will lead to overestimation of trip total fuel use and emissions. Accurate TFUE can be quantified based on incorporating transients using several approaches described here. Alternate approaches include measuring 1 Hz FUER for the entire trip duration or to use an appropriate modeling approach such as a model based on Locomotive Power Demand (LPD).

TABLE ES-1. Predicted Fuel Use and Emissions for a Model Case Study 1 To Illustrate the Effect of Grade Based on Model Predictions; and for a Model Case Study 2 To Illustrate the Effect of Trajectories Based on Model Predictions.

Species	Model Case Study 1: Grade			Model Case Study 2: Trajectories		
	Hilly Track[a]	Flat Track[b]	Percentage Reduction Compared to Hilly Track (%)	Trip 1[c]	Trip 2[c]	Percentage Reduction Compared to Trip 1 (%)
Fuel Use (kg)	2.4	0.8	65	713	530	24
NO_x Emissions (kg)	0.147	0.062	58	39	34	15
PM Emissions (g)	6.4	3.9	39	1122	978	17

The train for each case comprised of a Single-Locomotive Consist with Locomotive NC 1859 operated on Ultra-low Sulfur Diesel.

[a] *The hilly track case corresponds to a track with 0.5 miles of ascent at 1 percent grade followed by a 0.5 mile descent at -1 percent grade. The train is assumed to operate at a constant speed of 35 mph.*

[b] *The train is assumed to operate at a constant speed of 35 mph over a flat track.*

[c] *The trips had similar average speeds at 48 mph for Trip 1 and 48 mph for Trip 2. However, because of differences in the frequency and magnitude of accelerations, the average power demand for Trip 1 was 5 percent higher versus Trip 2.*

Based on measurements of two locomotives, the double-powered push/pull consist has 19% lower train trip average fuel consumption and CO_2 emissions versus a single-powered push/pull consist. Train trip average CO and NO_x emissions were 62 percent and 9 percent lower, respectively. In contrast, train trip average HC and PM emissions were 40 percent and 3 percent higher. The double-powered push/pull consist is preferred in terms of fuel savings and emissions reductions emissions of CO_2, CO, and NO_x with trade-offs of higher HC and PM emissions versus the single-powered consist. However, the differences between consists with respect to TFUE may be different for different locomotives. Thus, given the small sample size of these data, in that they are based on only two locomotives, further work is warranted to confirm or refine these findings.

The LPD model was found to be accurate for estimating average TFUE over multiple trips. At 1 Hz, predicted FUER may differ by as much as 30 percent from the empirical FUER. However, the modeled estimates of rates appropriately responded to variation in input variables including speed, acceleration, grade, and curvature. The model prediction precision is within ±7 percent on a trip average basis in most cases. The model prediction accuracy for a given combination of locomotive, consist, and fuel for TFUE is within ±2 percent in most cases. The model can be used to demonstrate emission reduction benefits related to infrastructure improvements. Potential emission reductions can be used to seek Federal funding for transportation improvement programs. Variation in train trajectories indicates that there is potential to reduce train fuel use and emissions via improved operational practices.

Inter-locomotive variability in the fuel use rates indicates the potential to reduce fuel consumption for NCDOT passenger rail operations by operating more fuel-efficient locomotives more frequently than less fuel-efficient locomotives.

Given that the real-world emission rates of HC, NO_x, and PM are higher than the levels of the corresponding Tier 0+ standards, mitigation strategies could be considered. Based on prior measurements of three NCDOT locomotives, switching from ULSD to B20 lowered cycle-average HC and PM emission rates by 54 percent and 34 percent, respectively. Assuming that these reductions could be achieved for each locomotive in the NCDOT fleet, a switch from ULSD to B20 fleet-wide might increase the number of locomotives with cycle average HC emission rates at or below the level of the Tier 0+ standard from 3 to 5. Likewise, the number of locomotives with cycle average PM emission rates at or below the level of the Tier 0+ standard would increase from 3 to 7.

Prior work on one NCDOT locomotive demonstrated that a retrofitted blended exhaust after treatment system (BATS) was able to achieve a reduction of 70 percent in cycle average rates. Assuming that the same reduction could be achieved for each locomotive in the NCDOT fleet, retrofitting BATS fleet-wide might increase the number of locomotives with cycle average NO_x emission rates at or below the level of the Tier 0+ standard from 2 to all locomotives in the NCDOT fleet.

Chapter 1. Introduction

This report deals with quantification and estimation of real-world locomotive fuel use and emission rates (FUER) based on real-world train operation. Existing data on locomotive FUER are typically based on steady-state load-based engine dynamometer and rail yard (RY) measurements. However, real-world operation differs from steady-state measurements because it involves transitions from one steady-state to another. Real-world operation may also involve consists with more than one locomotive operating together in a train. Locomotive FUER may differ for single locomotive operation versus multiple locomotives in a train consist due to the differences in tractive power provided by each locomotive. Therefore, to estimate FUER representative of actual operation, it is necessary to measure FUER during actual train operation including typical train consists during over-the-rail (OTR) measurements. The definitions of abbreviations used in this report are given in Appendix A.

Here baseline FUER and effects of several train consists observed on the Amtrak Piedmont passenger rail service on FUER are quantified. FUER are quantified for the two most locomotives recently acquired by the North Carolina Department of Transportation (NCDOT): NC 1871 and NC 1984. For each locomotive, FUER are quantified for steady-state and transient operation. Measured train consists include the double- and single-powered push/pull. In a push/pull consist, two locomotives are used at either end of a train. Typically, both locomotives provide equal tractive power and are referred to as double-powered. In case of malfunction of one locomotive, the other locomotive provides full power and is referred to as single-powered.

Steady-state operation based FUER are useful to benchmark locomotives to emission standards and enables the NCDOT to identify locomotives requiring emission reduction interventions for one or more pollutants. Transient operation based FUER are useful to quantify and reduce trip-based and cycle-average-based fuel use and emissions. The trade-offs of double- versus single-powered train consist are quantified. FUER for the double- versus single-powered and benchmarking to existing locomotives will enable the NCDOT to decide what locomotives and consists should be used more frequently to lower their annual fuel consumption and emissions.

To estimate FUER for a given train speed trajectory and to quantify emission reduction benefits of track infrastructure changes such as replacing a sloping track with a level track, a model to predict FUER based on train speed, acceleration, rail grade and track curvature is demonstrated. The model accounts for the train consists observed on the Piedmont passenger rail service and for fuels including ultra-low sulfur diesel (ULSD) and a blend of 20 percent biodiesel in diesel (B20). The model can be used to estimate trip-total fuel use and emissions for train trajectories on a given route. A choice could be made to operate a locomotive on a trajectory that lowers fuel consumption and emissions. Demonstration of emissions reductions is also required to procure Federal funding for transportation improvement projects.

1.1 Background

A typical U.S. passenger locomotive is powered by a diesel engine, known as a Prime Mover Engine (PME) that drives an electrical generator or alternator. The generator provides electricity to the traction motors, which in turn drive the locomotive wheels. Therefore, diesel locomotives are also referred to as "diesel-electric" locomotives. 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 locomotive is slowed using the mechanical brake or dynamic brake. In a dynamic brake, the traction motors act as generators and electricity is dissipated as heat through an electric resistance grid. Locomotives used for passenger rail service typically have an additional engine known as a Head End Power (HEP) engine. The HEP engine is used to generate alternating current electricity for hotel services in passenger cars, such as lighting and space conditioning (Hay, 1982; Profillidis, 2014). The load on the HEP engine is dependent on the number of passenger cars and therefore, is typically constant for a given train consist. PMEs and HEP engines are typically operated on ULSD (Amtrak, 2018; Elgowainy *et al.*, 2018; Graver and Frey, 2016).

Diesel engines are typically more energy efficient compared to light-duty gasoline vehicles, motorcycles, transit buses and air travel (Davis and Boundy, 2018; NCRRP, 2015; Sprung *et al.*, 2018). In 2017, rail transport accounted for 2.1 percent of U.S. transport petroleum use, and 1.2 percent of total U.S. petroleum consumption (Davis and Boundy, 2018; Sprung *et al.*, 2018). However, the magnitude of rail transport energy consumption was large at 520 trillion BTU with passenger rail accounting for 46 trillion BTU. Rail transport contributed 2.6 percent to greenhouse gas (GHG) emissions from the transportation sector. Savings in energy consumption that could be achieved from inter-modal shifts could lead to fuel cost savings and reduced GHG emissions.

Older diesel engines typically used for passenger rail service are high emitters of oxides of nitrogen (NO_x) and particulate matter (PM) (Dallmann and Harley, 2010; Graver and Frey, 2016; Kean *et al.*, 2000). Nitric oxide (NO) and nitrogen dioxide (NO_2) constitute NO_x (Guarnieri and Balmes, 2014). PM is typically classified based on particle size as PM_{10} (diameter $\leq$ 10 μm) and $PM_{2.5}$ (diameter $\leq$ 2.5 μm) (Weinmayr *et al.*, 2009). NO_2, PM_{10} and $PM_{2.5}$ are 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 (EPA, 2016). The majority of the rail sector in the U.S. is operated on diesel-powered locomotives (Amtrak, 2018; CARB, 2018; Davis and Boundy, 2018; EPA, 1998; Sprung *et al.*, 2018). High initial cost and long operation life of 40 years or more leads to a slow turnover rate of older high emitting locomotives (CARB, 2018; Elgowainy *et al.*, 2018; EPA, 1998). In 2017, according to the most recent National Emission Inventory (NEI 2014 v2), locomotives had a small share of 5 and 0.4 percent of total U.S. NO_x and PM emissions, respectively (EPA, 2018). However, locomotive emissions tend to be concentrated on particular corridors, many of which are close to densely populated locations (Bergin *et al.*, 2009, 2012).

NCDOT has a fleet of two F59PHI and six F59PH locomotives configured for passenger service. Two of the F59PHs, including NC 1871 and NC 1984, are recently acquired and rebuilt by NCDOT. 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. The Piedmont service between Raleigh and Charlotte, NC covers a one-way distance of 280 kilometers (173 miles) in a scheduled duration of 3 hours and 10 minutes.

1.2 Research Needs

This section describes the need for baseline measurements, baseline RY and OTR measurements, Amtrak Piedmont passenger train consists and a model to predict 1 Hz FUER and a review of FUER measurements conducted elsewhere.

1.2.1 Baseline Measurements

Baseline FUER measurements include the quantification of FUER at each throttle notch position of a locomotive. Baseline measurements enable the locomotive to be benchmarked to emission standards and other locomotives. Baseline measurements are useful to quantify the effect of changes such as fuels and retrofit emission controls on FUER and to assess emissions degradation over a period of time. Baseline measurements include: (1) Federal Reference Method (FRM); (2) rail yard; and (3) over-the-rail measurements.

The FRM are conducted at standard engine dynamometer test facilities. The FRM measurements have the advantage of highly accurate and precise 40 CFR 1065-complaint measurements under standard test conditions (40 CFR 1065, 2005). However, there are only a few FRM facilities in the U.S. where the engine should be shipped to for measurements. The shipping and measurement are costly and leads to loss of revenue during the period the locomotive is out of service. The FRM are based on discrete load steady-state engine operation. However, real-world engine operation involves steady-state operation and transition among steady-state load levels. Therefore, steady-state load-based measurements are not an accurate representation of real-world operation. Alternative baseline measurements include RY and OTR measurements.

1.2.2 Rail Yard Measurements

RY measurements are typically conducted in 6-8 h. RY measurements can be conducted using 40 CFR 1065-compliant instruments or using a Portable Emissions Measurement System (PEMS) (S. J. 40 CFR 1065, 2005; Frey *et al.*, 2012; Graver and Frey, 2013). The locomotive does not need to be shipped and is out of service for less than a day. Therefore, these measurements are less costly than FRM.

RY measurements are conducted at steady-state engine operation under controlled environment leading to repeatable measurements. However, real-world operation differs from RY because of: (1) transients between steady-state load levels; (2) engine power output for notches 7 and 8 is typically higher for real-world than for RY; and (3) two or more locomotives may be used with either one locomotive providing full tractive power and other(s) idling, or all locomotives equally sharing the tractive power.

1.2.3 Over-the-Rail Measurements

OTR measurements are conducted during actual revenue-generating service and are therefore least costly compared to the FRM and RY measurements. OTR measurements are representative of real-world operation, including steady-state and transients and provide FUER along a route which can be used to identify locations with highest emissions. OTR measurements enable quantification of locomotive FUER for different train consists. Limited space and safety considerations inside the locomotive limit the choice of instruments onboard typically leading to the use of less accurate instruments. This disadvantage is overcome by benchmarking the instrument to reference measurements.

1.2.4 Comparison of Piedmont Train Consists

The train consist on the Piedmont rail route includes 1-2 diesel-electric locomotives, 2-4 passenger cars and one café/baggage car. A train consist with only one locomotive is called here as 'single operation.' In a single operation, the train needs to be turned around for the return trip, requiring additional crew time. The time required to turn the train around may delay the return trip if the outbound trip is delayed. Locomotive malfunction may lead to delays and interruptions to rail traffic. Addition of passenger car(s) due to an anticipated increase in ridership demand may slow the train. Therefore, NCDOT sometimes used two locomotives placed one behind another, known as 'tandem operation.' In tandem operation, both locomotives provide equal tractive power.

To prevent train delays or interruptions due to locomotive failure or train turnaround, the NCDOT recently switched from a typical consist of one locomotive or tandem locomotives to using two locomotives at either end of the train while varying the number of passenger cars based on anticipated passenger ridership. The placement of locomotives at either end of a train is referred to as a push/pull consist. In a typical push/pull consist, both locomotives provide equal tractive power. The lead locomotive pulls the train, whereas the trailing locomotive pushes the train. This operation of a push/pull train is referred to as 'double-powered push/pull.' In the event of a locomotive failure, the other locomotive can be operated at full power and disruption in service can be avoided. A push/pull consist in which only one locomotive provides tractive power is referred to as 'single-powered push/pull.'

Locomotive FUER and trip fuel use and emissions (TFUE) may differ for the double- versus single-powered consists because of differences in tractive power provided by each locomotive. Therefore, FUER should be quantified separately for the double- and single-powered consists. The trade-offs of double- versus single-powered push/pull for FUER and TFUE need to be quantified.

1.2.5 Need for Spatially Resolved Locomotive FUER Measurements

Spatially resolved emission rates are needed to quantify the source contribution of railroad sector emissions accurately, air pollution exposure and health impacts (Bergin *et al.*, 2009, 2012; Fann *et al.*, 2011; Gould and Niemeier, 2009, 2011; Hubbell *et al.*, 2009; Kheirbek *et al.*, 2013; Lioy and Smith, 2013). Spatially resolved models are needed to evaluate impacts of train trajectory changes based on modifications to infrastructure such as track re-alignment on fuel use and emissions. Federal funding of infrastructure changes typically requires demonstration of emission reductions along a route (40 CFR 93, 1993).

Locomotive FUER are directly related to the tractive effort of the locomotive (AREMA, 2013; Hay, 1982; Profillidis, 2014). Locomotive FUER vary spatially due to differences in speed, acceleration, grade and curvature along a railroad route (Hay, 1982; Profillidis, 2014). Therefore, some locations may have higher emissions than others, leading to emissions hotspots. Spatial variability arises due to variation in PME operation. The HEP engine typically operates at a constant load throughout the trip.

Spatially resolved FUER are not available. Operation and track geometry data are often held confidential by railroad companies (Bergin *et al.*, 2009, 2012; Gould and Niemeier, 2009, 2011). To quantify spatial variability in emission rates, several studies used a top-down approach (Bergin *et al.*, 2009, 2012; CARB, 2018; EIIP Vol 4, 1996; Elgowainy *et al.*, 2018; EPA, 2018, 1992; ICF International, 2009; Perez, 2015; SCG, 2018; Sierra Research, Inc., 2004). In a top-down approach, national-level fuel use data reported by railroad companies are used to estimate national-level emissions. To estimate fuel use and emissions at a local scale, national-level fuel use and emissions are scaled to a local-level assuming emissions to be uniformly distributed along a route. For example, Gould and Niemeier, 2011 developed a spatially resolved model to estimate fuel use and emissions (Gould and Niemeier, 2011). Fuel consumption was estimated by dividing traffic density, gross ton-miles (GTM), by an estimate of fuel efficiency, GTM per gallon diesel fuel consumed (GTM/gal). Air pollutant emissions including hydrocarbons (HC), carbon monoxide (CO), NO_x, PM, sulfur dioxide (SO_2), and carbon dioxide (CO_2) were calculated by multiplying the fuel consumption estimate by fuel-based emission factors. Fuel efficiency for individual track segments was estimated based on local factors such as rail grade and locomotive fleet. However, this approach is unrealistic in that emissions depend on variability in locomotive operation and track geometry along a route. Therefore, the top-down approach using aggregated data may not be representative of localized train operation.

1.3 Prior Work by North Carolina State University

In 2008, North Carolina State University (NCSU) first began to use a Portable Emission Measurement System (PEMS) to measure NCDOT locomotive emissions during static load measurements in the rail yard (Graver and Frey, 2013). 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. In the years since, measurements of the PMEs for over 180 one-way trips on the Piedmont rail-route were conducted on nine NCDOT-owned locomotives: NC 1755, NC 1792, NC 1797, NC 1810, NC 1859, NC 1869, NC 1871, NC 1893 and NC 1984 (Frey *et al.*, 2016; Frey and Graver, 2012; Graver, 2016; Graver *et al.*, 2016; Graver and Frey, 2013, 2015). Locomotive NC 1792 was taken out of service in May 2010.

Highway vehicle emissions avoided by diesel passenger rail service were quantified based on real-world measurements (Graver and Frey, 2016). Avoided highway emissions were attributed to a 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.

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 (Frey *et al.*, 2016; Graver *et al.*, 2016). Using PEMS, cycle-average CO_2, CO, HC, NO_x and PM 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. Of the four fuels, B20 biodiesel was found to be the best fuel as the EPA line-haul cycle based emission rates of CO_2, CO, HC and PM were 4%, 33%, 54% and 29% lower, respectively, versus ULSD. Cycle-average NO_x emission rates increased by 5%.

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 (Frey and Hu, 2015). 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.

Interactions between emission control technology, operation, and fuels were evaluated (Frey and Rastogi, 2018). The retrofit of a selective catalytic reduction (SCR)-based Blended exhaust After Treatment System (BATS) for controlling NO_x emissions was evaluated based on Federal Equivalent Method (FEM) RY measurements by Engine Fuels and Emissions Engineering (EF&EE). Simultaneously, PEMS-based emission rates measured by NCSU were benchmarked to the EF&EE FEM measurements. The effect of differences in operation was assessed based on OTR measurements with PEMS by comparing one-way trips with the highest and lowest trip fuel use and emissions. Spatial variability in FUER was compared to spatial variability in train speed, acceleration, rail grade and rail curves. The BATS was able to achieve a NO_x reduction of 80 percent or higher for notches 3 through 8. Overall, the cycle-average NO_x emission rate with the BATS was 0.8 g/bhp-hr, which was lower than the level of the Tier 4 standard. Thus, the BATS was recommended for reducing NO_x emissions. On a mass per distance basis, FUER were found to be directly related to grade and acceleration and inversely related to train speed. Curves also impacted fuel use and emission rates directly. B20 biodiesel blend was effective in reducing CO, HC and PM emission rates by 33 percent, 54 percent and 30 percent, respectively. A combination of technology, operation and fuels was recommended to simultaneously reduce fuel use and emissions of CO, HC, NO_x and PM. This combination of interventions was estimated to eliminate all NO_x emission hotspots and more than 80 percent PM emission hotspots on the Piedmont route.

The prior studies have demonstrated PEMS to be a useful instrument for quantifying locomotive FUER for both RY and OTR measurements and demonstrated differences between RY and OTR measurements (Frey *et al.*, 2016, 2012; Frey and Graver, 2012; Frey and Hu, 2015, 2015; Graver *et al.*, 2016; Graver and Frey, 2013, 2016, 2015). PEMS-based measurements are reliable for quantifying the effect of technology, operation and fuels on FUER.

1.4 Objectives

In prior work, baseline FUER for the PME and the HEP engine were quantified for six locomotives by NCSU (Frey and Hu, 2015; Graver and Frey, 2015). Here, baseline FUER for the PMEs of two recently acquired locomotives are quantified for RY and OTR measurements. The effect of transients and consists on baseline FUER is quantified based on OTR measurements. In prior work, NCSU conducted OTR measurements during actual train service using a PEMS (Frey *et al.*, 2012; Frey and Graver, 2012; Graver and Frey, 2016, 2015). FUER, speed, acceleration, position and elevation for locomotives operated on ULSD and several biodiesel blends were measured at 1 Hz along the Piedmont passenger rail route. The data from these prior and current OTR measurements are used to develop a model to predict FUER.

The objectives of this current work include:

- Benchmark baseline fuel use and emission rates of locomotives to other locomotives and emission standards;
- Quantify the effect of transients on trip fuel use and emissions;
- Quantify the trade-offs in trip fuel use and emissions between double- and single-powered push/pull consists; and
- Calibration, validation, and application of a model to predict 1 Hz locomotive fuel use and emission rates.

1.5 Overview of the Report

Chapter 2 describes the instruments used for PEMS-based RY and OTR measurements, 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 3 provides the results of the baseline rail yard measurements made on locomotives NC 1871 and NC 1984. 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 measurements were conducted for each locomotive. Fuel use and emission rates were estimated for each replicate and the average of the three replicates. Cycle-average FUER were also quantified. Baseline RY FUER were benchmarked to other NCDOT locomotives. Baseline RY cycle-average emission rates (CAER) were benchmarked to other locomotives and locomotive emission standards.

Chapter 4 provides results for baseline over-the-rail measurements made on locomotives NC 1871 and NC 1984. For each locomotive, typically three one-way trips were measured for single-powered push/pull consist and three one-way trips were measured for double-powered push/pull consist. Measurements results are provided for each consist, for each one-way trip and each throttle notch position in each run. Notch-average and cycle-average fuel use and emission rates were quantified for both train consists based on steady-state operation. Baseline OTR FUER were benchmarked to other NCDOT locomotives. Baseline OTR CAER were benchmarked to other locomotives and to locomotive emission standards. Double- and single-powered push/pull consists were compared to each other in terms of trip fuel use and emissions.

Chapter 5 provides background information on the resistive forces opposing train motion. FUER are related to the tractive power a locomotive provides against resistive forces. Train speed, acceleration and rail grade and curvature are important variables that affect FUER. A model to predict FUER based on these variables is calibrated and validated. A model is calibrated for each of the NCDOT locomotives; fuels: ULSD and B20 biodiesel; and train consists: single operation, tandem operation, single-powered push/pull and double-powered push/pull. Examples of cases where the model will be beneficial to the NCDOT are demonstrated: identifying low fuel consumption and low-emitting speed trajectories, identifying high emitting locations along the route, and quantifying emission changes due to infrastructure changes.

Chapter 6 provides the conclusions of the measurements and analyses. Inter-locomotive and inter-consist variability in FUER helps the NCDOT identify high and low fuel consuming and emitting locomotives. This enables the NCDOT to vary the frequency and consist of locomotives such that fleet-wide fuel consumption and emissions could be reduced. Benchmarking to standards helps identify locomotives requiring emission reduction interventions.

Appendices provide additional detail regarding the NCDOT locomotive fleet, emission standards, the results of measurements and model specifications. The definition of abbreviations used in this report is given in Appendix A. Appendix B provides details of the NCDOT locomotive fleet, including specifications for the PME and HEP engines of these locomotives. Appendix C provides background regarding locomotive emission standards. Appendix D provides results for RY measurements of NC 1871 and NC 1984 including: measured notch-average concentrations; notch-average engine output-based FUER; and baseline RY notch-average FUER and CAER for other locomotives. Appendix E provides results for OTR measurements of NC 1871 and NC 1984. Appendix F contains details of the locomotive power demand model for FUER for each locomotive-train consist-fuel combination.

Chapter 2. Measurement Methods

This chapter describes the instruments and methods used to conduct rail yard (RY) and over-the-rail (OTR) measurements. The methods include measurement of engine-out exhaust gas and particulate matter (PM) concentrations and engine activity variables using a Portable Emission Measurement System (PEMS). The data collected from multiple instruments and sensors were time-aligned and screened for errors. Methods to estimate fuel use and emission rates (FUER) and cycle-average emission rates (CAER) are described. The definitions of abbreviations used in this report are given in Appendix A.

2.1 Instruments

Instruments used for data collection include PEMS, engine sensor array, global positioning system receivers with barometric altimeters (GPS/BA) and a locomotive activity data recorder. An Axion PEMS was used for OTR measurements, and an Axion and SEMTECH-DS PEMS were used for simultaneous RY measurements.

2.1.1 Axion Portable Emissions Measurement System

Engine exhaust was continuously sampled and measured using a Global MRV Axion PEMS. The Axion system 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 carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitric oxide (NO), and oxygen (O_2) in the vehicle exhaust. The two gas analyzers (referred to as "benches") work simultaneously. Periodically, one bench is taken offline for zeroing to prevent the instrument drift. While zeroing, the gas analyzer intakes ambient air instead of engine exhaust and switches back to exhaust when finished. This purging takes about ten seconds. The bench takes an additional 45 seconds for zeroing. The PM measurement capability includes a laser light scattering detector and a sample conditioning system. The Axion PEMS uses 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 specifications of the Axion PEMS are given in Table 2-1.

The Axion PEMS has an electrochemical sensor for NO only. Thus, it does not measure oxides of nitrogen (NO_x), which also includes nitrogen dioxide (NO_2). However, NO_x in engine-out diesel exhaust typically comprises 95% NO (Fritz *et al.*, 2000; Tsolakis *et al.*, 2007). Therefore, NO is a good surrogate for total NO_x. NDIR is well known to respond only partially to the total loading of hydrocarbon species in the exhaust, because it responds well to alkanes but is less responsive for other aromatics (Singer *et al.*, 1998). Correction factors for Axion PEMS measured NO and HC concentrations were estimated based on simultaneous exhaust concentration measurements of HC, total hydrocarbons (THC), NO and NO_2 using a SEMTECH-DS PEMS conducted during RY measurements as described in Section 2.1.3.

TABLE 2-1. Specifications of the Gas and Particulate Matter Analyzers for the Global MRV Axion and Sensors Inc. SEMTECH-DS Portable Emissions Measurement Systems

Attribute		Global MRV Axion	Sensors Inc. SEMTECH-DS
CO_2	Method	Non-Dispersive Infrared	Non-Dispersive Infrared
	Resolution	0.01 %	0.01 %
	Range	0.01 % to 16.00 %	0.01 % to 20 %
	Accuracy	± 0.30 % absolute	± 0.01 % (absolute) or ± 3 %
	Precision	± 0.30 % absolute	± 0.1 % (absolute) or ± 2 %
	Response	T_{90} & T_{10} < 3 s	T_{90} < 3 s
CO	Method	Non-Dispersive Infrared	Non-Dispersive Infrared
	Resolution	0.001 %	10 ppm
	Range	0.001 % to 10.000 %	0 % to 8 %
	Accuracy	± 0.02 % absolute	± 50 ppm or ± 3 %
	Precision	± 0.02 % absolute	± 20 ppm or ± 2 %
	Response	T_{90} & T_{10} < 3 s	T_{90} < 3 s
HC	Method	Non-Dispersive Infrared	Heated Flame Ionization Detection
	Resolution	1 ppmC	0.1 ppmC
	Range	1 ppmC to 2,000 ppmC	0.1 ppmC to 100 ppmC[c]
	Accuracy	± 4 ppmC	± 5 ppmC or ± 2 %
	Precision	± 4 ppmC	± 2 ppmC or ± 1 %
	Response	T_{90} & T_{10} < 3 s	T_{90} < 2 s
NO	Method	Electrochemical cell	Non-Dispersive Ultra Violet
	Resolution	1 ppm	1 ppm
	Range	1 ppm to 4000 ppm	1 ppm to 2,500 ppm[c]
	Accuracy	± 25 ppm	± 15 ppm or ± 3 %
	Precision	± 25 ppm	± 5 ppm or ± 2 %
	Response	T_{90} & T_{10} < 6 s	T_{90} < 2 s
NO_2	Method	-[a]	Non-Dispersive Ultra Violet
	Resolution	-	1 ppm
	Range	-	1 ppm to 500 ppm
	Accuracy	-	± 10 ppm or ± 3 %
	Precision	-	± 5 ppm or ± 2 %
	Response	-	T_{90} < 2 s
PM	Method	Laser light scattering	-
	Resolution	NA[b]	-
	Range	NA	-
	Accuracy	NA	-
	Precision	NA	-
	Response	NA	-
Dimensions		21.7" L × 16.9" W × 8.5" H	24.5" L × 20.3" W × 15.9" H
Weight		38 lbs (17.2 kg)	78 lbs (35.4 kg)

[a] *Instrument not capable of measuring the selected attribute*
[b] *Data not available for the selected attribute*
[c] *Higher concentration measurements are also possible at reduced resolution, accuracy, and precision*

The laser light scattering-based PM measurement is also typically biased low by a factor of 5, as shown by Durbin *et. al.*, 2007 (Durbin *et al.*, 2008). 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 (Durbin *et al.*, 2008).

The precursor PEMS model to the Axion system 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 (Myers *et al.*, 2003). The coefficients of determination (R^2) for the comparison exceeded 0.86 for all pollutants, indicating good precision. The slopes of the parity plot for CO, CO_2 and NO ranged from 0.92 to 1.05, indicating good accuracy.

The Axion PEMS was recently evaluated based on comparison to a Federal Equilvalent Method (FEM) while measuring emissions of locomotive NC 1859. Fuel use rates estimated using GlobalMRV Axion PEMS were compared to gravimetric fuel use rate. Emission rates estimated using PEMS and locomotive emission measurement system (LEMS) were compared (Frey and Rastogi, 2018). The LEMS provides 40 CFR 1065 Subpart J compliant measurements of CO_2, CO, HC, NO_x and PM (Weaver and Balam-Almanza, 2001). Simultaneous exhaust gas and PM concentration measurements were conducted at the combined exhaust outlet of the PME and HEP engine of locomotive NC 1859. The combined fuel use rate of both the engines was measured gravimetrically for each PME throttle notch position. The PEMS-based notch-average fuel use rates were highly correlated (with a correlation of 0.99) with the gravimetric measured notch-average fuel use rates. PEMS-based notch-average CO_2 and NO_x emission rates had a correlation of 0.99 and 0.97 with LEMS-based notch-average CO_2 and NO_x emission rates, respectively. The Axion PEMS-based notch-average PM emission rates had a correlation of 0.80 with LEMS-based notch-average PM emission rates. The LEMS is larger and heavier than PEMS and cannot be installed onboard a locomotive. Gravimetric fuel use measurements are infeasible for OTR measurements. Thus, the Axion PEMS is a reliable alternative to the more equipment-intensive gravimetric fuel-based method for OTR measurements.

2.1.2 Engine Sensor Array

A sensor array was installed on the engine and connected to the Axion PEMS. The sensor array includes sensors to record engine activity variables, including engine revolutions per minute (RPM), the intake air temperature (IAT), and the manifold absolute pressure (MAP) (also referred to as the “airbox pressure”). These data are required to estimate the dry molar exhaust flow rate, which is an important variable to estimate fuel use and emission rates.

A light sensor measured engine RPM, a thermocouple measured the temperature in the engine intake air manifold, and a pressure sensor measured pressure in the engine intake air manifold. The reflective tape was put on the engine flywheel, and a light beam was aimed towards the flywheel. The RPM sensor counts the number of times light is reflected from the flywheel to the sensor to quantify 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. The components of the Axion PEMS are shown in Figure 2-1.

FIGURE 2-1. The Global MRV 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.

2.1.3 Supplemental Measurements of NO_x and HC

Space constraints, high temperatures in the engine compartment, and safety considerations in the locomotive cab motivate the selection of a PEMS for the OTR measurements. Due to limited space inside a locomotive cab, only one PEMS was used for the OTR measurements.

As discussed in Section 2.1.1, the Global MRV Axion PEMS does not measure total NO_x and THC. Therefore, additional instruments are required to measure data from which bias corrections for the ratio of NO_x to NO and THC to HC can be quantified. Thus, SEMTECH-DS manufactured by Sensors Inc. was used simultaneously with Axion PEMS in prior RY measurements to estimate correction factors for NO_x and THC.

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 high molecular weight hydrocarbons in the exhaust sample. The specifications of the SEMTECH-DS PEMS are given in Table 2-1. However, the SEMTECH-DS does not measure PM. The Axion is compact and lightweight compared to SEMTECH-DS and, thus, easier to install on-board a locomotive. The engine sensor array can only be connected to the Axion PEMS. Thus, these factors motivate the use of Axion PEMS for the OTR measurements.

The disadvantage of not measuring NO_x and THC with Axion PEMS was overcome by simultaneous RY measurements with SEMTECH-DS to estimate correction factors. RY measurements are used to estimate notch-average NO_x/NO and THC/HC ratios based on SEMTECH-DS measurements. These ratios are used as correction factors and applied to Axion PEMS measured NO and HC concentrations to estimate NO_x and THC concentrations, respectively.

2.1.4 Locomotive Activity Data Recorder

To estimate cycle-average FUER, brake horsepower is required. Brake horsepower is the sum of the horsepower supplied to the main alternator and the mechanical horsepower required to operate auxiliary loads such as a secondary alternator (EPA, 1998). The power supplied to the main alternator is known as traction power output or net engine power output. The power required to operate oil and fuel pumps, or to circulate coolant for the engine, is not included in brake horsepower. The locomotive in-cab display screen shows real-time PME revolutions per minute (ENG RPM), throttle notch position (TH NOTCH), manufacturer specified engine power output at each notch position (HP REF), and net engine power output (HP) as shown in Figure 2-2. These data are displayed but not recorded by the locomotive activity data recorder. Periodically, the notch position and the main generator power output were noted during the measurements.

The auxiliary power was assumed to be proportional to engine RPM. The auxiliary power for EMD 12-710 PMEs at 904 RPM is 172 hp comprises of 4 hp, 50 hp, 90 hp, 12 hp and 16 hp for auxiliary generator, traction motor blower, cooling fans, inertial separator blower, and air compressor, respectively. Auxiliary power at each notch position was linearly interpolated based on notch-average engine RPM and added to notch-average main generator power output to estimate brake horsepower.

The throttle notch position for each second of data was inferred from solenoid valve settings (solenoid valves A, B, C, and D) and Generator, and Dynamic Brake indicators recorded by the locomotive activity recorder. The values for each are either 0 or 1. Unique combinations of these indicators were used to identify the notch position of the locomotive. The solenoid valve, generator, and dynamic brake configuration settings for each notch position are given in Table 2-2.

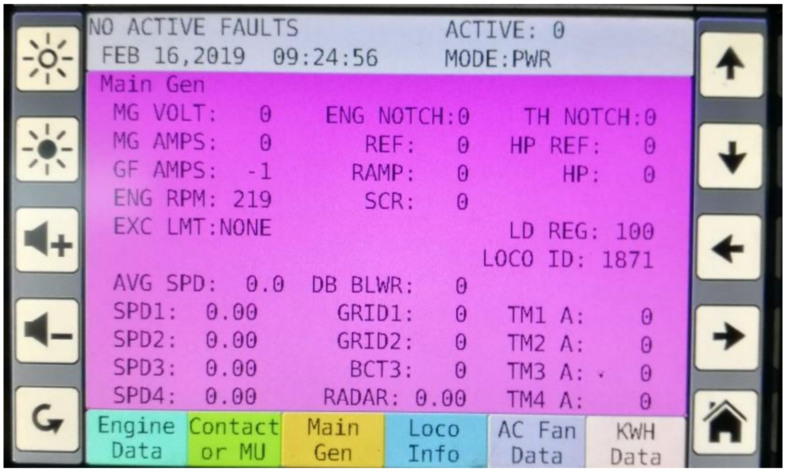


FIGURE 2-2. Locomotive Activity Recorder Display Screen on Locomotives NC 1871 and NC 1984.

TABLE 2-2. Notch Indicators Recorded by Locomotive Activity Recorder used to Infer Throttle Notch Position

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

2.2 Rail Yard Measurements

This section describes the measurements conducted at the rail yard. 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 measurements. The installation of the PEMS, engine sensor array, and the exhaust sample lines are described in this section.

2.2.1 Installation

The Axion PEMS was operated on 120 VAC shore power using a 12 VDC transformer. 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. The SEMTECH-DS PEMS requires just one exhaust sample line for the gas analyzer. The SEMTECH-DS has just one gas analyzer and zeroing during the measurement would result in loss of data. Therefore, the SEMTECH-DS PEMS was only zeroed between replicates.

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

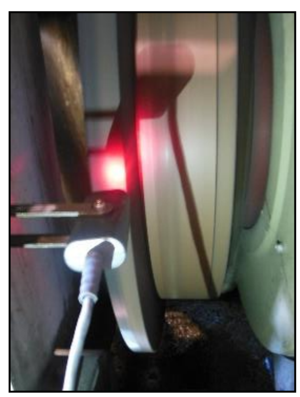
2.2.2 Measurement Schedule

During the RY measurements, the PME was measured under load. The electrical power generated by the PME 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 a dynamic braking grid.

(a) Axion and SEMTECH-DS PEMS

(b) Exhaust sampling port

(c) Manifold absolute pressure and temperature sensor



(d) Engine RPM sensor

FIGURE 2-3. Installation of Axion and SEMTECH-DS PEMS for Measuring Prime Mover Engine Exhaust For Rail Yard Measurements: (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 Intake Air Temperature Sensor; and (d) Engine Revolutions per Minute Sensor.

After the installation of all instruments, the PME was operated at idle for 45 minutes to warmup the engine. During the same time, both PEMS were warmed-up. Engine and PEMS warmup ensured consistent measurements. PME measurement followed a prescribed sequence and timing of throttle notch settings, as given in Table 2-3, 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 notches six through eight. The measurement 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.

2.3 Over-the-Rail Measurements

This section describes the OTR measurements conducted during regular revenue-generating passenger rail service. RY and OTR measurements are similar in terms of instrumentation, quality assurance, and data analysis procedures, except that the OTR measurements are made on-board the locomotive during revenue-generating train service instead of according to a predefined measurement schedule.

Exhaust gas and PM measurements were conducted for the PME. 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 fuel for the flame ionization detector of the SEMTECH-DS is also considered hazardous on-board. Therefore, NCDOT did not allow the use of the SEMTECH-DS PEMS for OTR measurements. The installation of the PEMS, engine sensor array, and the exhaust sample lines are described in this section.

TABLE 2-3. Railyard Measurement 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

2.3.1 Installation

The Axion PEMS and the engine sensor array were installed on-board the locomotive. Additionally, 10 GPS/BA receivers were installed on the locomotive to record 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 2-4. Engine sensor array installation was the same as for the RY measurements.

2.3.2 Measurement Schedule

The OTR measurement procedure is observational rather than controlled. Thus, there is not a predetermined measurement schedule, as was the case for rail yard measurements (e.g., Table 2-3). 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 2-5. The schedule of stops in both directions is given in Table 2-4.

FIGURE 2-4. Installation of Axion PEMS inside the Locomotive Cab

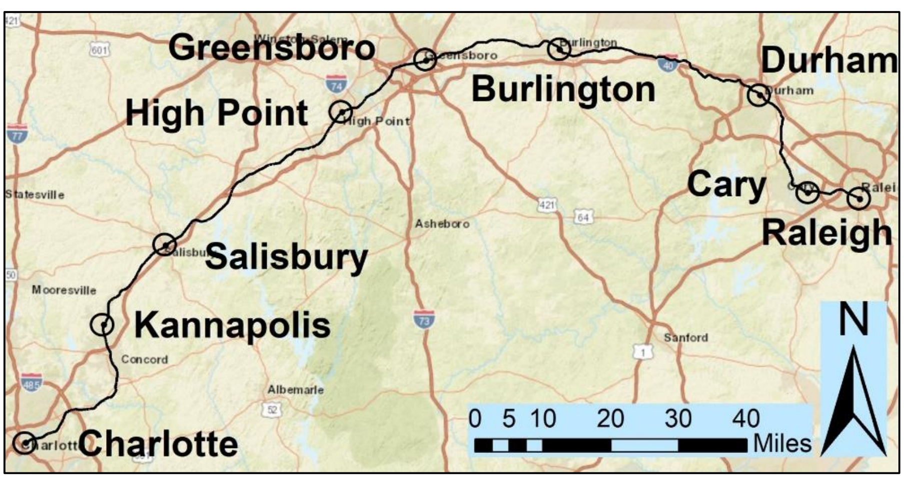


FIGURE 2-5. Route Map of the North Carolina Amtrak Piedmont Passenger Rail Service between Raleigh, NC and Charlotte, NC.

For OTR measurements, the locomotive was operated normally on the North Carolina Amtrak Piedmont rail service by Amtrak engineers. The thrice-daily Piedmont service covers a one-way distance of 280 kilometers in a scheduled 3 hours and 10 minutes. Measurements included push/pull train consists. The goal of the measurements was to get data for three one-way trips each for the double- and single-powered operations for each locomotive. The locomotives were operated on ULSD.

2.4 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 data sources such that each row of data corresponds to the same event. Time alignment between two measurement sources involves identification of a reference event from each source which is known to be simultaneous. 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.

TABLE 2-4. North Carolina Amtrak Piedmont Passenger Rail Service Daily Timetable for: (a) Westbound trains from Raleigh to Charlotte; and (b) Eastbound trains from Charlotte to Raleigh.

(a) Westbound Trains

Station	Train 73	Train 75	Train 77
Raleigh (RGH)	06:30	10:00	15:00
Cary (CYN)	06:42	10:12	15:12
Durham (DNC)	07:02	10:32	15:32
Burlington (BNC)	07:38	11:08	16:08
Greensboro (GRO)	08:03	11:33	16:33
High Point (HPT)	08:19	11:49	16:49
Salisbury (SAL)	08:53	12:23	17:23
Kannapolis (KAN)	09:09	12:39	18:10
Charlotte (CLT)	(arrival) 09:40	(arrival) 13:10	(arrival) 18:41

(b) Eastbound Trains

Station	Train 74	Train 76	Train 78
Charlotte (CLT)	10:30	15:15	19:00
Kannapolis (KAN)	10:55	15:40	19:25
Salisbury (SAL)	11:11	15:56	19:41
High Point (HPT)	11:44	16:29	20:14
Greensboro (GRO)	12:03	16:48	20:33
Burlington (BNC)	12:24	17:09	20:54
Durham (DNC)	13:03	17:48	21:33
Cary (CYN)	13:23	18:08	21:53
Raleigh (RGH)	(arrival) 13:41	(arrival) 18:26	(arrival) 22:10

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

Axion PEMS measured exhaust gas and PM concentrations were aligned to engine RPM using CO_2 concentration as a reference measurement. Locomotive speed recorded by the locomotive activity recorder was aligned to the engine RPM at station stops. The locomotive idles at a station stop. Hence, RPM is at its lowest operating value, and speed is zero. As the train prepares to depart, the PME is switched to a higher notch, at which time RPM increases as does train speed. The GPS data were aligned to the locomotive activity data. GPS measured speed was used as a reference and aligned to locomotive activity recorder measured speed. Thus, data from the engine sensor array, PEMS, locomotive activity recorder and GPS were time-aligned.

The gaseous and PM exhaust concentrations measured with the PEMS were aligned to the engine activity data using CO_2 concentration as secondary reference data. Changes in CO_2 concentration were aligned to changes in engine RPM. 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 2-6(a) and 2-6(b), respectively. In Figure 2-6(a), the dashed red line indicates the start of a rise in the engine RPM. A dashed blue line indicates an example of the corresponding start of a rise in the CO_2 concentration. 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 between the two dashed line, in this case, 18 seconds, such that the dashed lines fell exactly on top of each other, as shown in Figure 2-6(b). Exhaust gas and PM measurements from the same dataset were also shifted by the same time period.

Engine activity data were aligned 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 2-7(a) and 2-7(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. In this example, the locomotive activity recorder data was shifted by 11 seconds to align with the engine activity data.

The time-aligned locomotive speed was used as the primary reference to align the GPS data using locomotive speed inferred from a GPS receiver as secondary reference data. For this particular case, the data are aligned to obtain the 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 2-8(a) and 2-8(b), respectively. The correlation was 0.95 for the raw data and 0.99 for the aligned data. The GPS data were shifted by 7 seconds to align to the locomotive activity recorder data.

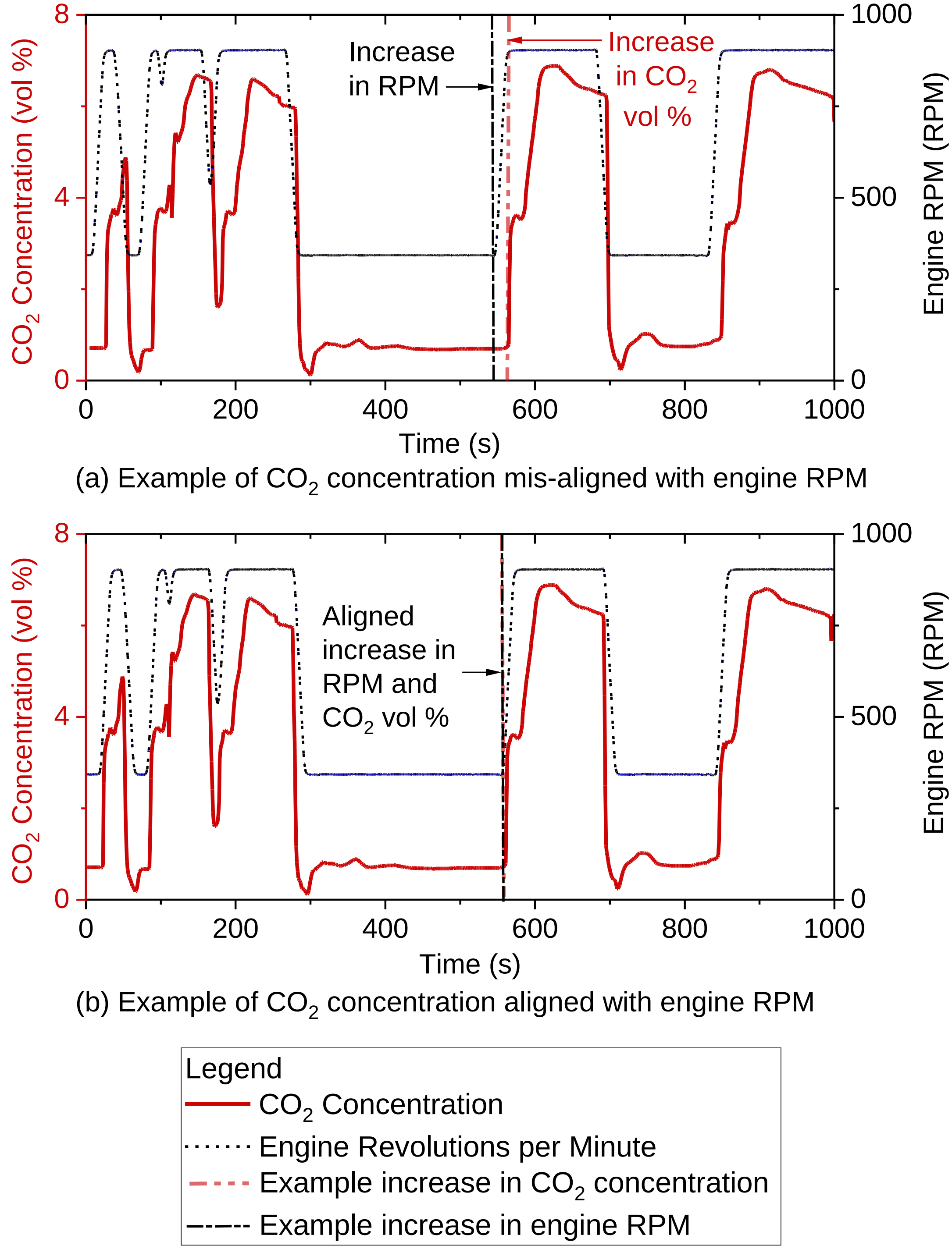
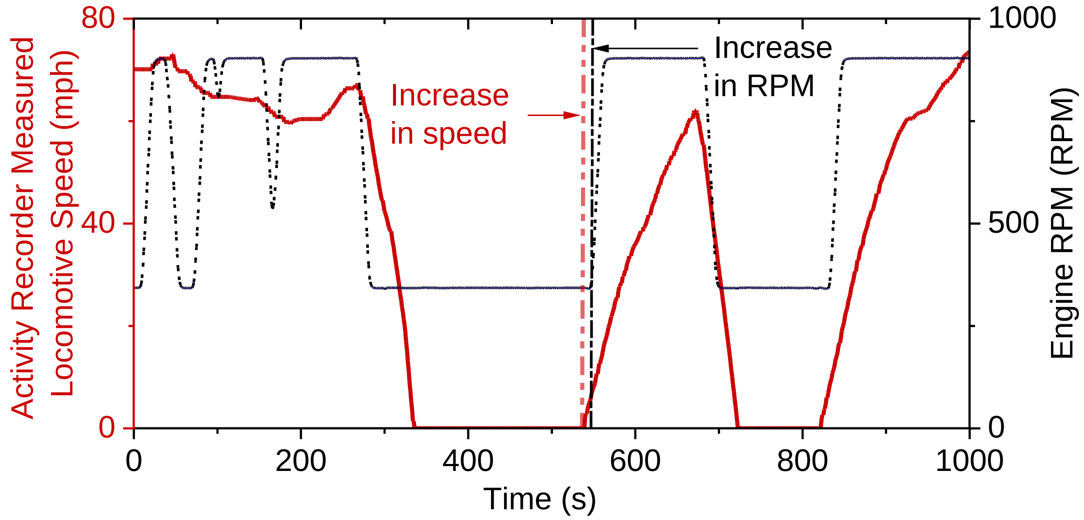
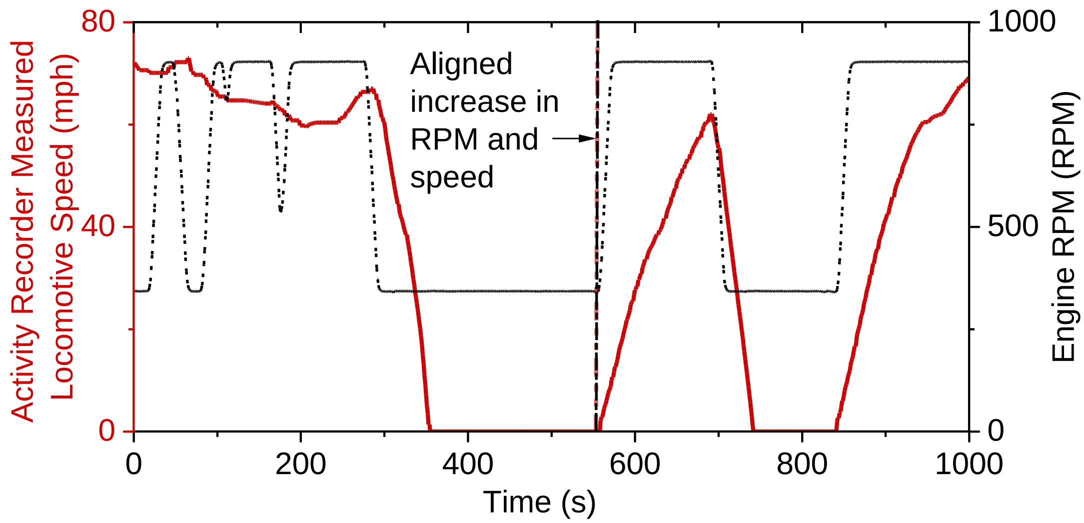


FIGURE 2-6. Example Time Series Plot of CO_2 Concentration and Engine Revolutions per Minute (RPM) measured with PEMS for: (a) Unaligned CO_2 Concentrations and Engine RPM; and (b) CO_2 Concentrations Aligned to Engine RPM.



(a) Example of Locomotive Speed mis-aligned with engine RPM



(b) Example of Locomotive Speed aligned with engine RPM

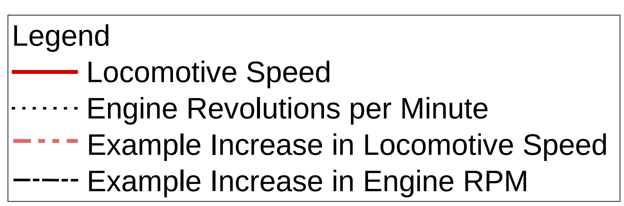
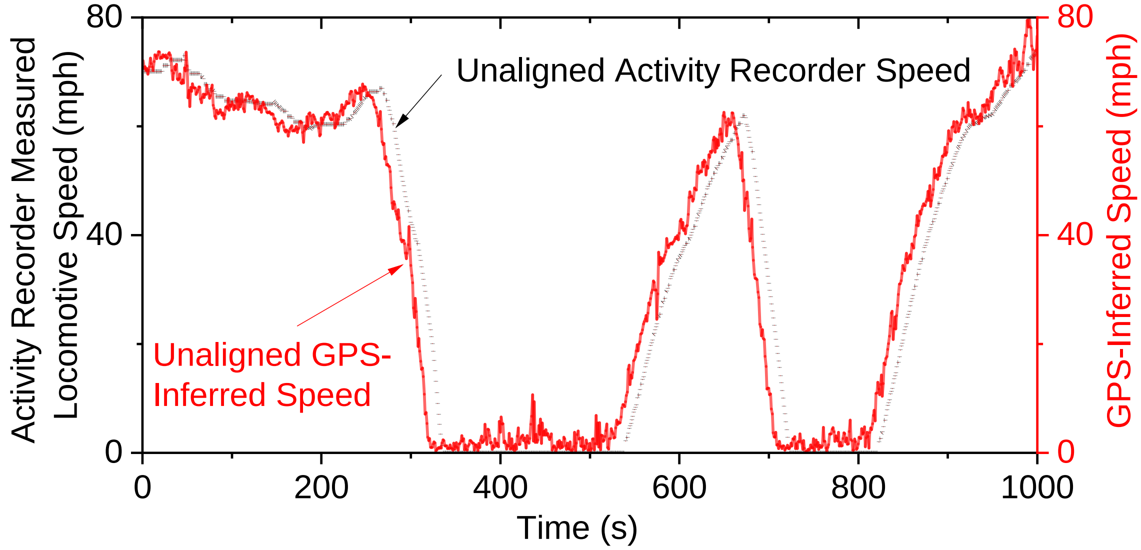
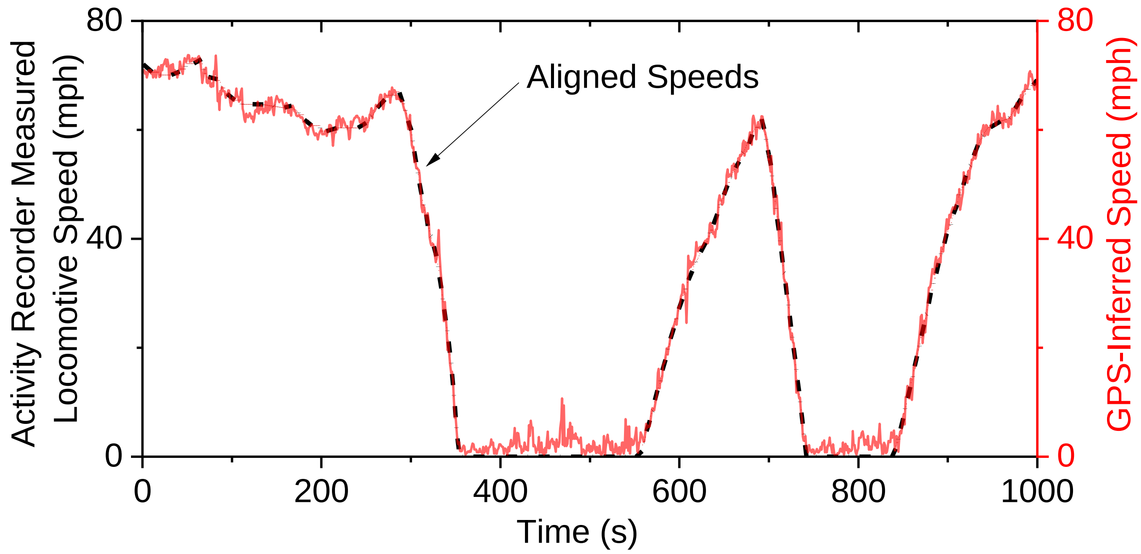


FIGURE 2-7. Example Time Series Plot of Locomotive Speed measured with Locomotive Activity Recorder and Engine Revolutions per Minute (RPM) measured with PEMS for: (a) Unaligned Locomotive Speed and Engine RPM; and (b) Locomotive Speed Aligned to Engine RPM.



(a) Example of GPS-inferred Speed mis-aligned with Locomotive Speed



(b) Example of GPS-inferred Speed aligned with Locomotive Speed

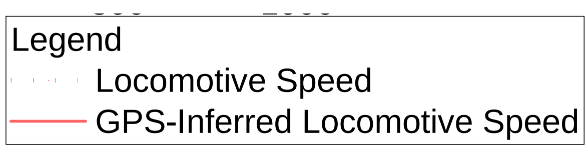


FIGURE 2-8. Example Time Series Plot of Locomotive Speed measured with Locomotive Activity Recorder and GPS Receiver for: (a) Unaligned Locomotive Speeds; and (b) Aligned Locomotive Speeds.

2.5 Quality Assurance

Erroneous data were either corrected or rejected from the data analysis. Typical errors in the data include: (1) errors in engine sensor array data; and (2) errors in gas analyzer data. Errors in engine sensor data were identified based on deviations from credible ranges of RPM, IAT, and MAP. The engine RPM of the locomotives measured varied between 268 RPM at idle to 901 RPM at Notch 8. The IAT typically varied between 10 °C and 125 °C. The MAP typically varied between 90 kPa and 250 kPa. Thus, any data outside these ranges were excluded from further analysis.

Errors in gas analyzer data were identified by comparing the measurements of both of the benches of an Axion PEMS when they operated simultaneously. If the relative error between the measurements was within a Maximum Allowable Difference (MAD), an average of the two values was taken. However, if the relative error exceeded the MAD, then further assessment of data quality was required. The MAD was based on twice the detection limit of each sensor. The MAD for CO_2, CO, HC, NO and O_2 are 0.6 %, 0.04 %, 28 ppm, 50 ppm, and 0.5 %, respectively. Discrepancies in measurements might be due to: (1) 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 cases, only the data from the properly working bench was used. The data from the erroneous bench were rejected. Negative values of concentrations are physically implausible and typically arise when the concentration was 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 were excluded. Negative concentrations that were lower than zero by less than the magnitude of the detection limit of the instrument were assumed to be zero. Additional details on quality assurance are provided elsewhere (Frey and Graver, 2012; Graver and Frey, 2013; Sandhu and Frey, 2013).

2.6 Fuel Use and Emission Rates

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. Mass per time emission rates of gases are estimated as a product of dry molar exhaust flow rate and the measured volumetric exhaust concentration. Thus, dry molar exhaust flow rate is a key variable in estimating FUER.

The Federal Reference Method (FRM) and locomotive emission standards are based on steady-state measurements at each throttle notch position. RY measurements are also conducted at steady-state. However, OTR measurements include both steady-state and transients. Therefore, for OTR measurements, FUER, CAER and TFUE were estimated for two cases: (1) steady-state operation only; and (2) transient operation. Steady-state based FUER and CAER enable locomotives to be benchmarked to the level of emission standards. However, FUER and CAER based on transients are representative of actual train operation. For OTR measurements, the PME was assumed to be operating at steady-state when: (1) the 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 RY measurements of the same PME. Transient data refers to all measured 1 Hz data inclusive of all locomotive operations, which can include periods of approximately steady-state operation.

2.6.1 Notch-Average Fuel Use and Emission Rates

Molar exhaust flow rate was estimated from the mass air flow and the air-to-fuel ratio. Mass air flow was estimated using the "speed-density method" based on engine activity variables and a previously developed estimate of engine volumetric efficiency (Graver and Frey, 2013). The speed-density method is based on the ideal gas law (Vojtisek and Kotek, 2014). The engine activity variables required include engine RPM, IAT, MAP and engine volumetric efficiency (η_{ev}). Volumetric efficiency is the ratio of the actual volume of air that flows through the engine cylinders versus the 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 the product of MAP and RPM from prior dynamometer measurements on similar EMD 12-710 PMEs (Graver and Frey, 2013). Thus, the volumetric efficiency of a PME was estimated based on measured RPM and MAP. The air to fuel ratio was 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.

The PME volumetric efficiency was estimated as (Graver and Frey, 2013):

$$\eta_{ev,t} = 4.3648 \times \left(\frac{ES_t \times P_{M,t}}{1000}\right)^{-0.298} \tag{2-1}$$

Where,

$\eta_{ev,t}$	=	engine volumetric efficiency of the engine at time *t*
ES_t	=	engine speed at time *t* (*RPM*)
$P_{M,t}$	=	engine manifold absolute pressure at time *t* (*kPa*)

The intake air flow rate for a PME for each second ($M_{a,t}$) was estimated as:

$$M_{a,t} = \frac{\left(P_{M,t} - \frac{P_B}{ER}\right) \times EV \times \left(\frac{ES_t}{30 \times EC}\right) \times \eta_{ev,t}}{R \times T_{int,t}} \tag{2-2}$$

Where,

$M_{a,t}$	=	intake molar air flow rate at time *t* (*gmol/s*)
EC	=	engine strokes per cycle (1 for two-stroke engines and 2 for four-stroke engines)
ER	=	engine compression ratio
EV	=	engine displacement (*L*)
P_B	=	barometric pressure (*101 kPa*)
$T_{int,t}$	=	intake air temperature at time *t* (*K*)
R	=	universal gas constant (*8.314 J mol^{-1} K^{-1}*)

Exhaust molar flow rate on a dry basis ($M_{e,\text{t,dry}}$) was estimated based on $M_{a,t}$ and air to fuel ratio (AFR) inferred from exhaust gas composition (Sandhu and Frey, 2013):

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

Where,

$M_{e,t,dry}$	=	molar exhaust flow rate at time t on a dry basis (gmol/s)
$y_{s,t,dry}$	=	mole fraction of pollutant species s at time t for a PME on a dry basis (gmol/gmol of dry exhaust)
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

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

$$m_{s,t} = y_{s,\mathrm{t},dry} \times M_{e,\mathrm{t,dry}} \times MW_s \quad (2\text{-}4)$$

Where,

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

Assuming that all the carbon in the exhaust is coming from the carbon content of fuel, and that carbon in fuel is distributed among CO_2, CO and HC in the exhaust, the mass per time fuel use rate was estimated as:

$$m_{f,t} = M_{e,\mathrm{t},dry} \times MW_f \times (y_{CO_2,t,dry} + y_{CO,\mathrm{t},dry} + m \times y_{HC,\mathrm{t},dry}) \quad (2\text{-}5)$$

Where,

$m_{f,t}$	=	mass fuel use rate by the engine at time t (g/s)
MW_f	=	equivalent molecular weight of fuel (g/gmolC)
m	=	moles of carbon per gram mole of the hydrocarbon

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

$$m_{PM,t,dry} = C_{PM,t,dry} \times M_{e,t,dry} \times \left(\frac{R\,T}{P_B}\right) \quad (2\text{-}6)$$

Where,

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

2.6.2 Cycle-average Emission Rates

Notch-average engine power output-based emission rates were weighted to selected locomotive duty cycles to obtain CAER:

$$CAER_s = \sum_{j=\,idle}^{8} \frac{\bar{M}_{ij} \times T_j^D \times bhp_j}{\sum_{j=idle}^{8} T_j^D \times bhp_j} \quad (2\text{-}7)$$

Where,

$CAER_s$	=	cycle-average emission rate for pollutant species s (g/bhp-hr)
$\bar{M}_{sj}$	=	steady-state emission rate for pollutant species s at notch j (g/bhp-hr)
T_j^D	=	time spent in notch j based on the duty cycle (hr)
bhp_j	=	brake horsepower at notch j (bhp)

For RY measurements, CAER of CO_2, CO, HC, NO and PM were estimated for the EPA line-haul duty cycle. The EPA line-haul duty cycle is estimated for freight trains and is used as a regulatory duty cycle for locomotives with a rated power of 2300 hp or higher. The EPA line-haul duty cycle is based on 2,475 hours of data provided by five railroad companies from 63 freight trains (EPA, 1998). The EPA also estimated the passenger duty cycle and found it to be different than the line-haul duty cycle. However, passenger locomotives are also regulated based on the EPA line-haul duty cycle.

For the OTR measurements, CAER were estimated for the EPA line-haul duty cycle and the three distinct real-world duty cycles corresponding to single, double- and single-powered push/pull consists. The average single locomotive Piedmont duty cycle was estimated by Graver and Frey (2015) based on 48 one-way trips. The average push/pull single-powered Piedmont duty cycle was estimated based on seven one-way on double-powered push/pull consist of locomotives NC 1871 and NC 1984. The average push/pull double-powered Piedmont duty cycle was estimated based on 17 one-way trips on double-powered push/pull consist of locomotives NC 1871 and NC 1984. The duty cycles are given in Table 2-5.

The EPA line-haul duty cycle, given here for a locomotive with one idle position, has the highest percentage of time in idle, followed by notch 8 and dynamic brake. Together, these three notch settings comprise 67 percent of the total time. The percentage of time in a given notch position decreases from idle through notch 7 and increases to 16 percent at notch 8. For locomotives with two idle positions, the total time spent in idle for locomotives with one notch position is equally distributed among the two idle positions and for locomotives without dynamic brake, the percentage of time in dynamic brake is assigned to high idle (EPA, 1998).

The average single operation Piedmont duty cycle has the highest percentage of time spent in notch 8, followed by idle and dynamic brake. Together these three notch settings comprise 78 percent of the total time. Idle and notch 8 have the highest inter-trip variation in the percentage of time in a notch of 40 percent and 30 percent, respectively. The operators did not use the dynamic brake for some of the trips. The average percentage of total time in notches 1 through 6 ranges between 2 percent and 5 percent. The lowest percent of the total time was spent in notch 7, comprising of 1 percent.

The average single-powered push/pull duty cycle had the highest percentage of time in notch 8, followed by idle. Notch 8 and idle comprised 85 percent of the total time. Other notch positions comprised 3 percent or lower time in each notch position with the least percent time in notch 7. Compared to the single Piedmont duty cycle, the percentage of time in notch 8 was higher for single-powered push/pull as the single locomotive had to provide more power due to the weight of an additional locomotive. The percentage of time in idle was also higher. Single-powered push/pull trips were typically affected by delays compared to single operation and double-powered. The engine idles at station stops and when the train is not in motion. Usually, schedule delays are associated with higher proportions of time in which the engine is at idle. However, the engine may also idle during coasting, which would depend on operator choices.

The average double-powered push/pull duty cycle had the highest percentage of time in idle, followed by notch 8. Together, idle and notch 8 comprised 69 of percent total time. The percentage of time in dynamic brake through notch 7 decreased from 6 percent to 1 percent, respectively. Compared to the other Piedmont duty cycles, the percent time in idle was higher and the percent time in notch 8 was lower for double-powered push/pull duty cycle. This is typical as two locomotives were sharing the tractive power demand, thereby reducing the power demand per locomotive.

TABLE 2-5. EPA Line-Haul Duty Cycle and Average Piedmont Single Locomotive, Single-powered Push/pull and Double-powered Push/pull Consist Duty Cycles

Notch	Percentage of time in each Notch (%)			
	EPA Line-Haul[a]	Average Single Operation Piedmont[a,b]	Single-powered Push/Pull Piedmont[a,c]	Double-powered Push/Pull Piedmont[a,d]
Idle	38.0 (1.0, 77.0)	28.4 (10.6, 51.8)	33.8 (22.8, 49.1)	44.0 (33.5, 56.7)
Dynamic Brake	12.5 (0.0, 41.0)	11.1 (0.0, 18.6)	2.8 (0, 8.7)	6.1 (0, 16.4)
1	6.5 (0.0, 23.0)	3.8 (0.6, 14.0)	2.5 (1.6, 3.3)	5.1 (2.7, 10.3)
2	6.5 (0.0, 23.0)	4.8 (1.6, 11.3)	2.6 (1.4, 3.5)	4.6 (2.6, 6.6)
3	5.2 (2.0, 13.0)	3.7 (0.7, 10.7)	2.9 (1.9, 5.5)	4.6 (3, 7.6)
4	4.4 (1.0, 11.0)	4.0 (0.9, 11.4)	2.6 (1.7, 3.7)	4.1 (2.9, 6.3)
5	3.8 (0.0, 12.0)	2.2 (0.4, 4.6)	2.1 (0, 4.2)	3.3 (1.5, 6.5)
6	3.9 (0.0, 11.0)	2.5 (0.2, 11.0)	2.4 (0, 4.5)	2.5 (0.4, 3.7)
7	3.0 (0.0, 18.0)	0.9 (0.0, 3.7)	1.6 (0.5, 3.5)	0.5 (0.1, 1.5)
8	16.2 (0.0, 39.0)	38.6 (22.7, 52.0)	46.6 (35.3, 59.8)	25.1 (17.4, 35.3)

[a] *The numbers in parentheses indicate the range of observed percentage of time in each notch position.*

[b] *The average single operation Piedmont duty cycle was estimated by Graver and Frey (2015) based on 48 single operation one-way trips conducted between Raleigh, NC and Charlotte, NC.*

[c] *The average Push/Pull single-powered Piedmont duty cycle was estimated based on 7 one-way trips conducted between Raleigh, NC and Charlotte, NC on double-powered push/pull consists of locomotives NC 1871 and 1984 conducted during the study period.*

[d] *The average Push/Pull double-powered Piedmont duty cycle was estimated based on 17 one-way trips conducted between Raleigh, NC and Charlotte, NC on double-powered push/pull consists of locomotives NC 1871 and 1984 during the study period.*

2.6.3 Fuel Specific Engine Output

Fuel Specific Engine Output (FSEO) for a given duty cycle is the cycle-average engine power output produced per unit fuel consumption. A locomotive is more energy-efficient than another locomotive if it produces higher output for the same fuel consumption. Therefore, FSEO if proportional to engine efficiency. FSEO for the EPA line-haul duty cycle is reported to typically be 20.8 bhp-hr/gal for the PMEs manufactured in mid-1990s (EPA, 1998). FSEO was used to benchmark NCDOT locomotives. FSEO was estimated as:

$$FSEO_f = \frac{\mu_f}{\sum_{j=idle}^{8} \frac{FR_{fj} \times DC_j \times bhp_j}{\sum_{j=idle}^{8} DC_j \times bhp_j}} \tag{2-8}$$

Where,

$FSEO_f$	=	cycle-average engine power output per unit fuel consumption for fuel *f* (*bhp-hr/gal*)
FR_{fj}	=	fuel use rate at notch *j* (*g/bhp-hr*)
μ_f	=	density of fuel *f* (*g/gal*) = 3184 g/gal for ULSD and 3229 g/gal for B20

2.6.4 Trip Fuel Use and Emissions

Trip fuel use and emissions (TFUE) are defined as the fuel use and emissions from the PME of a given locomotive-consist for a one-way trip. Since real-world notch-average PME FUER and duty cycles may differ from steady-state based FUER and regulatory duty cycles, respectively, five different approaches to estimate TFUE are presented and compared. These approaches are based on steady-state rates, transient rates, or a combination of both. The actual PME fuel consumption was estimated from the locomotive activity recorder display. The estimated actual fuel consumption was used as a benchmark of PME trip fuel use to aid in evaluating the accuracy and precision of the five approaches. The display recorder does not show or record emissions or emission rates.

2.6.4.1. Actual Estimated Trip Fuel Use

The locomotive activity recorder displays the fuel remaining in the fuel tank at any given instant. The same fuel tank provides fuel to the PME and the HEP engine. Therefore, the fuel use inferred by depletion of fuel in the fuel tank from the display is the combined PME and HEP engine fuel use. The actual trip total PME and HEP engine trip fuel use is inferred from the difference of the fuel in the tank at the beginning and the end of each one-way trip:

$$F_{L,C,i} = f_{L,C,i,t_{L,C,i,0}} - f_{L,C,i,t_{L,C,i,n}} \tag{2-9}$$

Where,

$F_{L,C,i}$	=	Actual trip total PME and HEP engine trip fuel use for locomotive *L* in consist *C* for the i^{th} one-way trip (*gal*).
$f_{L,C,i,t_{L,C,i,0}}$	=	Activity recorder display at the beginning of the i^{th} one-way trip for locomotive *L* in a consist *C* (*gal*).
$f_{L,C,i,t_{L,C,i,n}}$	=	Activity recorder display at the end of the i^{th} one-way trip for a locomotive *L* in a consist *C* (*gal*).
$t_{L,C,i,0}$	=	start of the i^{th} one-way trip for locomotive *L* in consist C (*s*)
$t_{L,C,i,n}$	=	end of the i^{th} one-way trip for locomotive *L* in consist C (*s*)
L	=	index for locomotive (NC 1871 or NC 1984)
C	=	index for consist (Double- or Single-powered)
i	=	index for one-way trips (= 1, 2, 3, ….., $N_{L,C}$)
$N_{L,C}$	=	number of one-way trips for locomotive *L* in consist C

The display has a resolution of 10 gallons. Therefore, each reading may vary by ± 5 gal and the actual fuel use may be within ±10 gal of the displayed value.

The actual PME trip fuel use was estimated as the difference between the combined PME and HEP engine trip fuel use, which is inferred by depletion of fuel in the fuel tank, and the estimated HEP engine trip fuel use. An estimate of the HEP trip fuel use was developed based on data from prior measurements. The HEP engine fuel use rate was measured for NC 1984 for three one-way trips each for the double- and single-powered push/pull consists. A Caterpillar Electronic Technician (CAT-ET) Electronic Control Unit scan tool was used to record the HEP engine fuel use rate. The CAT-ET records 1 Hz HEP engine fuel use rate, engine RPM, MAP, IAT, and boost pressure. The HEP engine fuel use rate was approximately constant during each trip and similar among trips for each of the measured trips and consists. The average HEP engine fuel use rate was 5.5 gal/hr. For the double- and single-powered consists, typically the HEP engine of one locomotive provides hotel power, and the HEP engine of the other locomotive is not operated. Thus, the estimated HEP fuel use is based on fuel consumption for one HEP engine. The estimated actual PME trip fuel use based on the locomotive activity recorder display for both engines less the estimated fuel consumption of the HEP engine was estimated as:

$$P_{L,C,i} = F_{L,C,i} - \frac{H \times t_{L,C,i,n} \times h_L}{3600} \tag{2-10}$$

Where,

$P_{L,C,i}$	=	Estimated actual trip PME fuel use estimated based on the locomotive activity recorder fuel tank display for the PME and HEP engine fuel use less the estimated fuel consumption of the HEP engine fuel use for locomotive L in consist C for the i^{th} one-way trip (*gal*).
H	=	Average HEP engine fuel consumption rate = 5.5 gal/hr
h_L	=	Index for the status of the HEP engine of locomotive L, = 1 if the HEP engine was ON and 0 if the HEP engine was OFF.

2.6.4.2. Estimated Trip Fuel Use and Emissions

Trip fuel use and emissions were estimated based on PEMS measurements using five approaches to account for differences between steady-state and transients, including two steady-state based approaches, one steady-state and transient based approach and two transient-based approaches.

The steady-state approach is useful for benchmarking locomotives to emission standards because the standards are based on steady-state notch-average rates. This approach is also useful for comparing locomotives under similar operating conditions. However, real-world operation involves transients. Excluding transients may lead to errors in estimating TFUE representative of real-world train operation. Therefore, TFUE estimates that take into account transients were also developed. Methods to estimate TFUE for each approach are given in this section.

Approach 1: Steady-State Rates and Steady-State Cycle (SRSC)

The steady-state rates and steady-state cycle (SRSC) approach is based on steady-state notch-average FUER weighted to the time in each notch position during steady-state operation:

$$SRSC_{s,L,C,i} = \sum_{j=idle}^{8} \overline{M'}_{s,j,L,C,i} \times T'_{j,L,C,i} \tag{2-11}$$

Where,

$SRSC_{s,L,C,i}$	=	Estimated trip PME fuel use or emissions of species *s* for locomotive *L* in consist *C* for the *i*th one-way trip based on the steady-state rates and steady-state cycle approach (*g*).
$\overline{M'}_{s,j,L,C,i}$	=	Estimated notch-average steady-state fuel use rate or emission rates of species *s* for notch *j* of locomotive *L* in consist *C* for *i*th one-way trip (*g/s*)
$T'_{j,L,C,i}$	=	Time spent in steady-state at notch *j* of locomotive L in consist *C* for the *i*th one-way trip (*s*).
s	=	fuel use or pollutant species *s*: fuel use, CO_2, CO, HC, NO_x or PM.
j	=	index for notch position ={low idle, high idle, dynamic brake, 1, 2, 3, 4, 5, 6, 7 and 8}

Because of inter-trip variability in FUER, the steady-state notch-average FUER were estimated for each one-way trip as:

$$\overline{M'}_{s,j,L,C,i} = \frac{\sum_{0}^{T'_{j,L,C,i}} m'_{s,j,L,C,i}}{T'_{j,L,C,i}} \tag{2-12}$$

$m'_{s,j,L,C,i}$	=	Steady-state 1 Hz fuel use rate or emission rate of species *s* at notch *j* of locomotive *L* in consist *C* for the *i*th one-way trip (*g/s*)

TFUE estimated using the SRSC approach are expected to be underestimated versus actual TFUE because this approach accounts for only a fraction of the trip duration. Trips with a larger percentage of time at steady-state versus transients will have smaller differences from actual TFUE versus trips with a relatively smaller percentage of time at steady-state versus transients.

Approach 2: Steady-State Rates and Actual Cycle (SRAC)

Approach 1 is explicitly based on less than the full operating time of train operation, since time spent during transients is not included. In contrast, Approach 2 accounts for all operating time. Approach 2, which is the steady-state rates and actual cycle (SRAC) approach, is based on steady-state notch-average FUER weighted to the time in each notch position for the actual duty cycle corresponding to a trip assuming every second of a trip to be at steady-state:

$$SRAC_{s,L,C,i} = \sum_{j=idle}^{8} \overline{M'}_{s,j,L,C,i} \times T^{D}_{j,L,C,i} \tag{2-13}$$

Where,

$SRAC_{s,L,C,i}$	=	Empirical trip PME fuel use or emission rates of species *s* for locomotive *L* in consist *C* for the *i*th one-way trip based on the steady-state rates and actual cycle approach (*g*).
$T^{D}_{j,L,C,i}$	=	Time spent in notch *j* of locomotive *L* in consist *C* for the *i*th one-way trip, based on the actual duty cycle (*s*)

Although Approach 2 accounts for all travel time, it is expected to produce a biased TFUE estimate because the locomotive does not operate at steady-state throughout the trip. FUER differ for steady-state versus transients. Transients occur when the operator switches from a predecessor notch (PN) to a successor notch (SN). The duration of a transition from PN to SN is estimated as the time needed to reach steady-state in the successor notch, or the time until the next change in notch position if steady-state is not reached first. The transition from a lower PN to a higher SN is described here as upshift. The transition from a higher PN to a lower SN is described here as downshift.

The difference between the FUER based on steady-state versus transients for a SN depends on whether the transition is an upshift or downshift. For example, in an upshift, at the beginning of the transition, the engine RPM, IAT, and MAP would be equal to the corresponding value at the PN. Since the PN, in this case, was lower than SN, RPM, IAT, and MAP would be lower than those corresponding to the SN at steady-state. Therefore, FUER for the SN at steady-state will be higher than during the period of the upshift from the transient. For an SN in a given one-way trip, more upshifts, i.e., more transient from a lower notch, than downshifts will typically lead to lower FUER during transients. Conversely, more downshifts lead to higher FUER during transients for the SN.

Transitions to idle inherently will have higher RPM, IAT, and MAP than steady-state operation at idle. During an upshift from idle to a higher notch position, RPM, IAT, and MAP will monotonically increase during the transient period. During a downshift from a higher notch to idle, RPM, IAT, and MAP will be elevated during the transition until they decline to idle values at steady-state. Thus, for either upshifts from idle or downshifts to idle, the transient FUER are higher than for steady-state at idle. Conversely, transient FUER will be lower during transients than at steady-state in notch 8. Therefore, the differences between steady-state versus transients are typically greatest for idle and notch 8 versus other notch positions. As explained in Section 2.6.2, the operators typically spend 70 percent or more of the total trip duration at idle and notch 8. Therefore, the differences in the estimated TFUE for steady-state versus transients are typically largely affected by differences in idle and notch 8 FUER for steady-state versus transients. Therefore, the SRAC approach typically overestimates the TFUE. Since the locomotive does not operate at steady-state for the entire trip, an approach based on steady-state and transients is presented in the next section.

Approach 3: Steady-State Rates and Cycle and Transition Modes (SRCT)
In the steady-state rate, cycle and transition (SRCT) modal approach, TFUE are estimated based on the SRSC approach to which additional modes are added that account for the effect of transients. Thus, this approach is expected to be less biased than the SRSC approach.

For a typical locomotive with 11 throttle notch settings, including two idle positions, notches 1 to 8, and dynamic brake, 121 unique transitions are possible. Each of the transitions may have FUER different than other transitions. However, durations of some of the transitions may be small or some may not be used at all by the operator. Therefore, the transitions were grouped into *k* transition modes such that each mode contributed at least 10 percent to the total of all transient PME fuel use for a one-way trip. Any transition with more than 10 percent contribution to transient fuel use was defined as a mode. All transitions with less than 10 percent contribution to transient fuel use were grouped into one mode. TFUE using this approach were estimated as:

$$SRCT_{s,L,C,i} = SRSC_{s,L,C,i} + \sum_{mode=1}^{k} \overline{K}_{s,mode,L,C,i} \times T''_{mode,L,C,i} \quad (2\text{-}14)$$

Where,

$SRCT_{s,L,C,i}$	=	Empirical trip PME fuel use or emission rates of species *s* for locomotive *L* in consist *C* for the i^{th} one-way trip based on the steady-state rate, cycle and transition modal approach (*g*)
$\overline{K}_{s,mode,L,C,i}$	=	Modal average rate of species s for fuel use or emissions for locomotive *L* in consist *C* for the i^{th} one-way trip (g/s)
$T''_{mode,L,C,i}$	=	Time spent in a transition mode of locomotive L for consist C for the i^{th} one-way trip (*s*)
k	=	Number of transition modes

This approach includes steady-state and transient modes and the time in each mode. Therefore, this approach is expected to provide more accurate TFUE estimates versus SRSC and SRAC approaches. However, for trips with complete data, the best approach to estimate TFUE is the sum of transient 1 Hz FUER, as described next.

Approach 4: Sum of Transient Rates (SOTR)
The sum of transient rates (SOTR) approach estimates TFUE as sum of all valid 1 Hz FUER:

$$SOTR_{s,L,C,i} = \sum_{t_{L,C,i,0}}^{t_{L,C,i,n}} m_{s,L,C,i} \quad (2\text{-}15)$$

Where,

$SOTR_{s,L,C,i}$	=	Empirical trip PME fuel use or emission rates of species *s* for locomotive *L* in consist *C* for the i^{th} one-way trip based on the sum of transient rates approach (*g*)
$m_{s,L,C,i}$	=	1 Hz fuel use rate or emission rate of species *s* for locomotive *L* in consist *C* for the i^{th} one-way trip based on the transient rate approach (*g/s*)

This is the simplest of all the approaches. However, this approach requires complete 1 Hz data. If the proportion of missing data is too large, then this approach will underestimate the actual TFUE. The proportion of missing data for each one-way trip was estimated based on time and distance. The proportion of missing data based on time was estimated based on the difference of the trip duration and the number of seconds of valid 1 Hz data after quality assurance. The distance-based proportion of missing data was quantified based on the route length less the length accounted for by valid data. The length of the trip with valid data was estimated based on the sum of all valid 1 Hz speeds obtained from locomotive activity recorder in miles per second. The criteria for data completeness are that no more than 5 percent of data are missing based on either time or distance.

Approach 5: Transient Rates Actual Cycle (TRAC)
As an alternative to Approach 4 in cases for which the Approach 4 data completeness criteria are not met, Approach 5 is applied. Approach 5 is the transient rates actual cycle (TRAC) approach,

in which transient based notch-average rates are weighted to the actual duty cycle based on total time spent in each notch position:

$$TRAC_{s,L,C,i} = \sum_{j=\,idle}^{8} \bar{M}_{s,j,L,C,i} \times T^{D}{}_{j,L,C,i} \qquad (2\text{-}16)$$

Where,

$TRAC_{s,L,C,i}$ = Estimated trip PME fuel use or emission rates of species s for locomotive L in consist C for the i^{th} one-way trip based on the transient rates and actual cycle approach (g).

The transient-based notch-average FUER for a given notch position is estimated based on the average of all valid 1 Hz FUER measured for the corresponding notch position:

$$\bar{M}_{s,j,L,C,i} = \frac{\sum_{0}^{T_{j,L,C,i}} m_{s,j,L,C,i}}{T_{j,L,C,i}} \qquad (2\text{-}17)$$

The TRAC approach based on valid FUER weighted to the actual duty cycle corrects for biases associated with missing data.

2.6.4.3. Accuracy

Given a resolution of 10 gal of the locomotive activity display, the total PME and HEP engine fuel use may be within 10 gal of the displayed value. Therefore, trip fuel use within 10 gal of the estimated PME fuel use was considered to be accurate. The locomotive recorder does not display or record emissions.

Chapter 3. Rail Yard Measurements

This chapter includes the results of rail yard (RY) measurements conducted on the prime mover engines (PMEs) of locomotives NC 1871 and NC 1984 operated on ultra-low sulfur diesel (ULSD). Baseline fuel use and emission rates (FUER) and cycle-average emission rates (CAER) were estimated and benchmarked to EPA dynamometer data, other NCDOT locomotives, and emission standards. Three RY measurements were conducted during the study period. Two RY measurements were conducted on the PME of NC 1871 on December 21, 2017 and June 11, 2019. One RY measurement was conducted for the PME of NC 1984 on January 25, 2018. Three replicates were conducted during each RY measurement.

Results of RY measurements of locomotives NC 1871 and NC 1984 are given below. Two RY measurements on NC 1871 are compared to each other to assess the effect of differences in engine operating variables and measured exhaust concentrations on FUER. Baseline FUER were benchmarked to EPA dynamometer data, other NCDOT locomotives, and emission standards. The definitions of abbreviations used in this report are given in Appendix A. and CAER for each replicate are given in Appendix D.

3.1 Locomotive NC 1871: December 21, 2017

This section provides a summary of measured notch-average engine activity variables and concentrations for RY measurements of NC 1871 conducted on December 21, 2017. FUER based on Axion PEMS measurements with correction factors applied and CAER for the EPA line-haul cycle are given here.

3.1.1 Engine Activity Variables

Notch-average engine revolutions per minute (RPM), intake air temperature (IAT), and manifold absolute pressure (MAP) for the three replicates are summarized in Table 3-1. Engine RPM varied from 268 RPM at idle and notch 1 to 903 RPM at notch 8. This PME has two idle positions but is configured to operate at only one idle position during RY measurement. The notch-average RPM had an inter-replicate coefficient of variation (CV) of 0.01 or lower for each notch position. Thus, the RPM measurements were highly repeatable.

Notch-average IAT varied from 345 K at notch 1 to 355 K at notches 7 and 8. In general, IAT increased with an increasing notch position. However, IAT differed by less than one Kelvin degree between adjacent notch positions. The inter-replicate CV for each notch position was 0.02 or lower. Therefore, IAT measurements were highly repeatable. Notch-average MAP varied from 103 kPa at idle to 205 kPa at notch 8. MAP increased with engine RPM. The inter-replicate CV for MAP was 0.01 or lower for each notch position. Therefore, MAP measurements were highly repeatable.

3.1.2 Exhaust Gas and PM Concentrations

Notch-average exhaust concentrations of CO_2, CO, HC, NO, and PM measured using an Axion PEMS are summarized in Table 3-2. Notch-average CO_2 concentrations varied from 0.65 vol % at idle to 5.15 vol % at notch 8. Notch-average CO_2 concentrations increased with increasing notch position except for notches 7 and 8, which had CO_2 concentrations within 0.06 vol % each other. Notch-average CO_2 concentrations were highly repeatable with an inter-replicate CV of 0.03 or lower for each notch position.

Notch-average CO and HC concentrations were below the detection limit of the Axion PEMS for all notch positions and all replicates. Notch-average NO concentrations varied between 159 ppm at idle and 1350 ppm at notch 6. Notch-average NO concentrations typically increased with increasing notch position from idle through notch 6 and decreased to 1210 ppm at notch 8. Notch-average NO concentrations were highly repeatable with an inter-replicate CV of 0.03 or lower for each notch position.

Notch-average PM concentrations varied from 4.5 mg/m^3 and 8.3 mg/m^3. Notch-average PM was within 0.4 mg/m^3 of each other for idle and notches 1 through 5. The notch-average PM concentrations increased with notch position to 8.3 mg/m^3 at notch 8. Notch-average PM concentrations were highly repeatable with an inter-replicate CV of 0.02 or lower for each notch position.

3.1.3 Fuel Use and Emission Rates

Notch-average fuel use and emission rates were estimated for locomotive NC 1871 based on Axion PEMS measurements of engine activity and exhaust gas and PM. Axion measured NO and HC concentrations were bias corrected for NO_x and THC using the NO_x/NO and THC/HC ratios given in Table D-4 of Appendix D. For PM, a correction factor of 5 was used based on literature review. Mass per time based and engine output-based emission rates were estimated. The notch-average engine output and mass per time-based fuel use rate and emission rates of CO_2, CO, THC, NO_x and PM are shown in Table 3-3.

Net engine power output increased monotonically from notch 1 through notch 8. During rail yard measurements, the PMEs of NCDOT-owned locomotives are configured to operate at lower than typical engine power output at notches 7 and 8 observed during OTR measurements to prevent overheating of the dynamic brake grid. Differences in engine power output for RY versus OTR measurements may lead to differences in measured exhaust notch-average concentrations at notches 7 and 8, and consequently differences in FUER. At idle, the net engine power output displayed by the locomotive activity recorder was zero. However, engine power output was assumed to be 9 hp based on prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).

Notch-average fuel use rates increased monotonically with increasing notch position for all the replicates and varied from 2.9 g/s at idle to 87 g/s at notch 8. Notch-average fuel use rates were highly repeatable at a given notch position. The inter-replicate CV for each of the notch positions was 0.04 or lower and was 0.02 or lower for seven of the nine throttle positions. Notch-average fuel use rates were low because of low notch-average CO_2 concentrations. Notch-average CO_2 emission rates had the same relative trend as fuel use rate because approximately 99 percent of the carbon in fuel is emitted as CO_2. Notch-average CO_2 emission rates were highly repeatable at a given notch position. The inter-replicate CV for each of the notch positions was 0.04 or lower.

TABLE 3-1. Rail Yard Measurement-based Notch-Average Engine Activity Variables for the Prime Mover Engine of Locomotive NC 1871 Measured on December 21, 2017.

Throttle Notch Position	Engine RPM (RPM)		Intake Air Temperature (K)		Manifold Absolute Pressure (kPa)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Idle	268	0.000	347	0.002	104	0.006
1	268	0.000	345	0.002	103	0.000
2	389	0.001	347	0.001	105	0.005
3	511	0.003	350	0.001	117	0.005
4	702	0.000	353	0.000	152	0.000
5	716	0.015	353	0.001	156	0.011
6	792	0.002	354	0.001	178	0.000
7	828	0.003	355	0.001	190	0.003
8	903	0.001	355	0.001	205	0.012

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

TABLE 3-2. Rail Yard Measurement-based Axion PEMS-measured Notch-average Concentrations for the Prime Mover Engine of Locomotive NC 1871 Measured on December 21, 2017.

Throttle Notch Position	CO_2 concentration (vol %)		CO concentration (vol %)		HC concentration (ppm)		NO concentration (ppm)		PM concentration (mg/m^3)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Idle	0.65	0.02	*0.000*	*0.00*	*6*	*0.2*	159	0.01	4.6	0.02
1	1.16	0.01	*0.000*	*0.00*	*12*	*0.4*	319	0.01	4.7	0.01
2	2.33	0.01	*0.000*	*0.00*	*10*	*0.6*	610	0.03	4.5	0.01
3	3.30	0.01	*0.000*	*0.00*	*8*	*0.5*	1030	0.01	4.6	0.01
4	3.57	0.02	*0.000*	*0.00*	*1*	*0.4*	1004	0.02	4.9	0.02
5	4.31	0.03	*0.000*	*0.00*	*8*	*0.5*	1300	0.02	4.9	0.02
6	4.93	0.03	*0.000*	*0.00*	*3*	*0.6*	1350	0.03	6.4	0.01
7	5.15	0.01	*0.004*	*0.01*	*6*	*0.3*	1263	0.01	8.1	0.02
8	5.09	0.03	*0.004*	*0.02*	*1*	*1.7*	1210	0.01	8.3	0.02

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*
The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

TABLE 3-3. Rail Yard Measurement-based Notch-Average Net Engine Output, Fuel Use and Emission Rates for the Prime Mover Engine of Locomotive NC 1871 Measured on December 21, 2017.

Throttle Notch Position	Net Engine Output	Fuel Use Rate (g/s)		CO_2 Emission Rate (g/s)		CO Emission Rate (g/s)		HC Emission Rate[b] (g/s)		NO_x Emission Rate[c] (g/s)		PM Emission Rate[d] (g/s)	
	(hp)	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Idle	10[e]	2.9	0.00	9	0.00	*0.0*	*1.2*	*0.0*	*0.19*	0.3	0.21	0.02	0.02
1	125	5.2	0.00	16	0.00	*0.0*	*1.7*	*0.1*	*0.35*	0.5	0.01	0.02	0.01
2	290	13.9	0.01	43	0.00	*0.0*	*0.0*	*0.1*	*0.58*	1.2	0.03	0.02	0.00
3	630	25.7	0.00	80	0.00	*0.0*	*0.0*	*0.1*	*0.44*	2.8	0.01	0.03	0.01
4	1000	42.3	0.02	132	0.00	*0.0*	*0.0*	*0.0*	*0.36*	4.1	0.02	0.05	0.02
5	1360	53.0	0.04	166	0.00	*0.0*	*0.0*	*0.2*	*0.49*	5.5	0.04	0.05	0.04
6	1920	71.3	0.02	223	0.00	*0.0*	*1.2*	*0.1*	*0.57*	6.7	0.03	0.08	0.01
7	2190	80.4	0.01	251	0.01	*0.2*	*0.1*	*0.2*	*0.34*	6.8	0.01	0.11	0.02
8	2230	87.2	0.04	273	0.04	*0.1*	*0.7*	*0.0*	*1.03*	7.1	0.03	0.13	0.01

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates.*
[b] *HC measured with Axion PEMS were multiplied with a correction factor shown in Table D-4(b) in Appendix D to obtain THC.*
[c] *NO measured with Axion PEMS were been multiplied with a correction factor shown in Table D-4(a) in Appendix D to obtain NO_x.*
[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*
[e] *Assumed from prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).*
The values in italics are based on measured concentrations below the detection limit of the Axion PEMS.

Notch-average CO emission rates were typically based on CO concentrations below the detection limit of the Axion PEMS. These notch positions had high CVs but the CO emission rates were low. Notch-average THC emission rates were based on HC concentrations below the detection limit of the PEMS for one or more replicates in each notch position, resulting in CV of 0.19 or higher and large inter-replicate variability. However, the THC emission rates were low.

Notch-average NO_x emission rates increased monotonically from 0.3 g/s at idle to 7.1 g/s at notch 8. Notch-average NO_x emission rates were highly repeatable at a given notch position. The inter-replicate CV for each of the notch positions was 0.04 or lower, except at idle. The inter-replicate CV at idle was 0.2 but NO_x emission rates at idle were low.

Notch-average PM emission rates were constant for idle through notch 2. For notches 3 and higher, notch-average PM emission increased monotonically to 0.13 g/s at notch 8. Notch-average PM emission rates were repeatable at a given notch position. The inter-replicate CV for each of the notch positions was 0.04 or lower.

Mass per time-based notch-average emission rates were divided by the corresponding notch-average net engine output to estimate notch-average engine output-based emission rates. Engine-output based emission rates were weighted to the EPA Line-haul cycle to estimate cycle-average emission rates. The results are shown in Table 3-4.

TABLE 3-4. The EPA Line-Haul based Cycle-average Emission Rates for the Rail Yard Measurement the Prime Mover Engine of Locomotive NC 1871 conducted on December 21, 2017.

Results	EPA Line-Haul Duty Cycle-average Emission Rates[a]			
	CO [g/bhp-hr]	HC[b] [g/bhp-hr]	NO_x[c] [g/bhp-hr]	PM[d] [g/bhp-hr]
Replicate 1	0.0	0.29	11.1	0.20
Replicate 2	0.1	0.26	10.7	0.20
Replicate 3	0.2	0.26	10.7	0.20
Average	0.1	0.27	10.8	0.20
CV[e]	0.6	0.06	0.02	0.007
Tier 0+	5.0	1.00	8.0	0.22
Tier 1+	2.2	0.55	7.4	0.22
Tier 2+	1.5	0.30	5.5	0.10

[a] *EPA Line-Haul include dynamic brake. Since dynamic brake measurements were not conducted due to unavailability of the dynamic braking grid, time spent in dynamic brake is assigned to idle.*

[b] *THC emission rates have been estimated from Axion PEMS measured HC and bias corrected for THC based on notch-average correction factor estimated in Table D-4(b) in Appendix D.*

[c] *NO_x emission rates have been estimated from Axion PEMS measured NO and bias corrected for NO_x based on notch-average correction factor estimated in Table D-4(a) in Appendix D.*

[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*

[e] *CV = Coefficient of Variation (Ratio of standard deviation and mean of three replicates).*

Cycle-average CO and HC emission rates were lower than the level of the Tier 2+ standard. The measured cycle-average NO_x emission rates were higher than the level of the Tier 0+ standard for each of the three replicates. The estimated cycle-average PM emission rates were higher than the level of the Tier 2+ standard but lower than the level of Tier 0+ and Tier 1+ standards.

3.2 Locomotive NC 1871: June 11, 2019

This section provides a summary of measured notch-average engine activity variables and concentrations for the RY measurements of NC 1871 conducted on June 11, 2019. Notch-average correction factors for NO_x/NO and THC/HC were estimated based on SEMTECH-DS measurements. FUER based on Axion PEMS measurements with correction factors applied and CAER for the EPA line-haul cycle are given here.

3.2.1 Engine Activity Variables

Notch-average RPM, IAT, and MAP for the three replicates are summarized in Table 3-5. Notch-average engine RPM varied from 268 RPM at idle and notch 1 to 902 RPM at notch 8. Notch-average RPM had an inter-replicate CV of 0.002 or lower for each notch position. Thus, the RPM measurements were highly repeatable.

Notch-average IAT varied from 313 K at notch 1 to 318 K at notches 4, 6, 7 and 8. In general, IAT increased with increasing notch position. However, IAT differed by less than one kelvin between adjacent notch positions. The inter-replicate CV for each notch position for IAT was 0.01 or lower. Therefore, IAT measurements were highly repeatable. Notch-average MAP varied from 98 kPa at idle to 201 kPa at notch 8. MAP increased with engine RPM. The inter-replicate CV for each notch position was 0.006 or lower. Therefore, MAP measurements were highly repeatable.

TABLE 3-5. Rail Yard Measurement-based Notch-Average Engine Activity Variables for the Prime Mover Engine of Locomotive NC 1871 Measured on June 11, 2019.

Throttle Notch Position	Engine RPM (RPM)		Intake Air Temperature (K)		Manifold Absolute Pressure (kPa)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Idle	269	0.002	314	0.008	98	0.000
1	268	0.000	313	0.003	97	0.006
2	389	0.000	314	0.005	106	0.000
3	509	0.000	316	0.007	118	0.000
4	702	0.000	318	0.008	148	0.004
5	728	0.000	317	0.006	155	0.004
6	819	0.000	318	0.005	178	0.003
7	859	0.000	318	0.011	193	0.006
8	902	0.002	318	0.005	201	0.003

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

3.2.2 Exhaust Gas and PM Concentrations

Notch-average exhaust concentrations of CO_2, CO, HC, NO and PM measured using an Axion PEMS are summarized in Table 3-6. Notch-average CO_2 concentrations varied from 0.71 vol % at idle to 6.09 vol % at notch 7. Notch-average CO_2 concentration at notch 8 was 6.03 vol %. Notch-average CO_2 concentrations increased with notch position for idle through notch 7. Notch-average CO_2 concentrations were highly repeatable with an inter-replicate CV of 0.06 or lower for each notch position.

Notch-average CO concentrations were below the detection limit of the Axion PEMS for idle through notch 5. The inter-replicate CVs for notch-average CO concentrations were 0.10 or lower. Notch-average HC concentrations were above the PEMS HC detection limit for notches 1 through 3 and lower for others. The inter-replicate CV was 0.2 or lower for notches with HC concentrations above the detection limit and 0.5 or lower for 6 out of the 9 notch positions.

Notch-average NO concentrations varied between 192 ppm at idle and 1460 ppm at notch 5. Notch-average NO concentrations typically increased with notch position from idle through notch 5 and decreased to 1206 ppm at notch 8. Notch-average NO concentrations were highly repeatable with the inter-replicate CV of 0.05 or lower for each notch position.

Notch-average PM concentrations varied from 4.4 mg/m^3 and 15.4 mg/m^3. Notch-average PM concentrations were within 0.4 mg/m^3 of each other for idle and notches 1 through 4. The notch-average PM concentrations increased with increasing notch position to 15.4 mg/m^3 at notch 7 and was 14.4 mg/m^3 at notch 8. Notch-average PM concentrations were highly repeatable with the inter-replicate CV of 0.02 or lower for each notch position.

TABLE 3-6. Rail Yard Measurement-based Axion PEMS-measured Notch-average Concentrations for the Prime Mover Engine of Locomotive NC 1871 Measured on June 11, 2019.

Throttle Notch Position	CO_2 concentration (vol %)		CO concentration (vol %)		HC concentration (ppm)		NO concentration (ppm)		PM concentration (mg/m^3)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Idle	0.71	0.06	*0.001*	*0.00*	*12*	*0.6*	192	0.05	4.8	0.15
1	1.21	0.03	*0.001*	*0.00*	15	0.1	332	0.02	4.7	0.07
2	2.41	0.00	*0.000*	*0.00*	14	0.2	697	0.02	4.9	0.04
3	3.53	0.00	*0.000*	*0.00*	13	0.2	1153	0.01	4.5	0.01
4	3.92	0.00	*0.000*	*0.00*	*5*	*0.5*	1146	0.02	4.4	0.08
5	4.98	0.01	*0.000*	*0.00*	*5*	*0.8*	1460	0.01	5.3	0.05
6	5.96	0.03	0.017	0.00	*4*	*0.4*	1403	0.01	11.6	0.04
7	6.09	0.01	0.037	0.03	*6*	*0.2*	1228	0.02	15.4	0.09
8	6.03	0.01	0.029	0.10	*1*	*0.9*	1206	0.03	14.4	0.14

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*
The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

3.2.3 Fuel Use and Emission Rates

Axion PEMS measured NO and HC concentrations were bias corrected for NO_x and THC concentrations using the NO_x/NO and THC/HC ratios given in Table C-9 of Appendix D. For PM, a correction factor of 5 was used based on literature review. Notch-average engine output and mass per time based fuel use rate and emission rates of CO_2, CO, THC, NO_x and PM are shown in Table 3-7.

Notch-average fuel use rates increased monotonically with increasing notch position for all the replicates and varied from 3.4 g/s at idle to 116 g/s at notch 8. Notch-average fuel use rates were highly repeatable at a given notch position. The inter-replicate CV for each notch position was 0.06 or lower and was 0.02 or lower for six of the nine notch positions. Notch-average CO_2 emission rates had the same relative trend as fuel use rate because approximately 99 percent of the carbon in fuel is emitted as CO_2. Notch-average CO_2 emission rates were highly repeatable at a given notch position. The inter-replicate CV for each notch position was 0.01 or lower.

Notch-average CO emission rates were typically based on CO concentrations below the detection limit of the Axion PEMS, except at notches 6 through 8. The inter-replicate CV was 0.3 or lower for eight of the nine notch positions. Notch-average THC emission rates were based on HC concentrations below the detection limit of the PEMS for one or more replicates in each notch position, resulting in CV of 0.13 or higher and large inter-replicate variability. However, the THC emission rates were low. For notches 1 through 3 where HC concentrations were above the detection limit, inter-replicate CV was 0.20 or lower.

Notch-average NO_x emission rates increased monotonically from 0.3 g/s at idle to 8.0 g/s at notch 8. Notch-average NO_x emission rates were highly repeatable at a given notch position. The inter-replicate CV for each notch position was 0.04 or lower. Notch-average PM emission rates increased monotonically from 0.02 g/s at idle to 0.25 g/s at notch 8. Notch-average PM emission rates were repeatable at a given notch position. The inter-replicate CV for each notch position was 0.17 or lower, and 0.04 or lower for six of the nine notch positions.

Engine output-based notch-average emission rates were weighted to the EPA line-haul duty cycle to estimate cycle-average emission rates. The results are shown in Table 3-8. Cycle-average CO and HC emission rates were lower and higher respectively, than the level of the Tier 2+ standard. The measured cycle-average NO_x emission rates were higher than the level of the Tier 0+ standard for each of the three replicates. The estimated cycle-average PM emission rates were higher than the level of the Tier 0+ standard.

3.3 Locomotive NC 1984: January 25, 2018

This section provides a summary of measured notch-average engine activity variables and concentrations for the RY measurement of locomotive NC 1984 conducted on January 25, 2018. Notch-average correction factors NO_x/NO and THC/HC were estimated based on SEMTECH-DS measurements. FUER based on Axion PEMS measurements with correction factors applied and CAER for the EPA line-haul cycle given here.

TABLE 3-7. Rail Yard Measurement-based Net Engine Output, Notch-average Fuel Use and Emission Rates for the Prime Mover Engine of Locomotive NC 1871 Measured on June 11, 2019.

Throttle Notch Position	Net Engine Output	Fuel Use Rate (g/s)		CO_2 Emission Rate (g/s)		CO Emission Rate (g/s)		HC Emission Rate[b] (g/s)		NO_x Emission Rate[c] (g/s)		PM Emission Rate[d] (g/s)	
	(hp)	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Idle	10[e]	3.4	0.06	11	0.00	*0.0*	*0.2*	*0.1*	*0.62*	0.3	0.04	0.02	0.00
1	125	5.8	0.04	18	0.00	*0.0*	*1.7*	0.1	0.15	0.5	0.03	0.02	0.00
2	290	16.0	0.00	50	0.00	*0.0*	*0.0*	0.1	0.20	1.6	0.01	0.03	0.00
3	630	30.7	0.01	96	0.00	*0.0*	*0.0*	0.2	0.17	3.4	0.01	0.03	0.17
4	1000	50.6	0.01	159	0.00	*0.0*	*0.0*	*0.1*	*0.56*	5.1	0.02	0.05	0.00
5	1360	68.1	0.01	213	0.00	*0.0*	*0.0*	*0.1*	*0.82*	6.9	0.01	0.06	0.09
6	1920	98.2	0.02	307	0.00	0.6	0.3	*0.1*	*0.52*	8.0	0.01	0.17	0.06
7	2190	110.3	0.01	343	0.01	1.3	0.0	*0.2*	*0.13*	7.6	0.02	0.23	0.04
8	2230	116.0	0.01	361	0.01	1.1	0.1	*0.0*	*0.78*	8.0	0.02	0.25	0.12

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates.*

[b] *HC measured with Axion PEMS were multiplied with a correction factor shown in Table D-9(b) in Appendix D to obtain THC.*

[c] *NO measured with Axion PEMS were been multiplied with a correction factor shown in Table D-9(a) in Appendix D to obtain NO_x.*

[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*

[e] *Assumed from prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).*

The values in italics are based on measured concentrations below the detection limit of the Axion PEMS.

TABLE 3-8. The EPA Line-Haul based Cycle-average Emission Rates for the Rail Yard Measurement of the Prime Mover Engine of Locomotive NC 1871 Measured on June 11, 2019.

Results	EPA Line-Haul Duty Cycle-average Emission Rates[a]			
	CO [g/bhp-hr]	HC[b] [g/bhp-hr]	NO_x[c] [g/bhp-hr]	PM[d] [g/bhp-hr]
Replicate 1	1.3	0.46	14.4	0.43
Replicate 2	1.4	0.28	14.6	0.37
Replicate 3	1.2	0.63	14.4	0.34
Average	1.3	0.46	14.5	0.38
CV[e]	0.08	0.38	0.01	0.11
Tier 0+	5.0	1.00	8.0	0.22
Tier 1+	2.2	0.55	7.4	0.22
Tier 2+	1.5	0.30	5.5	0.10

[a] *EPA Line-Haul include dynamic brake. Since dynamic brake measurements were not conducted due to unavailability of the dynamic braking grid, time spent in dynamic brake is assigned to idle.*

[b] *THC emission rates have been estimated from Axion PEMS measured HC and bias corrected for THC based on notch-average correction factor estimated in Table D-9(b) in Appendix D.*

[c] *NO_x emission rates have been estimated from Axion PEMS measured NO and bias corrected for NO_x based on notch-average correction factor estimated in Table D-9(a) in Appendix D.*

[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*

[e] *CV = Coefficient of Variation (Ratio of standard deviation and mean of three replicates).*

3.3.1 Engine Activity Variables

Notch-average RPM, IAT, and MAP for the three replicates are summarized in Table 3-9. Notch-average engine RPM varied from 219 RPM at low idle and notch 1 to 903 RPM at notch 8. The notch-average RPM had the inter-replicate CV of 0.008 or lower for each notch position. Thus, the RPM measurements were highly repeatable.

Notch-average IAT varied from 348 K at notches 1, 2 and 3 to 358 K at notches 7 and 8. In general, notch-average IAT increased with increasing notch position. However, notch-average IAT differed by less than two kelvin for adjacent notch positions. The inter-replicate CVs for IAT were 0.003 or lower for each notch poison. Therefore, IAT measurements were highly repeatable. Notch-average MAP varied from 98 kPa at idle to 213 kPa at notch 8. Notch-average MAP increased with an increase in engine RPM. The inter-replicate CV for MAP was 0.016 or lower for each notch position. Therefore, MAP measurements were highly repeatable.

3.3.2 Exhaust Gas and PM Concentrations

Notch-average measured exhaust concentrations of CO_2, CO, HC, NO and PM measured using Axion PEMS are summarized in Table 3-10. Notch-average CO_2 concentrations varied from 0.70 vol % at idle to 5.46 vol % at notch 8. Notch-average CO_2 concentrations increased with notch position for idle through notch 8. Notch-average CO_2 concentrations were highly repeatable with the inter-replicate CV of 0.04 or lower for each notch position.

TABLE 3-9. Rail Yard Measurement-based Notch-Average Engine Activity Variables for the Prime Mover Engine of Locomotive NC 1984 Measured on January 25, 2018.

Throttle Notch Position	Engine RPM (RPM)		Intake Air Temperature (K)		Manifold Absolute Pressure (kPa)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	219	0.000	348	0.003	98	0.001
High Idle	268	0.000	348	0.002	101	0.000
1	268	0.000	348	0.002	101	0.000
2	388	0.004	350	0.002	110	0.000
3	508	0.003	352	0.003	123	0.000
4	701	0.002	354	0.002	156	0.000
5	727	0.001	354	0.001	163	0.004
6	817	0.003	357	0.001	187	0.003
7	858	0.001	358	0.002	205	0.008
8	903	0.008	358	0.001	213	0.016

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

TABLE 3-10. Rail Yard Measurement-based Axion PEMS-measured Notch-average Concentrations for the Prime Mover Engine of Locomotive NC 1984 Measured on January 25, 2018.

Throttle Notch Position	CO_2 concentration (vol %)		CO concentration (vol %)		HC concentration (ppm)		NO concentration (ppm)		PM concentration (mg/m^3)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	0.70	0.02	*0.000*	*0.00*	*5*	*0.7*	181	0.05	6.8	0.04
High Idle	0.71	0.01	*0.000*	*0.00*	*4*	*0.6*	170	0.02	7.1	0.06
1	1.25	0.04	*0.000*	*0.00*	*5*	*0.4*	353	0.05	6.6	0.03
2	2.34	0.01	*0.000*	*0.00*	*8*	*0.1*	653	0.03	5.9	0.03
3	3.36	0.00	*0.000*	*0.00*	*7*	*0.2*	1089	0.04	5.6	0.02
4	3.63	0.01	*0.000*	*0.00*	*4*	*0.2*	1057	0.03	6.1	0.02
5	4.46	0.01	*0.000*	*0.00*	*4*	*0.5*	1383	0.06	6.2	0.02
6	5.24	0.01	*0.000*	*0.00*	*3*	*0.2*	1534	0.06	7.9	0.02
7	5.33	0.01	*0.000*	*0.00*	*5*	*0.8*	1462	0.05	8.8	0.03
8	5.46	0.02	*0.001*	*1.15*	*2*	*0.5*	1463	0.04	9.3	0.12

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*
The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

Notch-average CO concentrations were below the detection limit of the Axion PEMS for all notch positions. Notch-average HC concentrations were below the PEMS detection limit for all notch positions. The inter-replicate CV was 0.8 or lower for each notch position.

Notch-average NO concentrations varied between 170 ppm at high idle and 1534 ppm at notch 6. Notch-average NO concentrations typically increased with notch position from high idle through notch 5 and was 1463 ppm at notch 8. Notch-average NO concentrations were highly repeatable with the inter-replicate CV of 0.06 or lower for each notch position.

Notch-average PM concentrations varied from 5.6 mg/m^3 and 9.3 mg/m^3. Notch-average PM concentrations were highly repeatable with the inter-replicate CV of 0.12 or lower for each of the notch position, and 0.06 or lower for nine of the ten notch positions.

3.3.3 Fuel Use and Emission Rates

Notch-average fuel use and emission rates were estimated for locomotive NC 1984. Axion PEMS measured NO and HC concentrations were bias corrected for NO_x and THC concentrations using the NO_x/NO and THC/HC ratios given in Table D-14 of Appendix D. For PM, a correction factor of 5 was used based on literature review. Notch-average engine output and mass per time based fuel use rate and emission rates of CO_2, CO, THC, NO_x and PM are shown in Table 3-11.

Notch-average fuel use rates increased monotonically with increasing notch position for all the replicates and varied from 2.6 g/s at low idle to 96 g/s at notch 8. Notch-average fuel use rates were highly repeatable at a given notch position. The inter-replicate CV for each notch position was 0.04 or lower. Notch-average CO_2 emission rates had the same trend as fuel use rate. Notch-average CO_2 emission rates were highly repeatable at a given notch position. The inter-replicate CV for each of the notch positions was 0.04 or lower for each notch position.

Notch-average CO emission rates were based on CO concentrations below the detection limit of the Axion PEMS. The inter-replicate CV was 1.7 or lower for each notch position. However, CO emission rates were low. Notch-average THC emission rates were based on HC concentrations below the detection limit of the PEMS, resulting in CV of 0.14 or higher and large inter-replicate variability. However, the THC emission rates were low.

Notch-average NO_x emission rates increased monotonically from 0.2 g/s at idle to 8.9 g/s at notch 8. The inter-replicate CV for each notch position was 0.07 or lower. Notch-average NO_x emission rates were highly repeatable at a given notch position. Notch-average PM emission rates were approximately increased monotonically from 0.02 g/s at low idle to 0.15 g/s at notch 8. However, the increase between adjacent notch positions was 0.03 g/s or lower. The inter-replicate CV for each of the notch positions was 0.06 or lower for each notch position. Notch-average PM emission rates were repeatable at a given notch position.

TABLE 3-11. Rail Yard Measurement-based Net Engine Output, Notch-average Fuel Use and Emission Rates for the Prime Mover Engine of Locomotive NC 1984 Measured on January 25, 2018.

Throttle Notch Position	Net Engine Output	Fuel Use Rate (g/s)		CO_2 Emission Rate (g/s)		CO Emission Rate (g/s)		HC Emission Rate[b] (g/s)		NO_x Emission Rate[c] (g/s)		PM Emission Rate[d] (g/s)	
	(hp)	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	10[e]	2.6	0.02	8	0.00	*0.0*	*1.6*	*0.0*	*0.65*	0.2	0.05	0.02	0.05
High Idle	10[e]	3.1	0.02	10	0.00	*0.0*	*1.4*	*0.0*	*0.50*	0.3	0.02	0.03	0.06
1	125	5.5	0.04	17	0.00	*0.0*	*1.1*	*0.0*	*0.43*	0.5	0.04	0.03	0.04
2	290	14.2	0.00	44	0.00	*0.0*	*0.0*	*0.1*	*0.14*	1.4	0.03	0.03	0.03
3	630	26.8	0.00	84	0.00	*0.0*	*0.0*	*0.1*	*0.14*	3.0	0.04	0.04	0.01
4	1000	43.4	0.01	136	0.00	*0.0*	*0.0*	*0.1*	*0.18*	4.4	0.02	0.06	0.01
5	1360	56.4	0.00	176	0.00	*0.0*	*0.0*	*0.1*	*0.52*	6.0	0.05	0.07	0.03
6	1920	78.9	0.01	247	0.00	*0.0*	*1.7*	*0.1*	*0.21*	8.0	0.07	0.10	0.02
7	2190	88.8	0.02	278	0.01	*0.0*	*0.8*	*0.1*	*0.72*	8.4	0.04	0.13	0.04
8	2230	96.0	0.04	300	0.04	*0.0*	*1.5*	*0.0*	*0.45*	8.9	0.03	0.15	0.14

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates.*
[b] *HC measured with Axion PEMS were multiplied with a correction factor shown in Table D-14(b) in Appendix D to obtain THC.*
[c] *NO measured with Axion PEMS were been multiplied with a correction factor shown in Table D-14(a) in Appendix D to obtain NO_x.*
[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*
[e] *Assumed from prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).*
The values in italics are based on measured concentrations below the detection limit of the Axion PEMS.

Engine output-based notch-average emission rates were weighted to the EPA line-haul duty cycle to estimate cycle-average emission rates. The results are shown in Table 3-12. Cycle-average CO and HC emission rates were lower than the level of the Tier 2+ standard. The measured cycle-average NO_x emission rate was higher than the level of the Tier 0+ standard for each of the three replicates. The estimated cycle-average PM emission rates were higher than the level of the Tier 0+ standard.

3.4 Comparison Among NC 1871 Measurements

Locomotive NC 1871 was measured twice in RY at 19 months apart to assess the effect of differences in engine activity variables and measured exhaust concentrations on FUER. Notch-average engine activity variables and FUER measured during 12/21/2017 and 6/11/2019 were compared.

3.4.1 Engine Activity Variables

Notch-average engine activity variables for each of these measurements are given in Figure 3-1. Notch-average engine RPM for a given notch position were within 2 RPM of each other and differed by less than 0.1 percent. Therefore, notch-average engine RPM for a given notch position were comparable to each other for these two measurements.

TABLE 3-12. The EPA Line-Haul based Cycle-average Emission Rates for the rail Yard Measurement of the Prime Mover Engine of Locomotive NC 1984 Measured on January 25, 2018.

Results	EPA Line-Haul Duty Cycle-average Emission Rates[a]			
	CO [g/bhp-hr]	HC[b] [g/bhp-hr]	NO_x[c] [g/bhp-hr]	PM[d] [g/bhp-hr]
Replicate 1	13.9	0.0	0.16	0.30
Replicate 2	14.8	0.0	0.29	0.27
Replicate 3	14.5	0.1	0.25	0.27
Average	14.4	0.0	0.23	0.28
CV[e]	0.03	1.05	0.29	0.05
Tier 0+	5.0	1.00	8.0	0.22
Tier 1+	2.2	0.55	7.4	0.22
Tier 2+	1.5	0.30	5.5	0.10

[a] *EPA Line-Haul include dynamic brake. Since dynamic brake measurements were not conducted due to unavailability of the dynamic braking grid, time spent in dynamic brake is assigned to idle.*

[b] *THC emission rates have been estimated from Axion PEMS measured HC and bias corrected for THC based on notch-average correction factor estimated in Table D-14(b) in Appendix D.*

[c] *NO_x emission rates have been estimated from Axion PEMS measured NO and bias corrected for NO_x based on notch-average correction factor estimated in Table D-14(a) in Appendix D.*

[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*

[e] *CV = Coefficient of Variation (Ratio of standard deviation and mean of three replicates).*

IAT is affected by ambient temperature and notch position. Given varying ambient conditions between these measurements, it was expected that IAT would vary. The average ambient temperature at noon in Raleigh on December 21, 2017 and June 11, 2019 was 285 K and 300 K, respectively. On an absolute basis, notch-average IAT for a given notch position for June 2019 versus December 2017 measurement were 9 percent to 10 percent lower.

Notch-average MAP for notches 2 and 3 were 0.5 percent and 1.4 percent higher, respectively, for the June 2019 versus December 2017 measurement. Notch-average MAP for other notch positions were 1.7 percent to 5.6 percent lower for the June 2019 versus December 2017 measurement.

Notch-average measured exhaust CO_2 concentrations for a given notch position were 1.7 percent to 12 percent higher for the June 2019 versus December 2017 measurement. This difference for idle, notches 1 through 3, and notches 4 through 8 were 1.5 percent, 3 percent to 7 percent, and 10 to 14 percent higher, respectively.

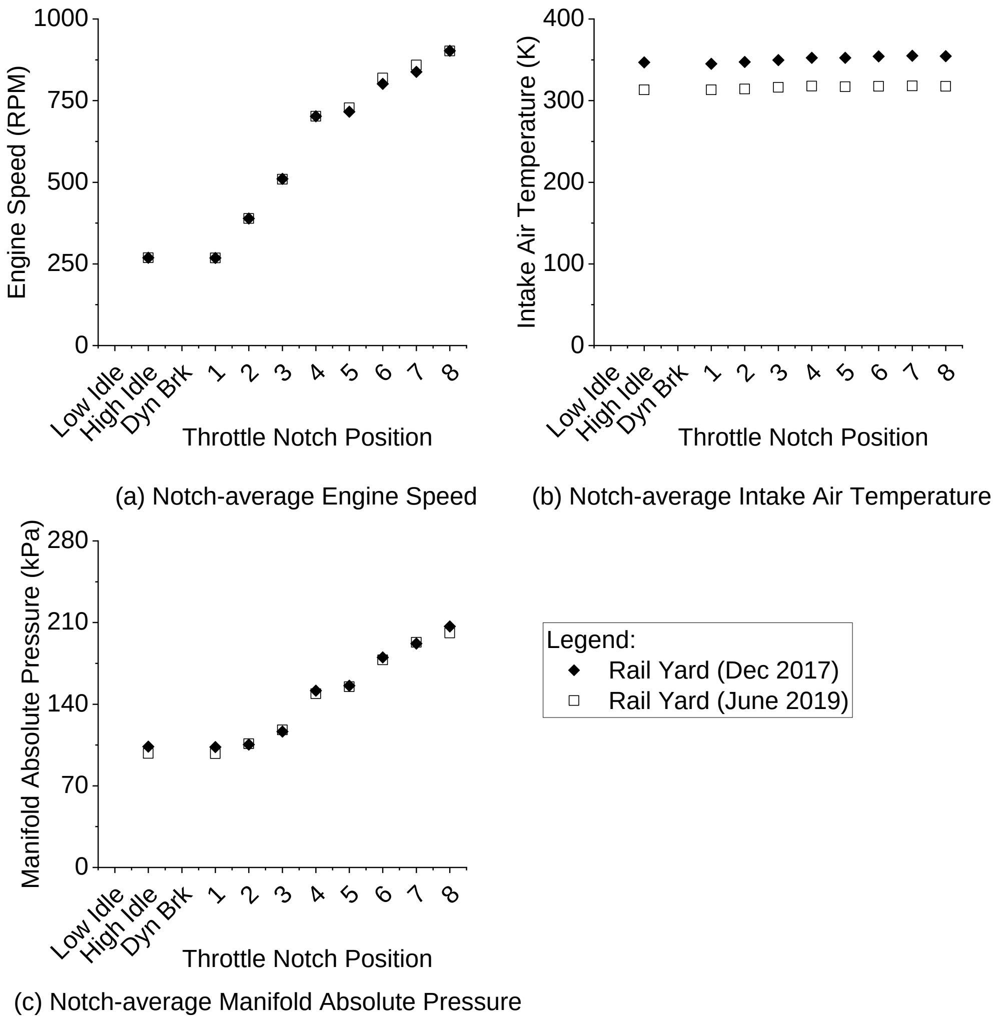


FIGURE 3-1. Comparison of Notch-average Engine Activity Variables for the Prime Mover Engine of Locomotive NC 1871 Between Rail Yard Measurements Conducted on 12/21/2017 and 6/11/2019: (a) Engine Revolutions per Minute; (b) Intake Air Temperature; and (c) Manifold Absolute Pressure.

Differences in notch-average RPM, IAT, and MAP lead to difference in mass air flow (MAF) rate. Differences in notch-average exhaust CO_2 concentrations arise due to differences in air to fuel ratio (AFR). Increased fuel flow rate indicates lower AFR and higher CO_2 concentrations. Therefore, differences in engine activity variables and exhaust concentrations lead to differences in FUER. To quantify the effect of changes in IAT, MAP and CO_2 concentrations on FUER, several sensitivity cases were compared to an illustrative baseline. The illustrative baseline includes notch-average IAT, MAP and CO_2 concentrations corresponding to the average of 3 replicates of the December 2017 measurement of locomotive NC 1871 at notch 8. Case 1 quantifies the effect of 10.0 percent lower IAT compared to the base case. Case 2 quantifies the effect of 5.6 percent lower MAP. Case 3 quantifies the effect of a 10.0 percent increase in CO_2 exhaust concentration. A 10.0 percent lower IAT resulted in 11.8 percent higher MAF and FUER. A 5.6 percent lower MAP reduced MAF and FUER by 4.0 percent. A 10.0 percent increase in CO_2 exhaust concentration decreased AFR by 6.8 percent and resulted in a 7.3 percent increase in fuel use and CO_2 emission rates and a 4.2 percent decrease in CO, HC, NO_x, and PM emission rates.

3.4.2 Fuel Use and Emission Rates

Given the differences in ambient temperatures, notch-average IAT, MAP and measured exhaust concentrations, FUER may between the two measurements. The difference in FUER among RY measurements of locomotive NC 1871 are quantified here.

Time-based notch-average fuel use rates and fuel-specific engine output (FSEO) for RY measurements are compared in Figure 3-2. Compared to the December 2017 measurement, the notch-average time-based fuel use rates for the June 2019 measurement increased by 9-15 percent for idle through notch 2 and 19-24 percent for notch 3 through notch 8. The net increases in time-based fuel use rates are a combined effect of approximately 10 percent higher IAT in June 2019 versus December 2017 and 12 percent higher average CO_2 concentrations, both of which increase fuel use rate, compared to only a 2 to 5 percent decrease in average MAP. Overall, these three differences led to a net increase in fuel use rate.

Lower notches such as low idle, high idle, dynamic brake and notch 1 have low engine efficiency; therefore, FSEO is typically low for these throttle settings. FSEO for the former RY measurement for notches 2 through 8 were about 24 bhp-hr/gal indicating that the locomotive was more fuel-efficient than an average mid-1990 locomotive. For the latter RY measurement, FSEO was typically within 2 percent to 12 percent of 20.8 bhp-hr/gal for notches 2 through to 8. Notch-average fuel use rate increased for these notch positions, whereas, the engine power output remained the same. Thus, more fuel was consumed to provide the same engine power output.

Time-based notch-average emission rates of CO_2, CO, HC, NO_x, and PM for the two RY measurements are illustrated in Figure 3-3. Time-based CO_2 emission rates had similar relative trends as time-based fuel use rates. Notch-average CO_2 concentrations for the June 2019 RY measurement were about 4 to 12 percent higher compared to the first RY measurement, indicating a higher fuel to air ratio leading to increased fuel use, in addition to reduced IAT.

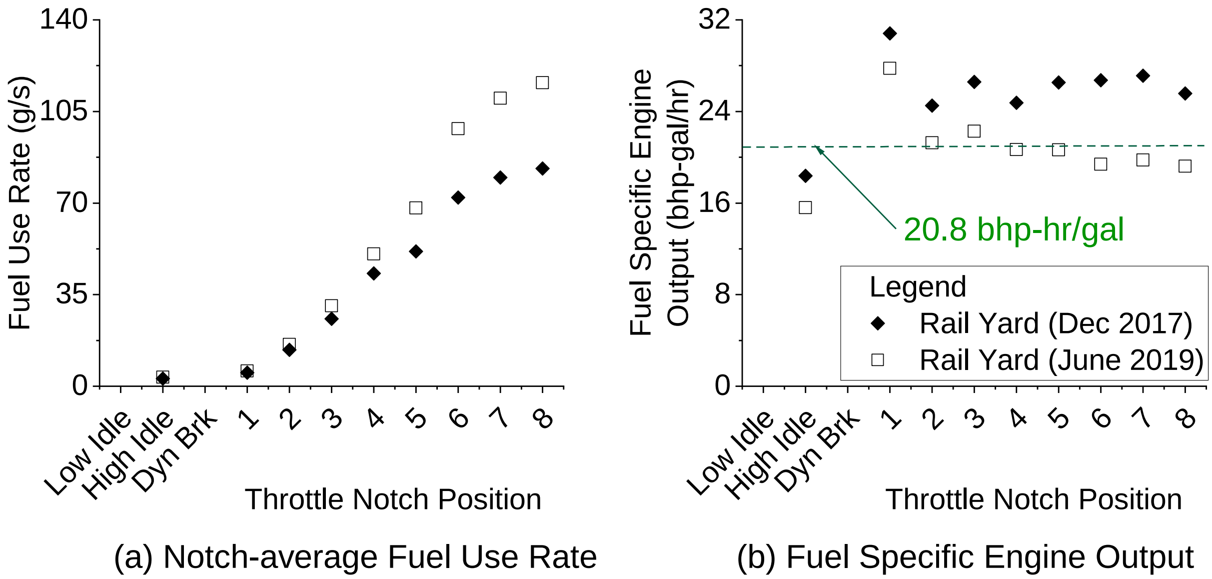


FIGURE 3-2. Comparison of Notch-average Fuel Use Rates for the Prime Mover Engine of Locomotive NC 1871 between Rail Yard Measurements Conducted on 12/21/2017 and 6/11/2019: (a) Time-Based Fuel Use Rate; and (b) Fuel Specific Engine Output.

Notch-average CO concentrations were typically below the PEMS detection limit for each notch position for the December 2017 RY measurement. For the June 2019 RY measurement, notch-average CO concentrations were above the PEMS detection limit for notches 6 through 8. Notch-average CO emission rates were the highest at notch 7 at 1.4 g/s for the June 2019 RY measurement. Notch-average HC emission rates were all based on concentrations below detection limit for each replicate of the December 2017 and June 2019 RY measurements.

Time-based notch-average NO_x emission rates were within 10 percent for a given notch position for each of the measurements from low idle through notch 2. For notches 3 through 8, notch-average NO_x emission rates for the June 2019 RY measurements were about 10 percent higher compared to the December 2017 measurements. Notch-average PM emission rates for notches 6 through 8 for June 2019 RY measurements were about 10 to 20 percent higher compared to the December 2017 RY measurements.

3.5 Benchmarking Locomotives

Locomotive FUER depend on exhaust flow rate and exhaust concentrations. Exhaust flow rate depends on air flow rate and fuel/air ratio. Fuel flow rate depends on the air flow rate and fuel/air ratio. The fuel/air ratio can be inferred from exhaust composition. Air flow rate depends on RPM, MAP, and IAT. Thus, variability in RPM, MAP, and IAT for a given notch position among locomotives can lead to inter-locomotive variability in air flow rate and, ultimately, in fuel use and emission rates. Therefore, the inter-locomotive variability in RPM, MAP, and IAT is identified to help explain inter-locomotive variability in fuel use and emission rates.

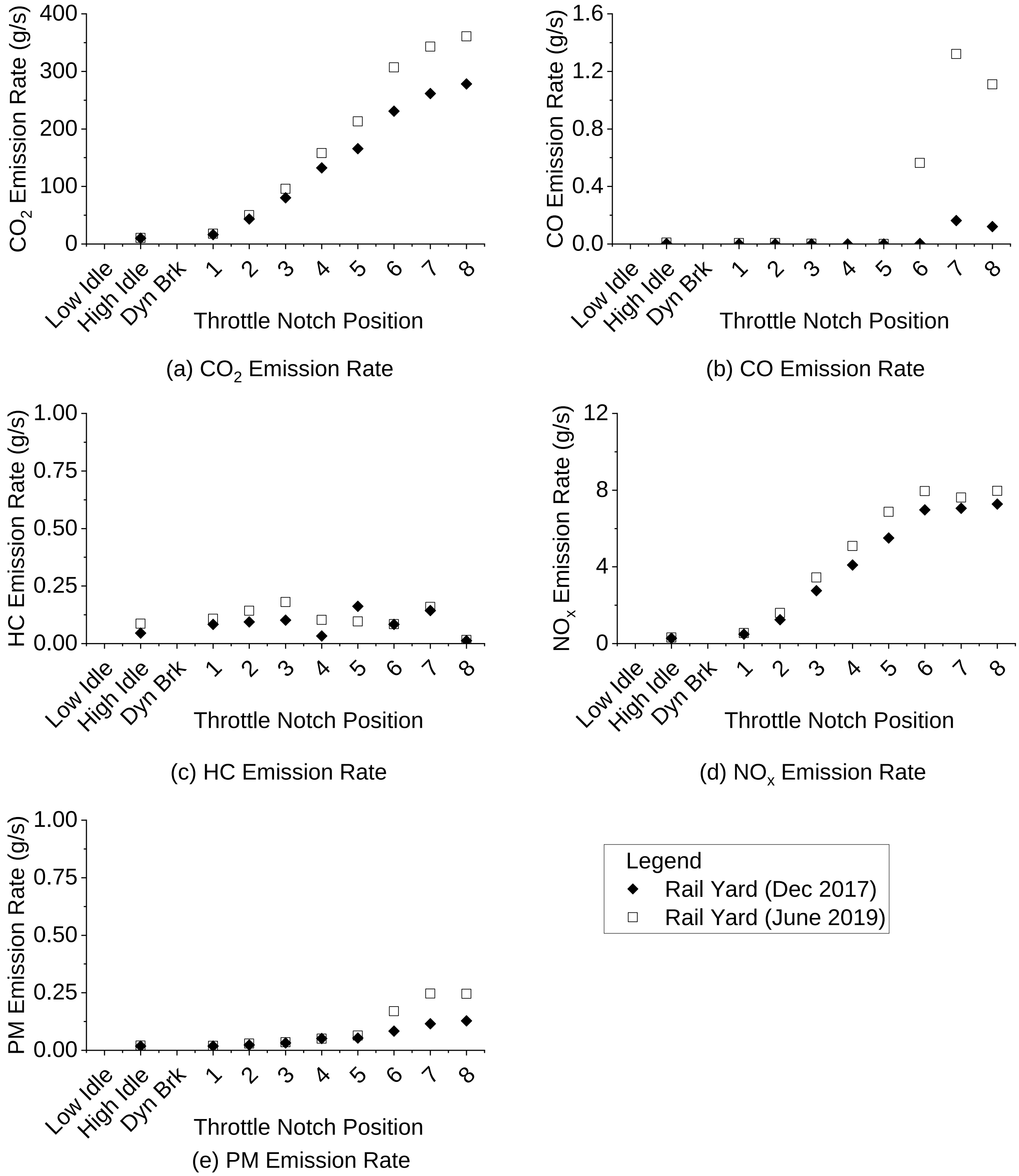


FIGURE 3-3. Comparison of Notch-average Time-Based Emission Rates for the Prime Mover Engine of Locomotive NC 1871 between Rail Yard Measurements Conducted on 12/21/2017 and 6/11/2019: (a) CO_2 Emission Rate; (b) CO Emission Rate; (c) HC Emission Rate; (d) NO_x Emission Rate; and (e) PM Emission Rate.

In this section, notch-average engine activity variables including engine output, RPM, IAT, and MAP, FUER and CAER for locomotives NC 1871 and NC 1984 were benchmarked to other NCDOT locomotives. Notch-average engine output and engine activity variables, FUER and CAER for other NCDOT locomotives were taken from prior work (Frey *et al.*, 2016; Graver and Frey, 2013). For any locomotive with more than one RY measurement, results from the most recent measurement were used. For example, for locomotive NC 1792, RY measurements were conducted before and after the rebuild. Therefore, results of post-rebuild measurements of NC 1792 are used here. Locomotives NC 1859 and NC 1871 were measured twice and the results of most recent measurements are presented.

3.5.1 Engine Activity Variables

Differences in how the fuel injection is governed, RPM, IAT, and MAP, when comparing the same notch position for different measurements or different locomotives, leads to differences in air flow rate. These differences lead to inter-locomotive variability in FUER. Differences in engine power output lead to differences in CAER because CAER are inversely related to the engine power output at a given notch position. Therefore, to quantify the differences in FUER and CAER among locomotives, fuel injection type and notch-average engine activity variables are compared.

The PMEs of F59PHI locomotives NC 1755 and NC 1797, and the F59PH locomotives NC 1871 and NC 1984 have electronically-governed fuel injection. The GP40 locomotive NC 1792 and F59PH locomotives NC 1810, NC 1859, NC 1869, and NC 1893 have electronically-governed fuel injection. Locomotives with electronically-governed fuel injection are more fuel-efficient versus mechanically-governed fuel injection (EPA, 1998).

Measured RY-based notch-average engine activity variables, including engine output, RPM, IAT, ambient temperature, and MAP for each of the NCDOT locomotives, are given in Table 3-13. The PMEs of locomotives NC 1792, NC 1755, NC 1797, NC 1871, and NC 1984 have two idle settings but do not operate at low idle during a static load RY measurement. The PMEs of all F59PHs with mechanical fuel injection operate at low idle during RY measurement.

All of the PMEs of NCDOT-owned locomotives have a rated power output of 3,000 hp. However, to prevent overheating of the dynamic braking grid during static load RY measurements, each PME is configured to operate at lower power output at notches 7 and 8. Notch-average engine output increased monotonically with notch position for each PME. For each PME, engine power output displayed by the locomotive activity recorder at idle position(s) was zero. However, engine power output was assumed to be 9 hp based on prior dynamometer measurements of one EMD 12-710 PME for all F59PH and F59PHI locomotives. Engine output at idle for the GP40 locomotive was assumed as 20 hp based on prior dynamometer measurement (Graver and Frey, 2013).

Notch-average engine output for a given notch position was the same among the PMEs of GP40, F59PHI and F59PH locomotives, except for F59PH locomotives with electronically governed fuel injection. All of the locomotives had the same engine output at notch 3. Notch-average engine output for notches 1 through 8 for a given notch position were equal to each other for the PMEs of two F59PH locomotives with electronically governed fuel injection. F59PH locomotives with electronically governed fuel injection had 40 hp to 60 hp lower engine output at notches 1 and 2 compared to the other locomotives. Engine output for notches 4 through 6 for F59PH locomotives with electronically governed fuel injection was 50 hp to 400 hp higher compared to other locomotives. Engine output for notches 7 and 8 for these two locomotives was 100 hp to 350 hp lower for a given notch position compared to other locomotives. These differences typically occur because each of the PMEs are configured to operate at different notch-average engine RPM and MAP. These differences in engine power output lead to differences in CAER because CAER are inversely related to the engine power output at a given notch position.

Notch-average engine RPM for a given notch position is configured by the manufacturer/remanufacturer and can be reconfigured to match the desired engine speed. Notch-average engine RPM for a given notch position was generally within 3 percent within, but not between, each of these five locomotive groups: (1) F59PHI; (2) F59PH with mechanically governed fuel injection; and (3) F59PH locomotives with electronically governed fuel injection, except for NC 1893; (4) NC 1893; and (5) GP40. At notch 7, all locomotives, except for the electronically-governed F59PH locomotives, had comparable RPM. At notch 8, all locomotives had comparable RPM.

Notch-average MAP for a given notch position of a locomotive was typically within 10 kPa of the corresponding notch-average MAP for other locomotives for notches idle through notch 3. For notches 4 and higher, notch-average MAP for a given notch position of a locomotive differed by more than 10 kPa but less than 40 kPa compared to the corresponding notch-average MAP for other locomotives. As explained in Section 3.4.1, lower MAP results in lower MAF and FUER. Thus, differences in MAP proportionately affect FUER.

Notch-average IAT varies based on notch position and ambient temperature. Notch-average IAT typically increases with notch position. However, the average IAT for adjacent notch positions typically differ by two kelvin or less. For a given locomotive, notch-average IAT between idle and notch 8 differed by 15 K or lower. For F59PHI locomotives, locomotive NC 1755 had 9 K to 11 K higher notch-average IAT for a given notch position versus NC 1797. However, ambient temperature was 2 K lower. Thus, the IAT differed among the F59PHI locomotives for approximately similar ambient temperatures. Notch-average IAT for F59PH locomotives with mechanical-governed fuel injection differed by less than 5 K for a given notch position. However, the ambient temperatures differed by up to 15 K for measurements of F59PH locomotives. Therefore, variability in IAT for the mechanically-governed F59PH locomotives seems to be relatively insensitive to ambient temperature. Notch-average IAT for F59PH locomotives with electronic-governed fuel injection for a given notch position were 33 K to 39 K higher for NC 1984 versus NC 1871. However, the ambient temperature for NC 1984 was 19 K lower than NC 1871. Therefore, the difference between IAT and ambient temperature may vary within a locomotive group. For the GP40 locomotive, ambient temperature and notch-average IATs were within 1 K of each other. Typically, notch-average IATs were higher than ambient temperature but the difference varied within and between locomotive groups. Notch-average IAT typically increases with engine load but can differ when comparing locomotives.

TABLE 3-13. Notch-average Engine Activity Variables for the Most Recent Rail Yard Measurement of the Prime Mover Engines of NCDOT-owned Locomotives: (a) Net Engine Output; (b) Engine Revolutions per Minute; (c) Intake Air Temperature; and (d) Manifold Absolute Pressure.

(a) Net Engine Output (hp)

Locomotive Model	GP40	F59PHI		F59PH					
Fuel Injection	Mechanical	Electronic		Mechanical				Electronic	
Throttle Notch Position	NC 1792	NC 1755	NC 1797	NC 1810	NC 1859	NC 1869	NC 1893	NC 1871	NC 1984
Low Idle	-[a]	-[a]	-[a]	9[b]	9[b]	9[b]	-[a]	9[b]	-[a]
High Idle	20[b]	9[b]	9[b]	9[b]	9[b]	9[b]	9[b]	9[b]	9[b]
1	190	190	190	190	190	190	190	130	130
2	345	350	350	350	350	350	350	310	310
3	675	675	675	675	675	675	675	675	675
4	1000	1000	1000	1000	1000	1000	1000	1050	1050
5	1300	1300	1300	1300	1300	1300	1300	1450	1450
6	1600	1600	1600	1600	1600	1600	1600	2000	2000
7	2400	2400	2400	2400	2400	2400	2400	2300	2300
8	2700	2700	2700	2700	2700	2700	2700	2350	2350

(b) Engine Revolutions per Minute (RPM)

Locomotive Model	GP40	F59PHI		F59PH					
Fuel Injection	Mechanical	Electronic		Mechanical				Electronic	
Throttle Notch Position	NC 1792	NC 1755	NC 1797	NC 1810	NC 1859	NC 1869	NC 1893	NC 1871	NC 1984
Low Idle	-[a]	-[a]	-[a]	238	238	238	201	-[a]	-[a]
High Idle	252	343	343	381	370	372	351	269	268
1	319	343	343	381	370	372	351	268	268
2	383	343	343	381	370	372	350	389	388
3	501	490	490	491	492	494	492	509	508
4	566	651	651	565	565	566	571	702	701
5	661	750	750	652	653	653	654	728	727
6	728	750	750	729	731	732	734	819	817
7	828	820	820	820	822	823	829	859	858
8	901	903	904	906	904	906	911	902	903

Table 3-13 Continued on next page.

Table 3-13 Continued from previous page.

(c) Intake Air Temperature (K)

Locomotive Model	GP40	F59PHI		F59PH					
Fuel Injection	Mechanical	Electronic		Mechanical				Electronic	
Notch Position	NC 1792	NC 1755	NC 1797	NC 1810	NC 1859	NC 1869	NC 1893	NC 1871	NC 1984
Low Idle	-[a]	-[a]	-[a]	331	335	335	337	-[a]	-[a]
High Idle	291	324	314	341	346	340	344	316	348
1	290	323	314	333	340	336	337	314	350
2	290	322	313	335	342	337	341	316	352
3	290	322	314	338	345	339	344	318	354
4	290	324	315	340	346	340	345	320	354
5	290	329	319	339	345	340	341	319	357
6	290	327	318	341	348	341	347	319	358
7	290	329	319	344	349	345	351	321	358
8	290	330	321	346	351	347	351	319	358
Ambient Temperature[c]	290	288	290	288	305	302	292	300	281

(d) Manifold Absolute Pressure (kPa)

Locomotive Model	GP40	F59PHI		F59PH					
Fuel Injection	Mechanical	Electronic		Mechanical				Electronic	
Notch Position	NC 1792	NC 1755	NC 1797	NC 1810	NC 1859	NC 1869	NC 1893	NC 1871	NC 1984
Low Idle	-[a]	-[a]	-[a]	101	100	104	103	-[a]	-[a]
High Idle	106	108	108	110	108	112	112	98	101
1	110	108	108	110	108	112	112	97	101
2	114	108	108	110	109	112	112	106	110
3	126	122	122	121	120	124	126	118	123
4	135	145	146	132	129	133	137	149	156
5	150	166	167	146	143	147	150	155	163
6	164	168	169	162	158	162	167	178	186
7	189	215	207	208	181	194	229	193	205
8	209	249	232	237	228	222	254	201	213

[a] *The prime mover engine only operates at high idle in the static test mode for NC 1792, NC 1755, NC 1797, NC 1871 and NC 1984.*
[b] *The locomotive activity recorder screen displays zero output at idle. Therefore, output was assumed from prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).*
[c] *Ambient temperatures correspond to the noon temperature for Raleigh, NC on the day of measurement recorded from www.timeanddate.com*

Differences in RPM, IAT, and MAP, when comparing the same notch position for different measurements or different locomotives, lead to differences in molar air flow rate. These differences lead to inter-locomotive variability in FUER. Differences may also arise based on fuel injection type and fuel injection timing.

3.5.2 Fuel Use Rate

Notch-average fuel use rates and FSEO based on RY measurements of the PMEs operated on ULSD for each of the NCDOT locomotives are given in Figure 3-4(a) and 3-4(c), respectively. As explained earlier, differences in notch-average RPM, IAT, MAP and engine output among locomotives for a given notch position may lead to inter-locomotive variability in notch-average FUER. Figure 3-4(b) illustrates such variability based on comparing fuel use rate per engine output among the locomotives. The EPA line-haul duty cycle based FSEO are given in Figure 3-4(d).

Notch-average fuel use rates versus notch position for each locomotive are given in Figure 3-4(a). Low idle and high idle notch-average fuel use rates were within 10 percent of each other for all of the locomotives. At notch 1, notch-average fuel use rates among the locomotives differed by up to 50 percent. However, the fuel use rates were lower than 20 g/s. Therefore, absolute differences in fuel use rates were small compared to those for notches with higher fuel use rates such as notch 8. Notch-average fuel use rates for notches 2 and 3 were within 7 percent of each other for all of the locomotives. Notch-average fuel use rates for notches 4 through 6 were within 6 percent of each other for all of the locomotives, except for locomotive NC 1871. For these notches, notch-average fuel use rates for locomotive NC 1871 were 5 to 10 percent higher than for any other locomotive. Notch-average fuel use rates at notch 7 were within 9 percent of each other for all the locomotives, except for locomotive NC 1984. For locomotive NC 1984 at notch 7, fuel use rates were 20 to 33 percent lower compared to other locomotives. Notch-average fuel use rates at notch 8 were within 11 percent of each other for all the locomotives, except for locomotive NC 1984. For locomotive NC 1984 at notch 8, fuel use rates were 23 to 35 percent lower compared to other locomotives.

Measured notch-average fuel use rate rates were compared with the notch-average fuel use rates based on engine dynamometer measurements for EMD 16-645E3 and EMD 12-710G3A PMEs reported by the EPA (EPA, 1998). Notch-average mass per time-based fuel use rates for EMD 16-645E3 and EMD 12-710G3A PMEs are given in Tables D-16 and D-17 of Appendix D, respectively. Measured notch-average fuel use rates for idle through notch 6 for NC 1792 were 5 to 13 percent lower for a given notch position compared to EPA reported notch-average fuel use rates for EMD 16-645E3 PMEs. For notches 7 and 8, fuel use rates were 16 to 22 percent lower. However, in the static load test used for RY measurements, in which engine output is dissipated as heat in the dynamic braking grid, the PME operates at lower engine output at notches 7 and 8 compared to dynamometer measurements. The EMD 16-645E3 engine on NC 1792 was rebuilt and performed more efficiently compared to prior to the rebuilt. The observed differences in notch-average fuel use rates between the rail yard and dynamometer measurements are explainable based on differences in engine load for some notch positions coupled with the underlying improvement in the status of the engine as a result of being rebuilt. Therefore, overall, the RY-based measured fuel use rates are consistent with those reported by the EPA.

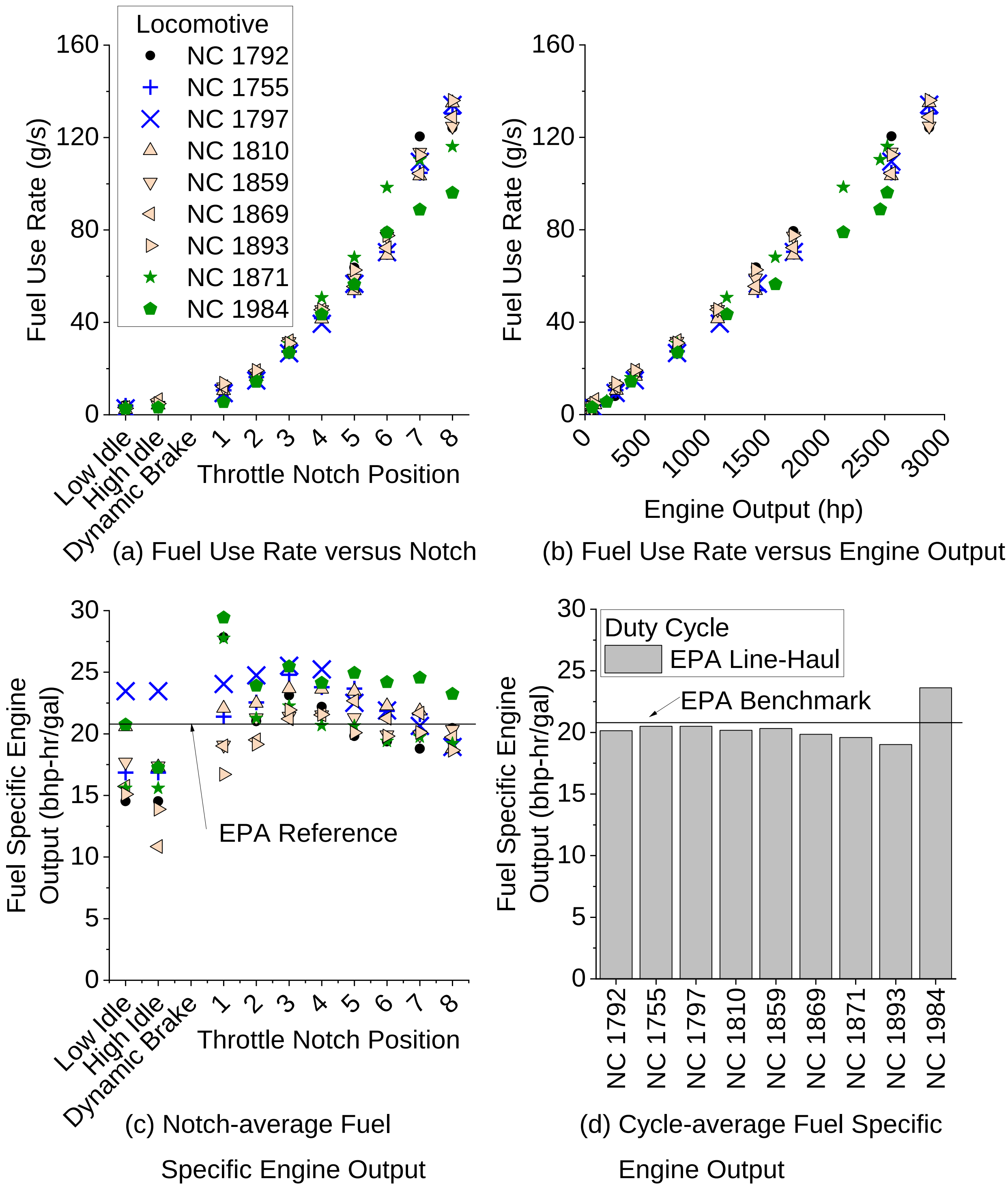


FIGURE 3-4. Notch-average Fuel Use Rates and Fuel Specific Engine Output for the Most Recent Rail Yard Measurement of the Prime Mover Engines of all NCDOT Locomotives Operated on Ultra-low Sulfur Diesel: (a) Notch-average Fuel Use Rate versus Notch Position; (b) Notch-average Fuel Use Rate versus Engine Output; (c) Notch-average Fuel Specific Engine Output; and (d) EPA Line-haul Cycle-average Fuel Specific Engine Output

Measured notch-average fuel use rates for the mechanically-governed F59PH locomotives for a given notch position were within 6 percent of the EPA reported notch-average fuel use rates for EMD12-710G3A PMEs, including notches 7 and 8. For electronically-governed F59PH locomotives, notch-average fuel use rates were within 7 percent of the EPA reported notch-average fuel use rates for EMD12-710G3A PMEs for idle through notch 5. At notch 6, the average fuel use rate was 5 percent higher. For notches 7 and 8, the average fuel use rates were 15 percent to 25 percent lower. These two locomotives had higher engine output at notch 6 and lower engine output at notches 7 and 8 compared to the EPA reported engine output. Thus, notch-average fuel use rates from the rail yard measurements for each of the locomotives are generally appropriate compared to the dynamometer measurements given differences in engine loads.

For each of the PMEs except for the PME of locomotive NC 1984, fuel use rates increased linearly with engine output as indicated in the Figure 3-4(b). For notches 4 through 7, locomotive NC 1984 had the highest FSEO compared to other locomotives and was, therefore, most fuel-efficient. Notch-average FSEO for each of the locomotives were lowest at idle and increased monotonically through notch 3. For notches 4 through 7, the FSEO for a given locomotive were within 5.8 bhp-hr/gal of each other and within 4.4 bhp-hr/gal of the EPA benchmark FSEO. At notch 8, all locomotives, except locomotive NC 1984, had 0.3 to 2.1 bhp-hr/gal lower FSEO than the EPA benchmark. At a given notch position, locomotive NC 1893 typically had the lowest FSEO whereas NC 1984 had the highest.

Cycle-average FSEO for all locomotives were estimated for the EPA line-haul duty cycle. Locomotive NC 1984 had the highest cycle-average FSEO of 23.6 bhp-hr/gal. All other locomotives had cycle-average FSEO lower than the EPA benchmark value of 20.8 bhp-hr/gal. However, the difference in cycle-average FSEO compared to the benchmark was 1 bhp-hr/gal or lower for 6 of the 9 locomotives. NC 1893 had the lowest cycle-average FSEO, at 18 bhp-hr/gal. The EPA reported mass-per time based notch-average fuel use rates for EMD 16-645E3 and EMD 12-710G3A PMEs were used to estimate the EPA line-haul cycle-average FSEO of 17.3 bhp-hr/gal and 19.1 bhp-hr/gal, respectively. Thus, measured FSEOs were approximately similar to the EPA reported values. Each of the NCDOT locomotives were rebuilt prior to the measurements. Therefore, these locomotives may be more fuel-efficient than those reported by the EPA.

3.5.3 Notch-Average Emission Rates

Notch-average mass per engine output-based emissions rates of CO, HC, NO_x and PM for EMD 16-645E3 and EMD 12-710G3A PMEs are given in Tables D-16 and D-17 of Appendix D, respectively. Mass-per time-based emission rates were estimated for NCDOT locomotives and benchmarked to emission rates reported by the EPA. Notch-average CO_2, CO, HC, NO_x and PM emission rates based on RY measurements of the PMEs operated on ULSD for each of the NCDOT locomotives are given in Figure 3-5. Notch-average CO_2 emission rates had similar relative trends as for notch-average fuel use rate.

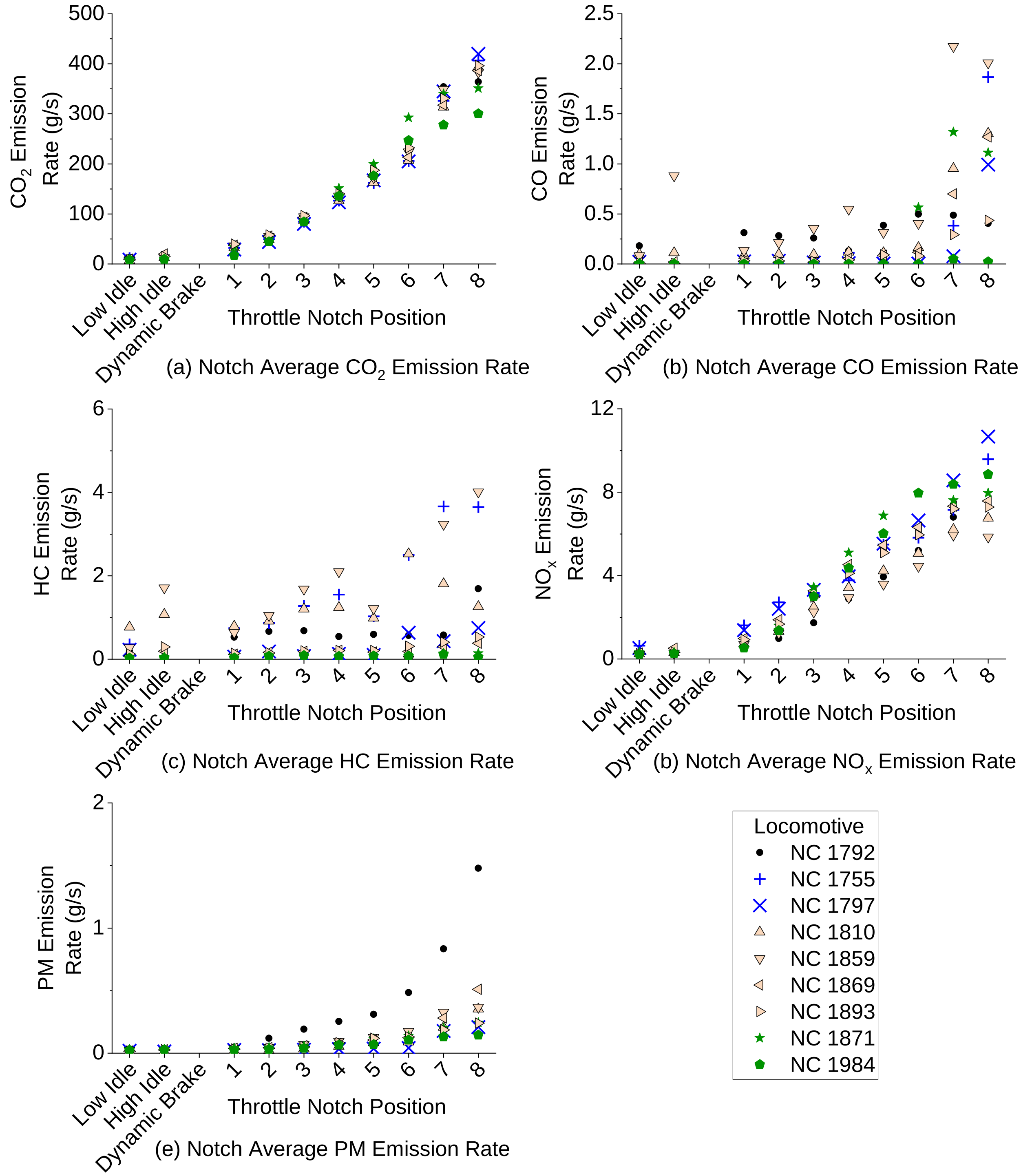


FIGURE 3-5. Notch-average Emission Rates for the Most Recent Rail Yard Measurement of the Prime Mover Engines of all NCDOT Locomotives Operated on Ultra-low Sulfur Diesel: (a) CO_2 Emission Rate; (b) CO Emission Rate; (c) HC Emission Rate; (d) NO_x Emission Rate; and (e) PM Emission Rate.

Notch-average CO and HC emission rates were typically based on CO and HC concentrations below the detection limit of the Axion PEMS, especially for idle through notch 5. Notch-average CO emission rates were lower than 2.5 g/s for all NCDOT locomotives at any given notch. The EPA reported CO emission rate at notch 8 for EMD 16-645E3 and EMD 12-710G3A PMEs was 1.6 g/s and 1.2 g/s, respectively. Therefore, CO emission rates measured here are within a factor of 2 of the EPA reported data. Notch-average HC emission rates were lower than 4 g/s for all NCDOT locomotives at any given notch. The EPA reported HC emission rate at notch 8 for EMD 16-645E3 and EMD 12-710G3A PMEs was 0.3 g/s and 0.1 g/s, respectively. Measured notch-average HC emission rates were typically several orders of magnitude higher compared to the EPA reported data.

Notch-average NO_x emission rates typically increased monotonically from idle through notch 8. There was large inter-locomotive variability in notch-average NO_x emission rates with NO_x emission rates, differing by as much as 60 percent from lowest to highest at a given notch position. Locomotive NC 1859 had the lowest notch-average NO_x emission rates for notches 6 and higher. Notch-average NO_x emission rates were lower than 10.7 g/s for all NCDOT locomotives at any given notch. The EPA reported NO_x emission rate at notch 8 for EMD 16-645E3 and EMD 12-710G3A PMEs was 10.3 g/s and 8.5 g/s, respectively. Therefore, the measured NO_x emission rates are approximately similar to the EPA reported emission rates, indicating agreement with the EPA reported data.

The highest PM emission rates for a given notch position were measured for the now out-of-service locomotive NC 1792. Notch-average PM emission rates increased monotonically for notches idle through notch 8 for all locomotives. For the existing NCDOT locomotives, notch-average PM emission rates were 0.5 g/s or lower for a given notch position. Notch-average PM emission rates were not measured for locomotive NC 1755. The EPA reported PM emission rate at notch 8 for EMD 16-645E3 and EMD 12-710G3A PMEs was 0.23 g/s and 0.20 g/s, respectively. Therefore, PM emission rates measured here are within a factor of 2 of the EPA reported data.

Results for all pollutants illustrate substantial inter-locomotive variability in emission rates. Measured CO, NO_x, and PM emission rates were within a factor of 2 of the EPA reported CO, NO_x and PM emission rates for the same model PMEs, indicating agreement.

3.5.4 Emission Standards

CAER based on the EPA line-haul duty cycle were estimated for CO_2, CO, HC, NO_x and PM. The EPA has set emission standards for CO, HC, NO_x and PM but not for CO_2. The PMEs of the NCDOT locomotives are certified to the Tier 0+ standard. A description of the emissions standards, applicability and CAER corresponding to each standard are given in Appendix C. CAER are given in Figure 3-6. Cycle-average CO_2 emission rates in Figure 3-6(a) varied from 420 g/bhp-hr for locomotive NC 1984 to 494 g/bhp-hr for locomotive NC 1893. Therefore, the inter-locomotive variability in cycle-average CO_2 emission rates was 11 percent or lower.

Cycle-average CO emission rates in Figure 3-6(b) varied from 0.03 g/bhp-hr for locomotive NC 1984 to 3.1 g/bhp-hr for locomotive NC 1859. There is large inter-locomotive variability in cycle-average CO emission rates, differing by two orders of magnitude. Locomotives NC 1797, NC 1893 and NC 1984 had cycle-average CO emission rates at or below the level of the Tier 4 standard.

For other locomotives except for NC 1859, cycle-average CO emission rates were between the level of the Tier 2+ and Tier 1+ standards. Cycle-average CO emission rates for locomotive NC 1859 were between the level of the Tier 1+ and Tier 0+ standards. The EPA reported line-haul duty cycle based CO emission rates of 1.85 g/bhp-hr and 1.09 g/bhp-hr for EMD 16-645E3 and EMD 12-710 PMEs, respectively (EPA, 1998). Thus, the range of inter-engine variability in Cycle-average CO emission rate for the NCDOT locomotive fleet encloses, and is of similar average magnitude as, numbers for similar engines reported by EPA.

Cycle-average HC emission rates in Figure 3-6(c) varied from 0.2 g/bhp-hr for locomotive NC 1984 to 6.9 g/bhp-hr for locomotive NC 1859, leading to large inter-locomotive variability differing by as much as a factor of 30. The two recently acquired locomotives, NC 1871 and NC 1984 had the lowest cycle-average HC emission rates and were at or below the level of the Tier 4 emission standard. Cycle-average HC emission rates for locomotive NC 1869 were lower than the level of the Tier 0+ standard. All other locomotives had cycle-average HC emission rates higher than the level of the Tier 0+ standard. The EPA reported line-haul duty cycle based HC emission rate of 0.48 g/bhp-hr and 0.15 g/bhp-hr for EMD 16-645E3 and EMD 12-710 PMEs, respectively (EPA, 1998). Cycle-average HC emission rates could be reduced by switching from ULSD to B20.

Cycle-average NO_x emission rates in Figure 3-6(d) varied from 8.4 g/bhp-hr for locomotive NC 1859 to 14.3 g/bhp-hr for locomotive NC 1984. Cycle-average NO_x emission rates were approximately similar to the range of cycle-average NO_x emission rates of 10.6 g/bhp-hr to 14.2 g/bhp-hr based on the EPA line-haul duty cycle reported by EPA for EMD 710 PMEs (EPA, 1998). The inter-locomotive variability in cycle-average NO_x emission rates was 51 percent or lower. Cycle-average NO_x emission rates for each of the PMEs was higher than the level of the Tier 0+ standard. These emissions rates could be reduced by an average of 80 percent or possibly more by installing retrofitted post-combustion emission control. For example, the BATS was demonstrated to reduce NO_x emission rates to below the level of the Tier 4 standard based on prior RY measurement of NC 1859.

Cycle-average PM emission rates in Figure 3-6(e) varied from 0.2 g/bhp-hr for locomotive NC 1797 to 1.5 g/bhp-hr for locomotive NC 1792. Except for locomotive NC 1972, the range of cycle-average PM emission rates was within the range of cycle-average PM emission rates of 0.23 g/bhp-hr to 0.35 g/bhp-hr based on the EPA line-haul duty cycle reported by EPA for EMD 710 PMEs (EPA, 1998). Cycle-average PM emission rates for each of the locomotives was higher than the level of the Tier 0+ standard. The cycle-average PM emission rate for locomotive NC 1755 was not measured. PM emission rates can be reduced by an average of 34 percent by switching from ULSD to B20.

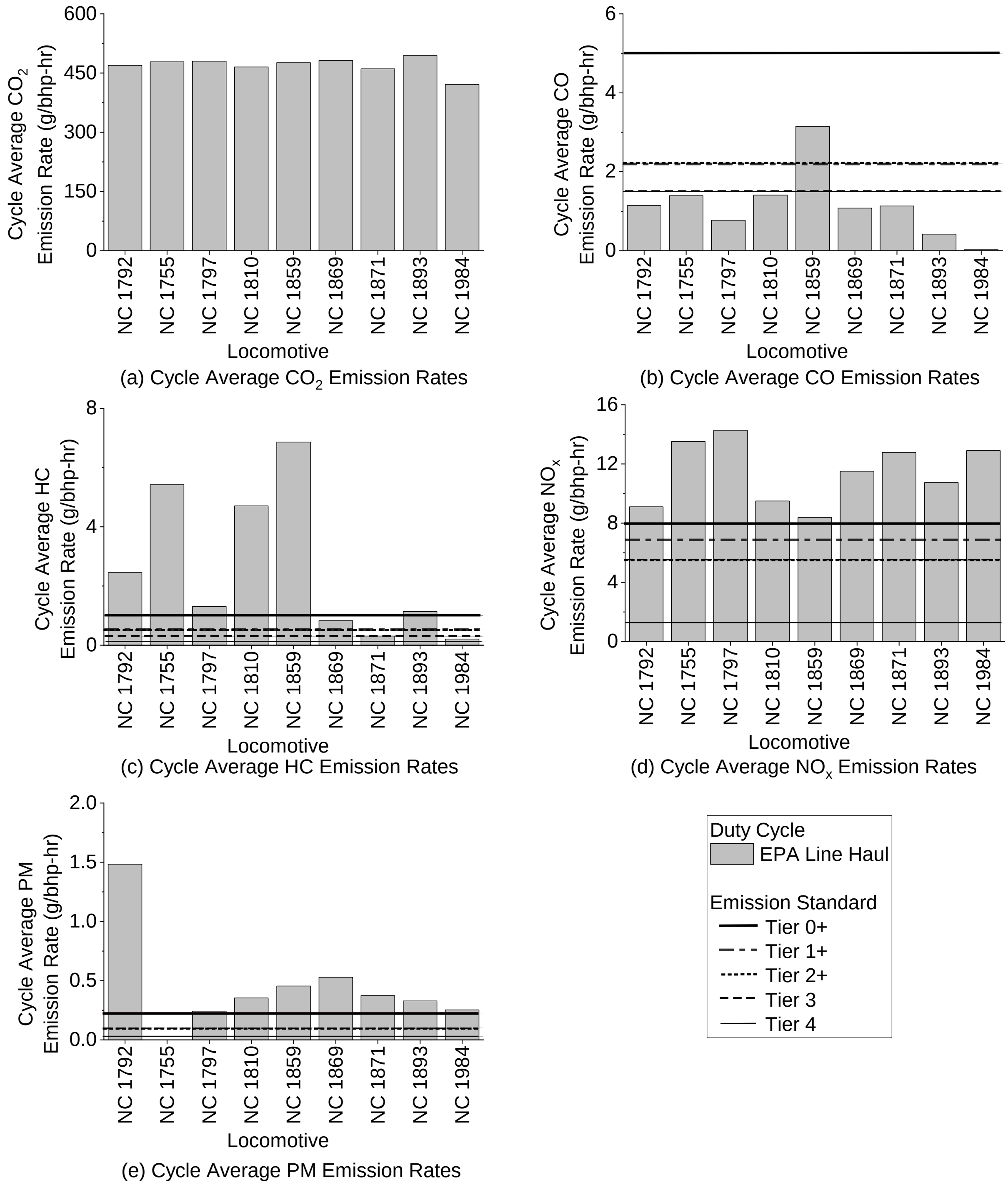


FIGURE 3-6. The EPA Line-Haul based Cycle-average Emission Rates for the Most Recent Rail Yard Measurement of the Prime Mover Engines of all NCDOT Locomotives Operated on Ultra-low Sulfur Diesel: (a) CO_2 Emission Rate; (b) CO Emission Rate; (c) HC Emission Rate; (d) NO_x Emission Rate; and (e) PM Emission Rate.

Chapter 4. Over-The-Rail Measurements

This chapter includes the results of over-the-rail (OTR) measurements conducted on the prime mover engines (PMEs) of locomotives NC 1871 and NC 1984 operated on ultra-low sulfur diesel (ULSD). Baseline fuel use and emission rates (FUER) and cycle-average emission rates (CAER) were estimated and benchmarked to locomotive emissions standards and other locomotives owned by the North Carolina Department of Transportation (NCDOT). Four OTR measurements were conducted including, two OTR measurements each on the PMEs of locomotives NC 1871 and NC 1984. Each OTR measurement included six one-way trips between Raleigh and Charlotte, NC. The definitions of abbreviations used in this report is given in Appendix A.

The first and second OTR measurements on locomotive NC 1871 were conducted between August 21, 2018 and August 23, 2018, and between January 30, 2019 and February 16, 2019, respectively. The first and second OTR measurements on locomotive NC 1984 were conducted between June 12, 2018 and June 14, 2018, and between June 18, 2019 and June 20, 2019, respectively. The purpose of the first measurements on each locomotive was to quantify baseline steady-state FUER for the now typical Piedmont double-powered push/pull consist. However, the train may also be operated as single-powered push/pull. Locomotive FUER may differ for the double- and single-powered push/pull consists. To quantify the differences in FUER for the double- versus single-powered consists, a second set of OTR measurements for each locomotive were made that included three one-way trips each in double- and single-powered push/pull consists. Only the indicated locomotives were measured during each one-way trip. Depending on the direction of travel, the measured locomotives were either pulling or pushing the train. The locomotive at the other end of the train was not measured.

To benchmark FUER to emission standards, which are based on steady-state operation, FUER were estimated based on steady-state data only. To quantify the effect of transients on FUER, FUER based on transient data were compared to the steady-state based FUER for the same OTR measurement. Transient data refers to all measured 1 Hz data inclusive of all locomotive operations, which can include periods of approximately steady-state operation.

Results of the OTR measurements of locomotives NC 1871 and NC 1984 include duty cycles and steady-state notch-average engine activity variables, exhaust gas concentrations and FUER. The effect of transients on trip fuel use and emissions (TFUE) is quantified. Section 4.1 and 4.2 have results of the OTR measurements of NC 1871 conducted during August 2018 and January - February 2019, respectively. Section 4.3 and 4.4 have results of the OTR measurements of NC 1984 conducted during June 2018 and June 2019, respectively. The OTR measurements for a given locomotive are compared to RY measurements on the same locomotive in Section 4.5. The effect of transients on TFUE is quantified in Section 4.6. The trade-offs in terms of TFUE between the double- and single-powered consists are quantified in Section 4.7. The steady-state based FUER and CAER were benchmarked to other NCDOT locomotives and to emission standards, respectively, in Section 4.8.

4.1 Locomotive NC 1871: August 2018

OTR measurements of the PME of NC 1871 were conducted between August 21, 2018 and August 23, 2018. Three one-way trips each were conducted for Trains 75 and 76 following the measurement schedule given in Table 2-4. The train consist included two locomotives, three passenger cars, and one baggage/café car. However, only the locomotive NC 1871 was measured. One one-way trip on Train 76 on August 21 was based on a single-powered push/pull consist of locomotive NC 1871 providing full power. The remaining five one-way trips were based on double-powered push/pull.

4.1.1 Duty Cycles

Measured duty cycles for each one-way trip are given in Table 4-1. A duty cycle is the total time in each throttle notch setting, inclusive of steady-state and transient operation. Train 75 on August 22 had the longest duration at 4h 5m, whereas Train 75 on August 21 had the shortest duration at 3h 13m. On average, the trip took 3h 35m. Train 75 on August 22-23 and Train 76 on August 22 were delayed by 36 minutes or longer due to a freight train that occupied one of the main tracks between High Point and Salisbury. Several trains from either direction had to take turns using the other track, leading to delays.

For the double-powered consist, the highest percentage of time was spent in idle, ranging between 33 percent and 44 percent, with an average of 37 percent. The next highest percentage of time was spent in notch 8, ranging between 19 percent and 35 percent, with an average of 25 percent. Dynamic brake accounted for 10 percent of the trip duration on average. Other notch positions accounted for less than 10 percent of the total time each. The lowest percentage of time was spent in notch 7. The engine idles at station stops and when the train is not in motion. Usually, schedule delays are associated with higher proportions of time in which the engine is at idle.

For the single-powered consist, the highest percentage of time was spent in notch 8, followed by idle and dynamic brake. Other notch positions accounted for less than 10 percent of the total time each. The percentage of time in notch 8 was considerably higher than for double-powered and the time in idle was lower. This is typical as the single-powered locomotive had to provide more power compared to one locomotive in a double-powered consist. Trains idle when stopped and train delays lead to a higher percentage of time in idle versus on-time trips.

4.1.2 Steady-State Engine Activity Variables

Steady-state notch-average RPM, IAT, and MAP are summarized in Table 4-2. The amount of steady-state data measured in each notch position depends on the number of times an operator transitions to a given notch position and the average time the operator stays in that notch position per transition. When the throttle is switched to a different position, the engine activity variables and FUER change over a period of 5 seconds to 30 seconds during a transition from steady-state operation in the preceding to the successive notch setting. The transition time depends on the difference between the two notches. For example, a switch to notch 8 from notch 1 will have a larger transition time than a switch to notch 8 from notch 7. In some cases, changes in notch positions occurred more frequently than the transition time required to achieve steady-state. Thus, in such cases, it was not possible for the engine operation to reach steady-state and no steady-state data were measured. Consequently, a larger percentage of time in one notch position versus another does not necessarily mean a higher percentage of steady-state operation. For example, no steady-state FUER data were measured in notch 7 for Train 76 on August 23, although this trip had the second highest percentage of time in notch 7 compared to other trips. Steady-state data at notch 7 was measured for the remaining one-way trips.

For notch positions for which steady-state data were not measured, notch-average RPM, MAP and exhaust concentrations were replaced by the average of other trips measured at that notch on the same locomotive and same consist. Notch-average IAT depends on notch position and ambient temperature. IAT for a given notch position of a locomotive may vary by 40 K based on the season in which the locomotive was measured. However, notch-average IAT typically differs by less than 15 K between idle and notch 8 on a given day. This latter difference has less than one percent effect on FUER. Therefore, for notch positions with no steady-state data, IAT was replaced by the average of notch-average IATs of the remaining notch positions.

The notch-average RPM for a given notch position was within 2 RPM for double- versus single-powered consists for each notch position, except for dynamic brake. Therefore, notch-average RPM for a given notch position was approximately similar for the two consists. Notch-average RPM varied from 219 RPM at low idle to 901 RPM at notch 8. Notch-average RPM increased monotonically from low idle to notch 8, except for dynamic brake. Dynamic brake can be initiated from any throttle notch position (Hay, 1982). Thus, the engine RPM at dynamic brake can vary substantially. Notch-average RPM for the double-powered consist had inter-trip CV of 0.01 or lower for each notch position, except for dynamic brake, for which the CV was 0.05. Thus, the RPM measurements were highly repeatable. Only one one-way trip was conducted for the single-powered consist. Therefore, the repeatability of the latter was not quantified.

TABLE 4-1. Percentage Time Spent in Each Notch Position for Locomotive NC 1871 for Over-the-Rail Measurements of Double- and single-powered Push/Pull Train Consists Conducted between August 21 and August 23, 2018.

Consist	Double-powered							Single-Powered
Throttle Notch Position	Percent time in each notch position (%)							
	Aug 21 Train 75	Aug 22 Train 75	Aug 22 Train 76	Aug 23 Train 75	Aug 23 Train 76	5 Trips Avg	5 Trips CV[a]	Aug 21 Train 76
Idle	33.5	39.4	33.5	44.7	33.8	37.0	0.14	28.7
Dynamic Brake	7.4	11.7	16.4	4.0	13.3	10.6	0.46	8.7
1	4.6	6.4	10.3	5.4	6.0	6.5	0.34	3.3
2	3.2	6.6	4.4	5.8	3.6	4.7	0.31	2.3
3	4.2	5.6	3.6	5.2	5.0	4.7	0.17	2.2
4	3.8	4.2	4.9	3.8	4.0	4.1	0.11	2.4
5	4.3	3.4	1.7	3.7	4.9	3.6	0.34	2.6
6	2.4	2.3	1.8	3.3	3.6	2.7	0.28	2.2
7	1.3	0.4	0.3	0.9	0.9	0.8	0.54	1.5
8	35.3	19.9	23.1	23	24.9	25.2	0.23	46.1
Trip Duration (*h:mm:ss*)	3:13:01	4:05:00	3:47:36	3:46:39	3:22:42	3:39:00	-	3:19:51

[a] *CV = coefficient of variation (standard deviation divided by mean)*

TABLE 4-2. Steady-State Notch-Average Engine Activity Variables for Locomotive NC 1871 for Over-the-Rail Measurements of Double- and single-powered Push/Pull Train Consists Conducted between August 21 and August 23, 2018.

Throttle Notch Position	Engine RPM (RPM)				Intake Air Temperature (K)				Manifold Absolute Pressure (kPa)			
	Double-Powered		Single-Powered		Double-Powered		Single-Powered		Double-Powered		Single-Powered	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	219	0.000[c]	219	-[b]	330	0.006	354	-[b]	93	0.004	93	-[b]
High Idle	268	0.000[c]	268	-[b]	333	0.037	356	-[b]	96	0.006	96	-[b]
Dynamic Brake	418	0.046	523	-[b]	333	0.037	358	-[b]	108	0.028	120	-[b]
1	268	0.000[c]	268	-[b]	333	0.036	358	-[b]	96	0.009	96	-[b]
2	389	0.000[c]	388	-[b]	333	0.037	356	-[b]	104	0.008	104	-[b]
3	509	0.001	509	-[b]	333	0.039	356	-[b]	115	0.011	116	-[b]
4	702	0.001	701	-[b]	333	0.045	361	-[b]	144	0.009	144	-[b]
5	726	0.003	727	-[b]	333	0.040	362	-[b]	150	0.010	151	-[b]
6	819	0.001	819	-[b]	333	0.042	363	-[b]	171	0.013	173	-[b]
7	855	0.006	858	-[b]	333	0.041	365	-[b]	182	0.033	200	-[b]
8	900	0.001	901	-[b]	333	0.046	364	-[b]	204	0.014	223	-[b]

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips*
[b] *No CV because of only one measured trip*
[c] *CV greater than zero but less than 0.0005*

Notch-average IAT for the double-powered consist varied from 330 K at low idle to 333 K for other notch positions. Notch-average IAT for the double-powered consist had inter-trip CVs of 0.05 or lower for each notch position. Thus, the IAT measurements were highly repeatable. Notch-average IAT for the single-powered consist varied from 354 K at low idle to 365 K at notch 7.

The notch-average MAP for a given notch position was within 2 kPa for double- versus single-powered consists for each notch position, except for dynamic brake, notch 7 and notch 8. Therefore, notch-average MAP for a given notch position were approximately similar for the two consists, except for dynamic brake, notch 7 and notch 8. For the double-powered consist, notch-average MAP varied from 93 kPa at low idle to 204 kPa at notch 8. Notch-average MAP for the double-powered consist had inter-trip CV of 0.03 or lower for each notch position. Thus, the MAP measurements were highly repeatable. For the single-powered consist, notch-average MAP varied from 93 kPa at low idle to 223 kPa at notch 8. For both consists, notch-average MAP increased monotonically from low idle to notch 8, except for dynamic brake. The single-powered consist had 19 kPa to 20 kPa higher MAP at notches 7 and 8 versus the double-powered consist. Higher MAP results in a greater air flow and exhaust flow rate.

4.1.3 Steady-State Exhaust Gas and PM Concentrations

Steady-state notch-average exhaust concentrations of CO_2, CO, HC, NO and PM measured using an Axion PEMS are summarized in Table 4-3. Steady-state notch-average CO_2 concentrations for the double-powered consist varied from 0.68 vol % at low idle to 5.29 vol % at notch 8. Notch-average CO_2 concentrations increased monotonically from low idle through notch 8. Notch-average CO_2 concentrations for a given notch position had inter-trip CV of 0.2 or lower for each notch position. The inter-trip CV for notch positions at which operators typically spent more than 70 percent of time including low idle, high idle, dynamic brake and notch 8 was 0.07 or lower. Thus, these measurements were highly repeatable.

Steady-state notch-average CO concentrations for the double-powered consist varied from 0.000 vol % at low idle to 0.035 vol % at notch 8. The notch-average CO concentrations were below the detection limit of the Axion PEMS for low idle through notch 6. For notches 7 and 8, CO concentrations were above the detection limit and inter-trip CV was lower compared to other notch positions.

Steady-state notch-average HC concentrations for the double-powered consist varied from 10 ppm at notch 8 to 28 ppm at dynamic brake. The notch-average HC concentration was below the detection limit of the PEMS at notch 8. Inter-trip CV for a given notch position was 0.6 or lower for each notch position. However, notch-average HC concentrations were low, with the highest being 2.5 times the detection limit.

Steady-state notch-average NO concentrations for the double-powered consist varied from 199 ppm at dynamic brake to 1275 ppm at notch 6. Notch-average NO concentrations increased monotonically with notch position for high idle through notch 6 and the average concentration was 1058 ppm at notch 8. Notch-average NO concentrations for a given notch position had inter-trip CV of 0.3 or lower for each notch position. Inter-trip CV for low idle, high idle, dynamic brake and notch 8 was 0.1 or lower. Thus, these measurements were repeatable, with the latter being highly repeatable.

TABLE 4-3. Steady-State Notch-Average Concentrations for Locomotive NC 1871 for Over-the-Rail Measurements of Push/Pull Train Consists Conducted between August 21 and August 23, 2018: (a) Double-powered; and (b) Single-powered.

(a) Double-powered Push/Pull Consist

Throttle Notch Position	CO_2 concentration (vol %)		CO concentration (vol %)		HC concentration (ppm)		NO concentration (ppm)		PM concentration (mg/m^3)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	0.68	0.07	*0.000*	*0.00*[c]	26	0.03	227	0.04	4.0	0.05
High Idle	0.72	0.02	*0.001*	*0.56*	23	0.29	201	0.09	4.5	0.06
Dynamic Brake	0.88	0.05	*0.000*	*1.37*	28	0.56	199	0.11	4.1	0.03
1	0.99	0.18	*0.001*	*0.91*	23	0.42	291	0.22	4.9	0.05
2	2.15	0.17	*0.001*	*0.71*	20	0.48	569	0.23	5.4	0.10
3	3.28	0.08	*0.001*	*1.15*	25	0.42	983	0.16	5.7	0.09
4	3.65	0.12	*0.005*	*1.38*	17	0.26	946	0.12	5.6	0.14
5	4.19	0.09	*0.002*	*0.61*	20	0.51	1123	0.11	5.6	0.12
6	5.07	0.23	*0.006*	*0.27*	17	0.50	1275	0.30	7.4	0.09
7	5.13	0.20	0.021	0.48	34	0.41	1222	0.17	8.2	0.70
8	5.29	0.06	0.035	0.22	*10*	*0.40*	1058	0.11	13.8	0.18

(b) Single-powered Push/Pull Consist

Throttle Notch Position	CO_2 concentration (vol %)		CO concentration (vol %)		HC concentration (ppm)		NO concentration (ppm)		PM concentration (mg/m^3)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	0.77	-[b]	*0.001*	-[b]	47	-[b]	194	-[b]	3.0	-[b]
High Idle	0.64	-[b]	*0.001*	-[b]	41	-[b]	184	-[b]	3.5	-[b]
Dynamic Brake	0.99	-[b]	*0.002*	-[b]	36	-[b]	179	-[b]	3.6	-[b]
1	0.80	-[b]	*0.001*	-[b]	70	-[b]	220	-[b]	4.8	-[b]
2	1.81	-[b]	*0.001*	-[b]	42	-[b]	453	-[b]	4.9	-[b]
3	3.38	-[b]	*0.001*	-[b]	87	-[b]	945	-[b]	6.1	-[b]
4	3.70	-[b]	*0.004*	-[b]	72	-[b]	918	-[b]	6.3	-[b]
5	4.41	-[b]	0.009	-[b]	57	-[b]	1169	-[b]	6.7	-[b]
6	4.64	-[b]	0.009	-[b]	52	-[b]	1075	-[b]	8.1	-[b]
7	6.22	-[b]	0.030	-[b]	15	-[b]	1297	-[b]	18.0	-[b]
8	5.75	-[b]	0.047	-[b]	25	-[b]	1101	-[b]	15.2	-[b]

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips*
[b] *No CV because of only one measured trip*
[c] *CV greater than zero but less than 0.0005*
The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

Steady-state notch-average PM concentrations for the double-powered consist varied from 4.0 mg/m^3 at low idle to 13.8 mg/m^3 at notch 8. Notch-average PM concentrations were within 10 percent of each other for low idle, high idle and dynamic brake. Notch-average PM concentrations for notches 1 through 5 were within 7 percent of each other, but higher than for low idle, high idle and dynamic brake. Notch-average PM concentrations increased monotonically from 5.6 mg/m^3 at notch 5 to 13.6 mg/m^3 at notch 8. Notch-average PM concentrations for a given notch position had inter-trip CV of 0.7 or lower for each notch position. Inter-trip CV for low idle, high idle, dynamic brake and notch 8 was 0.2 or lower. Thus, these latter measurements were repeatable.

The CV for inter-trip variability in the OTR measurements was typically higher than CV for inter-replicate variability in RY measurements because of more inherent variability in real-world operation.

The steady-state notch-average CO_2 concentrations for the single-powered consist varied from 0.77 vol % at low idle to 6.22 vol % at notch 7. Only 10 seconds of steady-state data were measured at notch 7 compared to at least 30 seconds for other notch positions and at least 1000 seconds each for high idle and notch 8. Therefore, high average concentration at notch 7 was an anomaly of small sample size. Notch-average CO_2 concentrations for a given notch position for the double- versus single-powered consist were not statistically significantly different from each other, except for notch 7 and notch 8. The notch-average CO_2 concentration at notch 8 was 10 percent higher for the double- versus single-powered consist. The differences in the steady-state notch-average CO and HC concentrations for the double- versus single-powered consist are associated with random errors from CO and HC concentrations that were typically below the detection limit of the PEMS.

The steady-state notch-average NO concentrations were 3 to 30 percent higher for idle through notch 7 and 4 to 6 percent lower at notches 7 and 8 for the double- versus single-powered consist. The steady-state notch-average PM concentrations were 2 to 30 percent higher for idle through notch 2 and 6 to 30 percent lower at notches 3 through 7 for the double- versus single-powered consist. At notch 8, the notch-average PM concentrations for the double-powered consist were 9 percent lower versus the single-powered consist. Five percent or higher differences in the notch-average NO and PM concentrations were typically due to artifacts of random variations in small sample sizes measured for notches 1 through 7 compared to the much larger sample sizes at idle and notch 8, and due to only one one-way trip for the single-powered consist. Differences in NO and PM concentrations led to differences in NO_x and PM emission rates for the double- versus single-powered consist.

4.1.4 Steady-State Fuel Use and Emission Rates

Steady-state notch-average engine output, fuel use rate and emission rates of CO_2, CO, HC, NO_x and PM are summarized in Table 4-4. No differences in the steady-state notch-average engine output were observed for the double- versus single-powered consists. The net engine power output increased monotonically from notch 1 through notch 8. For the OTR measurements, net engine power output at notches 7 and 8 was 400 hp and 650 hp higher, respectively, versus RY measurements. At idle, the net engine power output displayed by the locomotive activity recorder was zero. However, engine power output was assumed to be 9 hp based on prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).

TABLE 4-4. Steady-State Notch-Average Net Engine Output, Fuel Use and Emission Rates for Locomotive NC 1871 for Over-the-Rail Measurements of Push/Pull Train Consists Conducted between August 21 and August 23, 2018: (a) Double-powered; and (b) Single-powered.

(a) Double-Powered Push/Pull Consist

Throttle Notch Position	Net Engine Output (hp)	Fuel Use Rate (g/s)		CO_2 Emission Rate (g/s)		CO Emission Rate (g/s)		HC Emission Rate[b] (g/s)		NO_x Emission Rate[c] (g/s)		PM Emission Rate[d] (g/s)	
		Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	9[e]	2.6	0.07	8	0.09	0.0	0.09	0.2	0.24	0.3	0.00	0.15	0.09
High Idle	9[e]	3.2	0.06	10	0.05	0.0	0.05	0.1	0.39	0.3	0.16	0.15	0.31
Dynamic Brake	9[e]	5.9	0.10	18	0.10	0.0	0.10	0.3	0.64	0.5	0.17	0.29	0.58
1	130	4.4	0.19	14	0.18	0.0	0.18	0.2	0.46	0.5	0.19	0.15	0.42
2	310	13.0	0.18	41	0.18	0.0	0.18	0.2	0.50	1.2	0.26	0.18	0.51
3	675	26.4	0.10	83	0.12	0.0	0.12	0.3	0.41	2.7	0.19	0.31	0.40
4	1050	44.0	0.09	137	0.09	0.1	0.09	0.3	0.33	3.9	0.11	0.31	0.30
5	1450	52.8	0.06	165	0.07	0.1	0.07	0.4	0.54	4.9	0.12	0.38	0.51
6	2000	77.2	0.24	240	0.24	0.2	0.24	0.4	0.51	6.7	0.31	0.38	0.45
7	2700	85.5	0.24	266	0.24	0.7	0.24	0.8	0.40	7.0	0.25	0.84	0.40
8	3000	97.8	0.07	303	0.07	1.3	0.07	0.3	0.58	6.7	0.14	0.27	0.41

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips.*
[b] *HC measured with Axion PEMS were multiplied with a correction factor shown in Table D-4(b) in Appendix D to obtain THC.*
[c] *NO measured with Axion PEMS were been multiplied with a correction factor shown in Table D-4(a) in Appendix D to obtain NO_x.*
[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*
[e] *Assumed from prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).*
The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

Table 4-4 Continued on next page.

Table 4-4 Continued from previous page.

(b) Single-Powered Push/Pull Consist

Throttle Notch Position	Net Engine Output (hp)	Fuel Use Rate (g/s)		CO_2 Emission Rate (g/s)		CO Emission Rate (g/s)		HC Emission Rate[b] (g/s)		NO_x Emission Rate[c] (g/s)		PM Emission Rate[d] (g/s)	
		Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	9[e]	2.7	-[f]	8	-[f]	0.0	-[f]	0.5	-[f]	0.2	-[f]	0.25	-[f]
High Idle	9[e]	2.7	-[f]	8	-[f]	0.0	-[f]	0.4	-[f]	0.3	-[f]	0.26	-[f]
Dynamic Brake	9[e]	7.9	-[f]	24	-[f]	0.0	-[f]	0.6	-[f]	0.5	-[f]	0.43	-[f]
1	130	3.4	-[f]	10	-[f]	0.0	-[f]	0.5	-[f]	0.3	-[f]	0.44	-[f]
2	310	10.0	-[f]	32	-[f]	0.0	-[f]	0.5	-[f]	0.9	-[f]	0.37	-[f]
3	675	26.0	-[f]	80	-[f]	0.0	-[f]	0.4	-[f]	2.5	-[f]	1.01	-[f]
4	1050	41.0	-[f]	128	-[f]	0.1	-[f]	0.3	-[f]	3.5	-[f]	1.21	-[f]
5	1450	52.0	-[f]	162	-[f]	0.2	-[f]	0.5	-[f]	4.7	-[f]	1.03	-[f]
6	2000	65.0	-[f]	203	-[f]	0.3	-[f]	0.5	-[f]	5.2	-[f]	1.10	-[f]
7	2700	99.0	-[f]	309	-[f]	0.9	-[f]	0.5	-[f]	7.1	-[f]	0.35	-[f]
8	3000	104	-[f]	321	-[f]	1.7	-[f]	0.6	-[f]	6.8	-[f]	0.69	-[f]

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips.*
[b] *HC measured with Axion PEMS were multiplied with a correction factor shown in Table D-4(b) in Appendix D to obtain THC.*
[c] *NO measured with Axion PEMS were been multiplied with a correction factor shown in Table D-4(a) in Appendix D to obtain* NO_x.
[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*
[e] *Assumed from prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).*
[f] *No CV because of only one measured trip*
The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

The steady-state notch-average fuel use rates for the double-powered consist varied from 2.6 g/s at low idle to 97.8 g/s at notch 8. Notch-average fuel use rate increased monotonically from low idle through notch 8. Notch-average fuel use rate for a given notch position had an inter-trip CV of 0.2 or lower for each notch position. The inter-trip CV for low idle, high idle, dynamic brake and notch 8 was 0.07 or lower. Thus, fuel use rate measurements for the latter were highly repeatable. Steady-state notch-average CO_2 emission rates had similar relative trends as fuel use rate.

The steady-state notch-average CO and HC emission rates for the double-powered consist were typically based on low CO and HC concentrations; typically the highest concentration was only 2-3 times higher than the detection limit. Therefore, the CO and HC emission rates were low. Notch-average CO and HC emission rates increased monotonically with notch position.

The steady-state notch-average NO_x emission rates for the double-powered consist varied from 0.3 g/s at low idle to 7.0 g/s at notch 7. Notch-average NO_x emission rates increased monotonically from low idle through notch 7 and the rate was 6.7 g/s at notch 8. Notch-average NO_x emission rates for a given notch position had inter-trip CV of 0.3 or lower for each notch position. The inter-trip CV for low idle, high idle, dynamic brake and notch 8 was 0.1 or lower. Thus, NO_x emission rate measurements were repeatable for these latter notch positions.

The steady-state notch-average PM emission rates for the double-powered consist varied from 0.15 g/s at low idle, high idle and notch 1 to 0.84 g/s at notch 7. Notch-average PM emission rates typically increased from low idle through notch 7, except for dynamic brake. However, some of the adjacent notch positions had notch-average rates similar to each other. Notch-average PM emission rates for a given notch position had inter-trip CV of 0.6 or lower for each notch position.

Only one measurement was conducted for the single-powered consist. Steady-state notch-average fuel use rates and emission rates of CO_2, CO, HC, NO_x and PM for each notch position for the single-powered consist were typically 5 percent to 20 percent higher than for the double-powered consist. This is a result of differences in notch-average engine activity variables and exhaust concentrations for double- versus single-powered consists. However, for a more robust comparison based on a larger sample size, additional OTR measurements were conducted on the PME of locomotive NC 1871 as described in the next section.

4.2 Locomotive NC 1871: January-February 2019

OTR measurements on the PME of locomotive NC 1871 were conducted again to include more measurements for the single-powered consist compared to measurements in the previous section. Eight OTR measurements were conducted, including four measurements each on double-powered and single-powered consists. The engine sensor array failed during one OTR measurement for each consist. Therefore, results were obtained for only three one-way trips for each consist. Results of the valid measurements on January 30, 2019, February 13, 2019, and February 16, 2019 are given here. Train 75 was operated as single-powered and Train 76 was operated as double-powered. Steady-state notch-average engine activity variables, measured exhaust concentrations and FUER were estimated.

4.2.1 Duty Cycles

Measured duty cycles for each one-way trip are given in Table 4-5. Approximately similar travel times for each trip were observed ranging between 3h 7m and 3h 20m. These actual travel times were close to the scheduled duration of 3h 10m.

For the double-powered consist, the highest percentage of time was spent in idle, ranging between 38 percent and 46 percent, with an average of 42 percent. The next highest percentage of time was spent in notch 8, ranging between 24 percent and 30 percent, with an average of 27 percent. Other notch positions and dynamic brake accounted for less than 6 percent of the total time each.

For the single-powered consist, the highest percentage of time was spent in notch 8, followed by idle. The time spent in notch 8 and idle was 52 percent and 30 percent on average, respectively. To slow the train, the locomotive operator preferred to use the mechanical brake or coasting versus the dynamic brake for some of the trips. Other notch positions accounted for less than 3 percent of the total time each on average. Differences in driver behavior were observed among similar duration trips. For example, Train 75 trips on January 30th and February 14th were approximately close to scheduled travel time. However, the operator of the second trip spent a higher percentage of time in notch 8 and idle compared to the operator of the first trip, and a lower percentage of time in the intermediate notch positions and dynamic brake. Thus, trips of similar duration may have different duty cycles based on operator behavior.

4.2.2 Steady-State Engine Activity Variables

The steady-state notch-average RPM, IAT, and MAP are summarized in Table 4-6. Notch-average RPM for a given notch position was within 3 RPM for double- versus single-powered consists for each notch position, except for dynamic brake. Therefore, notch-average RPM for a given notch position was approximately similar for the two consists. Notch-average RPM varied from 219 RPM at low idle to 902 RPM at notch 8. Notch-average RPM increased monotonically from low idle to notch 8, except for dynamic brake. Engine RPM at dynamic brake varied substantially. Notch-average RPM for double- and single-powered consists had inter-trip CV of 0.009 or lower for each notch position. Thus, the RPM measurements were highly repeatable.

The notch-average IAT for the double-powered consist varied from 331 K at low idle to 341 K at notch 8. Notch-average IAT for the double-powered consist had inter-trip CV of 0.07 or lower for each notch position. Thus, the IAT measurements were highly repeatable for the double-powered consist. Notch-average IAT for the single-powered consist varied from 342 K at low idle to 352 K at dynamic brake. Notch-average IAT for the double-powered consist had inter-trip CV of 0.09 or lower for each notch position. Thus, the IAT measurements were highly repeatable for the single-powered consist.

The notch-average MAP for a given notch position was within 5 kPa for double- versus single-powered consists for each notch position, except for notches 7 and 8. Therefore, notch-average MAP for a given notch position was approximately similar for the two consists, except for notches 7 and 8. For the double-powered consist, notch-average MAP varied from 95 kPa at low idle to 212 kPa at notch 8. For the single-powered consist, notch-average MAP varied from 95 kPa at low idle to 237 kPa at notch 8. Notch-average MAP for double- and single-powered consists had inter-trip CV of 0.03 or lower for each notch position. Thus, the MAP measurements were highly repeatable. For both consists, notch-average MAP increased monotonically from low idle to notch 8, except for dynamic brake. The single-powered consist had 10 kPa to 25 kPa higher MAP at notches 7 and 8 versus the double-powered consist. Higher MAP results in a higher mass air flow rate and AFR.

4.2.3 Steady-State Exhaust Gas and PM Concentrations

Steady-state notch-average exhaust concentrations of CO_2, CO, HC, NO and PM measured using an Axion PEMS for the double- and single-powered consists are summarized in Table 4-7.

Steady-state notch-average CO_2 concentrations for the double-powered consist varied from 0.50 vol % at low idle to 6.28 vol % at notch 7. Notch-average CO_2 concentrations increased monotonically with notch position for low idle through notch 7 and decreased to 5.01 vol % at notch 8. The inter-trip CV for a given notch position was 0.2 or lower for each notch position and 0.1 or lower for high idle and notches 1, 5, 6 and 8. For these latter notch positions, the measurements were highly repeatable. Notch-average CO_2 concentrations varied from 0.54 vol % at low idle to 5.98 vol % at notch 7 for the single-powered consist and typically increased with notch position. For low idle and notches 1, 3, 4, 5, 7 and 8, the differences in notch-average CO_2 concentrations for double- versus single-powered consists were not statistically significant.

TABLE 4-5. Percentage Time Spent in Each Notch Position for Locomotive NC 1871 for Over-the-Rail Measurements of the Double- and Single-powered Push/Pull Train Consists Conducted between January 30 and February 16, 2019.

Throttle Notch Position	Double-Powered					Single-Powered				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 76	Train 76	Train 76	Avg	CV[a]	Train 75	Train 75	Train 75	Avg	CV[a]
Idle	45.6	42.3	38.6	42.2	0.08	22.8	31.2	36.8	30.3	0.23
Dynamic Brake	0.0	1.8	2.7	1.5	0.92	6.0	0.0	0.0	2.0	1.73
1	4.8	4.5	7.1	5.5	0.26	1.6	1.7	3.0	2.1	0.37
2	5.0	5.4	3.7	4.7	0.19	2.8	1.4	2.9	2.4	0.35
3	4.2	7.6	6.0	5.9	0.29	2.9	1.9	2.5	2.4	0.21
4	3.3	5.9	6.3	5.2	0.32	3.1	1.7	3.2	2.6	0.31
5	4.7	3.5	6.5	4.9	0.31	2.5	0.0	2.2	1.6	0.87
6	2.2	1.5	3.7[b]	2.5	0.46	2.7	0.0	3.6[b]	2.1	0.89
7	0.6	0.4	1.5[b]	0.8	0.70	0.9	2.5	3.5[b]	2.3	0.57
8	29.5	27.1	24.0	26.8	0.10	54.7	59.8	42.3	52.3	0.17
Trip Duration (h:mm:ss)	3:10:02	3:10:15	3:07:54	3:09:44		3:12:04	3:10:19	3:20:17	3:14:13	

[a] *CV = coefficient of variation (standard deviation divided by mean)*

[b] *Approximately 0.5 percent of the total steady-state time was due to the request made by NC State to operate the locomotive at a steady-state for about one minute to enable steady-state load at notches 6 and 7.*

TABLE 4-6. Steady-State Notch-Average Engine Activity Variables for Locomotive NC 1871 for Over-the-Rail Measurements of Double- and single-powered Push/Pull Train Consists Conducted between January 30 and February 16, 2019.

Throttle Notch Position	Engine RPM (RPM)				Intake Air Temperature (K)				Manifold Absolute Pressure (kPa)			
	Double-Powered		Single-Powered		Double-Powered		Single-Powered		Double-Powered		Single-Powered	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	219	-[b]	219	-[b]	331	-[b]	342	-[b]	95	-[b]	95	-[b]
High Idle	268	0.000[c]	268	0.000[c]	337	0.062	342	0.059	97	0.006	97	0.000[c]
Dynamic Brake	417	0.000[c]	428	-[b]	331	0.079	352	-[b]	112	0.013	113	-[b]
1	268	0.000[c]	268	0.000[c]	337	0.062	342	0.060	97	0.000[c]	98	0.006
2	389	0.000[c]	389	0.000[c]	336	0.068	342	0.058	106	0.005	106	0.000[c]
3	509	0.001	509	0.001	339	0.059	342	0.051	118	0.000[c]	118	0.005
4	702	0.001	699	0.008	340	0.062	346	0.066	150	0.007	155	0.049
5	725	0.003	723	0.009	341	0.063	338	0.075	156	0.010	158	0.004
6	819	0.003	819	0.000[c]	340	0.068	340	0.087	180	0.003	182	0.016
7	858	-[b]	858	0.001	341	-[b]	346	0.068	202	-[b]	212	0.018
8	901	0.000[c]	902	0.000[c]	341	0.068	346	0.066	212	0.014	237	0.033

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips*
[b] *No CV because of only one measured trip with steady-state data*
[c] *CV greater than zero but less than 0.0005*

TABLE 4-7. Steady-State Notch-Average Concentrations for Locomotive NC 1871 for Over-the-Rail Measurements of Push/Pull Train Consists Conducted between January 30 and February 16, 2019: (a) Double-powered; and (b) Single-powered.

(a) Double-powered Push/Pull Consist

Throttle Notch Position	CO_2 concentration (vol %)		CO concentration (vol %)		HC concentration (ppm)		NO concentration (ppm)		PM concentration (mg/m^3)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	0.50	-[b]	*0.000*	-[b]	*2*	-[b]	170	-[b]	3.8	-[b]
High Idle	0.67	0.03	*0.001*	*1.15*	*8*	*0.54*	213	0.04	4.2	0.02
Dynamic Brake	0.76	0.22	*0.001*	*1.41*	*7*	*0.54*	216	0.26	4.4	-[b]
1	0.79	0.10	*0.001*	*1.15*	*8*	*0.48*	259	0.08	4.3	0.03
2	2.23	0.11	*0.001*	*1.00*	*11*	*0.55*	688	0.10	5.9	0.23
3	2.95	0.16	*0.000*	*1.73*	*9*	*0.87*	1038	0.14	5.0	0.05
4	3.59	0.10	*0.000*	*1.73*	*7*	*0.65*	1219	0.17	5.0	0.03
5	4.23	0.05	*0.001*	*1.73*	*7*	*0.57*	1461	0.05	4.9	0.07
6	4.66	0.05	*0.002*	*0.47*	*6*	*0.50*	1440	0.11	6.0	0.04
7	6.28	-[b]	0.024	-[b]	*4*	-[b]	1570	-[b]	11.2	-[b]
8	5.01	0.11	0.012	0.25	*5*	*0.54*	1293	0.06	8.1	0.02

(b) Single-powered Push/Pull Consist

Throttle Notch Position	CO_2 concentration (vol %)		CO concentration (vol %)		HC concentration (ppm)		NO concentration (ppm)		PM concentration (mg/m^3)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	0.54	-[b]	*0.000*	-[b]	*8*	-[b]	195	-[b]	4.0	-[b]
High Idle	0.59	0.07	*0.001*	*0.87*	*12*	*0.45*	190	0.03	3.5	0.14
Dynamic Brake	0.83	-[b]	*0.002*	-[b]	*10*	-[b]	215	-[b]	3.4	-[b]
1	0.69	0.06	*0.001*	*0.87*	*11*	*0.51*	212	0.15	3.7	0.24
2	1.96	0.18	*0.001*	*0.87*	14	*0.45*	607	0.12	5.1	0.13
3	2.96	0.15	*0.002*	*0.69*	*12*	*0.66*	1004	0.13	5.4	0.03
4	4.20	0.27	*0.007*	*1.39*	*11*	*0.78*	1284	0.16	5.7	0.19
5	4.05	0.05	*0.004*	*1.06*	*8*	*0.85*	1346	0.02	6.0	0.20
6	5.08	0.02	*0.003*	*0.47*	*9*	*0.63*	1592	0.00	7.3	0.32
7	5.57	0.06	0.010	0.94	*10*	*0.69*	1549	0.03	10.8	0.21
8	5.18	0.01	0.016	0.27	*6*	*0.44*	1347	0.01	9.8	0.21

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips*

[b] *No CV because of only one measured trip with steady-state data*

The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

Steady-state notch-average CO concentrations for the double-powered consist varied from 0.000 vol % at low idle to 0.016 vol % at notch 8. Notch-average CO concentrations were below the detection limit of the Axion PEMS for low idle through notch 6. For notches 7 and 8, CO concentrations were above the detection limit. The inter-trip CV for a given notch position was 1.4 or lower. Steady-state notch-average HC concentrations for the double-powered consist varied from 2 ppm at low idle to 11 ppm at notch 2. Notch-average HC concentrations were below the detection limit of the PEMS for each notch position. Inter-trip CV for a given notch position was 0.9 or lower for each notch position.

Steady-state notch-average NO concentrations for the double-powered consist varied from 170 ppm at low idle to 1570 ppm at notch 7. Notch-average NO concentrations increased monotonically with notch position for low idle through notch 7. The average NO_x concentration at notch 8 was 1293 ppm. Notch-average NO concentrations for a given notch position had inter-trip CV of 0.3 or lower. The inter-trip CV for high idle, notch 2, notch 5 and notch 8 was 0.1 or lower. Thus, these latter measurements were highly repeatable. Except for notches 5 and 6, no statistically significant differences were found between notch-average NO concentrations for the double- versus single-powered consist.

The steady-state notch-average PM concentrations for the double-powered consist varied from 3.8 mg/m^3 at low idle to 11.1 mg/m^3 at notch 7. Notch-average PM concentrations were within 10 percent of each other for low idle, high idle, dynamic brake and notch 1. Notch-average PM concentrations for notches 3 through 5 were within 5 percent of each other. Notch-average PM concentrations for a given notch position had inter-trip CV of 0.2 or lower for each notch position. The inter-trip CV for each notch position except for notch 2 was 0.08 or lower. Thus, these latter measurements were highly repeatable. No valid PM concentration measurements were available for the trips on the 13th of February because the PM sensor had failed.

4.2.4 Steady-State Fuel Use and Emission Rates

The steady-state notch-average engine output, fuel use rate and emission rates of CO_2, CO, HC, NO_x and PM are summarized in Table 4-8. The net engine power output increased monotonically from notch 1 through notch 8 for each consist. The notch-average FUER for the double- and single-powered consists are given in the next Section.

4.2.4.1. Double-powered consist

The steady-state notch-average fuel use rate varied from 2 g/s at low idle to 117 g/s at notch 7. Notch-average fuel use rates increased monotonically from low idle through notch 7. The average fuel use rate was 94.3 g/s at notch 8. The inter-trip CV of notch-average fuel use rates for a given notch position was 0.16 or lower. Thus, these measurements were repeatable. Notch-average CO_2 emission rates varied from 6 g/s at low idle to 364 g/s at notch 7. Notch-average CO_2 emission rates had similar relative trends as fuel use rate.

The notch-average CO and HC emission rates were 0.1 g/s or lower for low idle through notch 6. The inter-trip CV of CO and HC emission rates for a given notch position were 1.5 or lower for each notch position. The notch-average CO and HC emission rates were low.

TABLE 4-8. Steady-State Notch-Average Net Engine Output, Fuel Use, and Emission Rates for Locomotive NC 1871 for Over-the-Rail Measurements of Push/Pull Train Consists Conducted between January 30 and February 16, 2019: (a) Double-powered; and (b) Single-powered.

(a) Double-Powered Push/Pull Consist

Throttle Notch Position	Net Engine Output (hp)	Fuel Use Rate (g/s)		CO_2 Emission Rate (g/s)		CO Emission Rate (g/s)		HC Emission Rate[b] (g/s)		NO_x Emission Rate[c] (g/s)		PM Emission Rate[d] (g/s)	
		Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	9[e]	2.0	-[f]	6	-[f]	*0.0*	-[f]	*0.0*	-[f]	0.2	-[f]	0.0	-[f]
High Idle	9[e]	3.0	0.00[g]	9	0.06	*0.0*	*1.1*	*0.1*	*0.87*	0.3	0.17	0.0	-[f]
Dynamic Brake	9[e]	5.5	0.13	17	0.13	*0.0*	*1.4*	*0.1*	*1.41*	0.6	0.13	0.0	0.00[g]
1	130	3.7	0.16	11	0.09	*0.0*	*1.0*	*0.1*	*0.87*	0.4	0.16	0.0	0.00[g]
2	310	13.7	0.08	43	0.05	*0.0*	*0.9*	*0.1*	*1.00*	1.4	0.04	0.0	0.20
3	675	24.3	0.10	75	0.11	*0.0*	*1.7*	*0.1*	*1.00*	2.9	0.07	0.0	0.00
4	1050	44.0	0.14	138	0.14	*0.0*	*1.1*	*0.1*	*0.43*	5.2	0.20	0.1	0.13
5	1450	54.7	0.06	171	0.06	*0.0*	*1.5*	*0.1*	*0.43*	6.5	0.09	0.1	0.13
6	2000	72.3	0.10	226	0.10	*0.0*	*0.2*	*0.1*	*0.43*	7.7	0.14	0.1	0.08
7	2700	117.0	-[f]	364	-[f]	0.9	-[f]	*0.1*	-[f]	10.0	-[f]	0.2	-[f]
8	3000	94.3	0.02	294	0.02	0.5	0.2	*0.1*	*0.43*	8.4	0.05	0.1	0.10

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips.*
[b] *HC measured with Axion PEMS were multiplied with a correction factor shown in Table D-4(b) in Appendix D to obtain THC.*
[c] *NO measured with Axion PEMS were been multiplied with a correction factor shown in Table D-4(a) in Appendix D to obtain NO_x.*
[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*
[e] *Assumed from prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).*
[f] *No CV because of only one measured trip with steady-state data*
[g] *CV greater than zero but less than 0.005*
The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

Table 4-8 Continued on next page.

Table 4-8 Continued from previous page.

(b) Single-Powered Push/Pull Consist

Throttle Notch Position	Net Engine Output (hp)	Fuel Use Rate (g/s)		CO_2 Emission Rate (g/s)		CO Emission Rate (g/s)		HC Emission Rate[b] (g/s)		NO_x Emission Rate[c] (g/s)		PM Emission Rate[d] (g/s)	
		Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	9[e]	2.0	-[f]	6	-[f]	*0.0*	-[f]	*0.0*	-[f]	0.2	-[f]	0.0	-[f]
High Idle	9[e]	3.0	0.00[g]	8	0.00[g]	*0.0*	*0.9*	*0.1*	*0.87*	0.3	0.00[g]	0.0	0.47
Dynamic Brake	9[e]	6.0	-[f]	17	-[f]	*0.0*	-[f]	*0.1*	-[f]	0.5	-[f]	0.0	-[f]
1	130	3.0	0.00[g]	10	0.06	*0.0*	*0.9*	*0.1*	*0.87*	0.3	0.17	0.0	0.47
2	310	12.3	0.12	37	0.12	*0.0*	*0.4*	0.1	0.43	1.3	0.08	0.0	0.28
3	675	24.0	0.08	74	0.10	*0.0*	*1.0*	*0.2*	*0.69*	2.8	0.09	0.0	0.00[g]
4	1050	50.7	0.21	158	0.21	*0.2*	*1.3*	*0.2*	*0.87*	5.3	0.10	0.1	0.33
5	1450	53.0	0.03	166	0.04	*0.1*	*1.0*	*0.2*	*0.47*	6.1	0.07	0.1	0.20
6	2000	80.5	0.08	252	0.08	*0.1*	*0.6*	*0.2*	*0.71*	8.7	0.10	0.1	0.42
7	2700	100.3	0.10	314	0.10	0.4	1.0	*0.2*	*0.65*	9.6	0.06	0.2	0.31
8	3000	105.3	0.07	328	0.07	0.6	0.3	*0.2*	*0.35*	9.4	0.08	0.2	0.27

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips.*
[b] *HC measured with Axion PEMS were multiplied with a correction factor shown in Table D-4(b) in Appendix D to obtain THC.*
[c] *NO measured with Axion PEMS were been multiplied with a correction factor shown in Table D-4(a) in Appendix D to obtain* NO_x.
[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*
[e] *Assumed from prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).*
[f] *No CV because of only one measured trip with steady-state data*
[g] *CV greater than zero but less than 0.005*
The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

The steady-state notch-average NO_x emission rates varied from 0.2 g/s at low idle to 10.0 g/s at notch 7. Notch-average NO_x emission rates increased monotonically from low idle through notch 7. The average NO_x emission rate was 8.4 g/s at notch 8. The inter-trip CV of notch-average NO_x emission rates for a given notch position was 0.20 or lower for each notch position. Thus, these measurements were repeatable.

The steady-state notch-average PM emission rates varied from 0.02 g/s at low idle to 0.22 g/s at notch 7. Notch-average PM emission rates increased monotonically from low idle through notch 7. The average PM emission rate was 0.15 g/s at notch 8. The inter-trip CV of notch-average PM emission rates for a given notch position was 0.20 or lower for each notch position. Thus, these measurements were repeatable.

4.2.4.2. Single-powered Consist

The steady-state notch-average fuel use rate varied from 2 g/s at low idle to 105 g/s at notch 8. Notch-average fuel use rate increased monotonically from low idle through notch 8. The inter-trip CV of notch-average fuel use rates for a given notch position was 0.21 or lower for each notch position. Thus, these measurements were repeatable. Notch-average CO_2 emission rates varied from 6 g/s at low idle to 328 g/s at notch 8. Notch-average CO_2 emission rates had similar relative trends as fuel use rate. For the single-powered consist, the fuel use rate at notch 8 was 10 percent higher compared to the fuel use rate at notch 8 for the double-powered consist.

The notch-average CO and HC emission rates for the double-powered consist for a given notch position were not statistically significantly different than for the single-powered consist. Notch-average NO_x and PM emission rates for the double-powered consist for a given notch position were not statistically significantly different than for the single-powered consist, except at notch 8. At notch 8, NO_x and PM emission rates for the double-powered consist were lower than the single-powered consist due to lower measured concentrations and exhaust flow rate.

Measured exhaust concentrations and FUER were 5 percent to 10 percent lower at notch 8 for the double-powered versus single-powered consist. Operators typically spent the highest or the second highest percentage of time in notch 8 and notch 8 has the highest fuel use rate versus all notch positions. Therefore, differences in average FUER at notch 8 for the double- versus single-powered consists lead to differences in TFUE and CAER.

4.3 Locomotive NC 1984: June 2018

OTR measurements of the PME of NC 1984 were conducted between June 12, 2018 and June 14, 2018. Three one-way trips each were conducted for Trains 75 and 76 following the measurement schedule given in Table 2-4. The train consist included two locomotives, three passenger cars and one baggage/café car. Each of the trips was measured as a double-powered push/pull consist.

4.3.1 Duty Cycles

Measured duty cycles for each one-way trip are given in Table 4-9. Train 76 on June 13 had the longest duration at 3h 26m, whereas, Train 76 on June 14 was the fastest at 3h 10m. On average, the trip took 3h 20m. The percentage of time spent in each notch position is given in Table 4-9. The highest percentage of time in any trip was spent at idle, ranging between 42.3 percent and 54.0

percent. The next highest percentage of time was spent at notch 8, ranging between 17.4 percent and 25.6 percent. Dynamic brake also accounted for a significant percentage of time, ranging between 3.8 percent and 11.3 percent. Together, these three accounted for an average 79 percent of the trip duration, ranging between 75 percent and 85 percent. Notch 1 and notch 2 together accounted for about 10 percent. Notch 7 had the lowest percentage of time, typically less than 0.2 percent.

4.3.2 Steady-State Engine Activity Variables

The steady-state notch-average RPM, IAT, and MAP are summarized in Table 4-10. Notch-average RPM varied from 219 RPM at low idle to 900 RPM at notch 8. Notch-average RPM increased monotonically from low idle to notch 8, except for dynamic brake. Engine RPM at dynamic brake varied substantially. Notch-average RPM for a given notch position had inter-trip CV of 0.03 or lower for each notch position. Thus, the RPM measurements were highly repeatable.

The notch-average IAT varied from 314 K at low idle to 318 K at notch 5. Notch-average IAT for a given notch position had inter-trip CV of 0.01 or lower for each notch position. Thus, the IAT measurements were highly repeatable.

The notch-average MAP varied from 95 kPa at low idle to 200 kPa at notch 8. Notch-average MAP for a given notch position had an inter-trip CV of 0.03 or lower for each notch position. Thus, the MAP measurements were highly repeatable.

TABLE 4-9. Percent Time Spent in Each Notch Position for Locomotive NC 1984 for Over-the-Rail Measurements of Double-powered Push/Pull Train Consist Conducted between June 12, 2018 and June 14, 2018.

Throttle Notch Position	Jun 12	Jun 12	Jun 13	Jun 13	Jun 14	Jun 14	6 Trips	
	Train 75	Train 76	Train 75	Train 76	Train 75	Train 76	Avg	CV[a]
Idle	48.5	54.0	42.3	46.6	49.4	49.2	48.3	0.08
Dynamic Brake	5.3	3.8	11.3	9.3	6.5	5.8	7.0	0.40
1	2.9	4.6	4.7	4.7	3.5	6.8	4.5	0.29
2	5.7	6.5	4.3	5.7	2.6	4.5	4.9	0.28
3	3.0	4.9	4.7	4.0	3.5	3.0	3.9	0.21
4	4.6	3.9	2.9	3.2	3.2	4.6	3.7	0.20
5	2.6	2.5	1.5	2.1	1.5	2.6	2.1	0.25
6	3.5	2.3	2.5	1.1	0.4	3.2	2.2	0.56
7	0.2	0.2	0.3	0.1	0.2	0.2	0.2	0.32
8	23.6	17.4	25.6	23.1	29.1	20.2	23.2	0.18
Trip Duration (h:mm:ss)	3:22:39	3:25:23	3:15:51	3:25:51	3:19:34	3:10:00	3:19:53	-

[a] *CV = coefficient of variation (standard deviation divided by mean)*

TABLE 4-10. Steady-State Notch-Average Engine Activity Variables for Locomotive NC 1984 for Over-the-Rail Measurements of Double-powered Push/Pull Train Consist Conducted between June 12, 2018 and June 14, 2018.

Throttle Notch Position	Engine RPM (RPM)		Intake Air Temperature (K)		Manifold Absolute Pressure (kPa)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	219	0.002	314	0.012	93	0.016
High Idle	268	0.002	315	0.012	101	0.010
Dynamic Brake	450	0.037	315	0.012	113	0.030
1	268	0.000[c]	316	0.011	97	0.009
2	389	0.001	316	0.011	105	0.011
3	509	0.000[c]	316	0.013	116	0.014
4	703	0.001	316	0.012	146	0.014
5	719	0.014	318	0.016	148	0.040
6	820	0.004	317	0.013	172	0.021
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	900	0.000[c]	316	0.011	200	0.023

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips based on steady-state operation.*
[b] *No steady-state data for the given notch position.*
[c] *CV greater than zero but less than 0.0005.*

4.3.3 Steady-State Exhaust Gas and PM Concentrations

The steady-state notch-average exhaust concentrations of CO_2, CO, HC, NO and PM measured using an Axion PEMS are summarized in Table 4-11. Steady-state notch-average CO_2 concentrations varied from 0.74 vol % at low idle to 4.87 vol % at notch 6. Notch-average CO_2 concentrations increased monotonically from low idle through notch 6. The average concentration was 4.80 vol % at notch 8. Notch-average CO_2 concentrations for a given notch position had an inter-trip CV of 0.16 or lower for each notch position. The inter-trip CV for low idle, high idle, dynamic brake and notch 8 was 0.11 or lower. Thus, these measurements were repeatable.

The steady-state notch-average CO concentrations were below the detection limit of the Axion PEMS for low idle through notch 7. Steady-state notch-average HC concentrations varied from 13 ppm at notch 5 to 29 ppm at low idle, dynamic brake and notch 3. Notch-average HC concentration was below the detection limit of the PEMS only at notch 5. However, notch-average HC concentrations were low, the highest was 2.1 times the detection limit.

The steady-state notch-average NO concentrations for the double-powered consist varied from 174 ppm at dynamic brake to 1320 ppm at notch 6. Notch-average NO concentrations increased monotonically with notch position for high idle through notch 6. The average concentration was 995 ppm at notch 8. Notch-average NO concentrations for a given notch position had an inter-trip CV of 0.1 or lower for each notch position. Thus, these measurements were highly repeatable.

TABLE 4-11. Steady-State Notch-Average Concentrations for Locomotive NC 1984 for Over-the-Rail Measurements of Double-powered Push/Pull Train Consist Conducted between June 12, 2018 and June 14, 2018.

Throttle Notch Position	CO_2 concentration (vol %)		CO concentration (vol %)		HC concentration (ppm)		NO concentration (ppm)		PM concentration (mg/m^3)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	0.74	0.11	*0.002*	*0.99*	29	0.35	183	0.03	6.0	0.15
High Idle	0.87	0.05	*0.003*	*0.70*	22	0.47	210	0.03	7.0	0.06
Dynamic Brake	0.96	0.16	*0.002*	*0.94*	29	0.83	174	0.10	6.5	0.03
1	0.99	0.08	*0.001*	*1.13*	24	0.71	277	0.03	7.1	0.05
2	2.40	0.10	*0.001*	*1.40*	17	0.75	657	0.10	7.4	0.04
3	3.38	0.10	*0.000*	*2.45*	29	0.50	1054	0.10	6.8	0.02
4	4.09	0.04	*0.000*	*1.37*	19	0.64	1171	0.05	6.6	0.03
5	4.44	0.07	*0.004*	*0.68*	*13*	*1.25*	1225	0.11	6.6	0.06
6	4.87	0.08	*0.004*	*0.99*	17	0.78	1320	0.04	8.2	0.08
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	4.80	0.07	0.019	0.26	14	0.53	995	0.08	13.7	0.10

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips*

[b] *No steady-state data for the given notch position.*

The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

The notch-average PM concentrations varied from 6.0 mg/m^3 at low idle to 13.7 mg/m^3 at notch 8. Notch-average PM concentrations for a given notch position had an inter-trip CV of 0.15 or lower for each notch position. Thus, these measurements were repeatable.

4.3.4 Steady-State Fuel Use and Emission Rates

The steady-state notch-average engine output, fuel use rate and emission rates of CO_2, CO, HC, NO and PM are summarized in Table 4-12. The net engine power output increased monotonically from notch 1 through notch 8.

The notch-average fuel use rates varied from 2.7 g/s at low idle to 92.1 g/s at notch 8. Notch-average fuel use rates increased monotonically from low idle through notch 8. The inter-trip CV of notch-average fuel use rates for a given notch position was 0.20 or lower for each notch position and 0.1 or lower for each notch position except for dynamic brake. Thus, these measurements were repeatable. Notch-average CO_2 emission rates varied from 9 g/s at low idle to 286 g/s at notch 8. The notch-average CO_2 emission rates had similar relative trends as the fuel use rate.

The notch-average CO emission rates varied from 0.01 g/s at low idle to 0.75 g/s at notch 8. Notch-average HC emission rates varied between 0.2 g/s and 0.4 g/s. CO and HC emission rates were low.

TABLE 4-12. Steady-State Notch-Average Net Engine Output, Fuel Use and Emission Rates for Locomotive NC 1984 for Over-the-Rail Measurements of Double-powered Push/Pull Train Consist Conducted between June 12, 2018 and June 14, 2018.

Throttle Notch Position	Net Engine Output (hp)	Fuel Use Rate (g/s)		CO_2 Emission Rate (g/s)		CO Emission Rate (g/s)		HC Emission Rate[b] (g/s)		NO_x Emission Rate[c] (g/s)		PM Emission Rate[d] (g/s)	
		Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	9[e]	2.7	0.08	9	0.09	*0.00*	*0.72*	0.2	0.41	0.3	0.19	0.0	0.83
High Idle	9[e]	4.6	0.06	15	0.08	*0.04*	*0.84*	0.2	0.54	0.7	0.55	0.0	0.55
Dynamic Brake	9[e]	7.5	0.20	23	0.20	*0.03*	*1.09*	0.3	0.77	0.5	0.28	0.0	0.53
1	130	4.7	0.07	14	0.07	*0.01*	*0.94*	0.2	0.64	0.5	0.11	0.0	0.54
2	310	16.7	0.02	45	0.24	*0.01*	*1.10*	0.2	0.73	1.3	0.30	0.0	0.54
3	675	29.0	0.10	90	0.10	*0.00*	*1.06*	0.4	0.48	3.1	0.11	0.0	0.53
4	1050	52.4	0.02	164	0.02	*0.01*	*0.92*	*0.4*	*0.52*	5.2	0.03	0.1	0.02
5	1450	58.8	0.05	180	0.06	*0.09*	*0.84*	0.3	1.32	6.3	0.02	0.1	0.10
6	2000	79.6	0.07	248	0.08	*0.14*	*0.94*	0.4	0.73	7.4	0.06	0.1	0.22
7	-[f]	-[f]	-[f]	-[f]	-[f]	-[f]	-[f]	-[f]	-[f]	-[f]	-[f]	-[f]	-[f]
8	3000	92.1	0.08	286	0.08	0.75	*0.26*	0.4	0.56	6.5	0.09	0.2	0.56

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips.*
[b] *HC measured with Axion PEMS were multiplied with a correction factor shown in Table D-4(b) in Appendix D to obtain THC.*
[c] *NO measured with Axion PEMS were been multiplied with a correction factor shown in Table D-4(a) in Appendix D to obtain* NO_x.
[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*
[e] *Assumed from prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).*
[f] *No steady-state data for the given notch position.*
The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

The notch-average NO_x emission rates varied from 0.3 g/s at low idle to 7.4 g/s at notch 6. Notch-average NO_x emission rates increased monotonically from low idle through notch 6. The average NO_x emission rate at notch 6 was 7.4 g/s. The inter-trip CV of notch-average NO_x emission rates for a given notch position was 0.6 or lower for each notch position and 0.1 or lower for 6 of the 10 measured notch positions. Thus, NO_x emission rate measurements were highly repeatable for 6 of the 10 measured notch positions.

The steady-state notch-average PM emission rates varied from 0.02 g/s at low idle to 0.23 g/s at notch 8. Notch-average PM emission rates increased monotonically from low idle through notch 8. The inter-trip CV of notch-average PM emission rates for a given notch position was 0.83 or lower for each notch position.

4.4 Locomotive NC 1984: June 2019

The OTR measurements of the PME of NC 1984 were conducted from June 18 to June 20, 2019. Six one-way trips were conducted for the Trains 75 and 76 following the measurement schedule given in Table 2-4. Three one-way trips were conducted each for the double- and single-powered consists. During the trips on June 18, the net engine output for each consist was periodically recorded manually from the locomotive activity recorder display.

4.4.1 Duty Cycles

Train 75 on June 20 had the longest duration at 4h 36m, whereas, Train 76 on June 18 had the shortest duration at 3h 9m. On average, the trip took 3h 20m. The percentage of time spent in each notch position is given in Table 4-13. The average trip duration for the double-versus single-powered consists was 3h 32m and 4h 3m, respectively. Trips on the single-powered consist were affected by train delays which were not encountered on the double-powered consist.

For the double-powered consist, the highest percentage of time was spent in idle, ranging between 45.2 percent and 56.7 percent, with an average of 49.0 percent among the one-way trips. The next highest percentage of time was spent in notch 8, ranging between 20.4 percent and 30.8 percent among the one-way trips, with an average of 27.2 percent. Other notch positions and dynamic brake accounted for less than 4.6 percent of the total time each because the operator used these positions typically to switch the operation from idle to notch 8 or vice versa. For Train 76 on 20^{th} June, the operator used mechanical braking or coasting to slow the train and did not use the dynamic brake.

For the single-powered consist, the highest percentage of time was spent in notch 8, ranging between 35.3 percent and 51.0 percent among the one-way trips, with an average of 41.2 percent. The next highest percentage of time was spent in idle, ranging between 31.2 percent and 49.1 percent among the one-way trips, with an average of 39.1 percent. For Train 75 on 19^{th} June, the locomotive operator used mechanical braking or coasting to slow the train and did not use the dynamic brake. Other notch positions accounted for less than 3.6 percent of the total time each on average because the operator used these positions typically to switch the operation from idle to notch 8 or vice versa.

TABLE 4-13. Percentage Time Spent in Each Notch Position for Locomotive NC 1984 for Over-the-Rail Measurements of Double- and single-powered Push/Pull Train Consists Conducted between June 18 and June 20, 2019.

Throttle Notch Position	Double-Powered					Single-Powered				
	Jun 18	Jun 19	Jun 20	3 Trips		Jun 18	Jun 19	Jun 20	3 Trips	
	Train 76	Train 76	Train 76	Avg	CV[a]	Train 75	Train 75	Train 75	Avg	CV[a]
Idle	45.2	45.3	56.7	49.0	0.13	37.1	49.1	31.2	39.1	0.23
Dynamic Brake	2.1	1.5	0.0	1.2	0.90	1.5	0.0	3.2	1.6	1.02
1	4.2	2.7	3.0	3.3	0.24	3.1	2.5	2.2	2.6	0.18
2	4.3	4.5	2.6	3.8	0.27	3.5	2.6	2.9	3.0	0.15
3	4.4	5.8	3.7	4.6	0.23	5.5	2.4	2.9	3.6	0.46
4	3.3	4.2	4.2	3.9	0.13	3.7	1.9	2.4	2.7	0.35
5	2.1	2.8	5.4	3.5	0.51	4.2	1.6	1.5	2.4	0.63
6	3.1	2.5	3.6	3.1	0.18	4.5	2.1	1.9	2.8	0.51
7	0.5	0.3	0.4	0.4	0.25	1.7	0.5	0.9	1.0	0.59
8	30.8	30.3	20.4	27.2	0.22	35.3	37.3	51.0	41.2	0.21
Trip Duration (h:mm:ss)	3:08:37	3:34:23	3:53:25	3:32:08		4:06:34	3:25:41	4:36:17	4:02:51	

[a] *CV = coefficient of variation (standard deviation divided by mean)*

4.4.2 Steady-State Engine Activity Variables

The steady-state notch-average RPM, IAT, and MAP are summarized in Table 4-14. Notch-average RPM for a given notch position was within 3 RPM for double- versus single-powered consists for each notch position, except for dynamic brake. Therefore, notch-average RPM for a given notch position was approximately similar to each other for the two consists. Notch-average RPM varied from 219 RPM at low idle to 902 RPM at notch 8. Notch-average RPM increased monotonically from low idle to notch 8, except for dynamic brake. Engine RPM at dynamic brake varied substantially. Notch-average RPM for a given notch position for the double- and single-powered consist each had inter-trip CV of 0.03 or lower for each notch position. Thus, the RPM measurements were highly repeatable.

The notch-average IAT for the double-powered consist varied from 353 K at low idle to 361 K at notch 8. Notch-average IAT for the double-powered consist had inter-trip CV of 0.04 or lower for each notch position. Thus, the IAT measurements were highly repeatable. Notch-average IAT for the single-powered consist varied from 352 K at low idle to 365 K at notch 8. Notch-average IAT for the single-powered consist had inter-trip CV of 0.04 or lower for each notch position. Thus, the IAT measurements were highly repeatable.

TABLE 4-14. Steady-State Notch-Average Engine Activity Variables for Locomotive NC 1984 for Over-the-Rail Measurements of Double- and single-powered Push/Pull Train Consists Conducted between June 18 and June 20, 2019.

Throttle Notch Position	Engine RPM (RPM)				Intake Air Temperature (K)				Manifold Absolute Pressure (kPa)			
	Double-Powered		Single-Powered		Double-Powered		Single-Powered		Double-Powered		Single-Powered	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	219	0.000[c]	219	0.000[c]	353	0.010	352	0.002	100	0.000[c]	101	0.000[c]
High Idle	268	0.000[c]	268	0.000[c]	354	0.004	356	0.006	103	0.006	103	0.006
Dynamic Brake	386	0.024	477	0.021	355	0.006	358	0.002	110	0.000[c]	120	0.000[c]
1	268	0.002	268	0.002	354	0.002	356	0.007	103	0.006	103	0.000[c]
2	389	0.001	389	0.000[c]	355	0.003	357	0.005	110	0.000	111	0.005
3	509	0.000[c]	509	0.000[c]	356	0.000[c]	360	0.011	121	0.010	122	0.005
4	702	0.001	703	0.001	358	0.009	361	0.007	149	0.000[c]	150	0.000[c]
5	727	0.001	727	0.002	358	0.004	361	0.007	155	0.004	154	0.007
6	818	0.001	819	0.001	360	0.007	364	0.004	175	0.000[c]	176	0.000
7	870	-[b]	859	0.001	356	-[b]	364	0.010	200	0.000[c]	203	-[b]
8	901	0.001	901	0.001	361	0.003	365	0.004	205	0.008	213	0.014

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips*
[b] *No CV because of only one measured trip with steady-state data*
[c] *CV greater than zero but less than 0.0005.*

The notch-average MAP for a given notch position was within 2 kPa for the double- and single-powered consists for each notch position, except for dynamic brake, notch 7 and notch 8. Therefore, notch-average MAP for a given notch position was approximately similar for the two consists, except for dynamic brake notch 7 and notch 8. For the double-powered consist, notch-average MAP varied from 100 kPa at low idle to 205 kPa at notch 8. For the single-powered consist, notch-average MAP varied from 101 kPa at low idle to 212 kPa at notch 8. For both consists, notch-average MAP increased monotonically from low idle to notch 8, except for dynamic brake. The single-powered consist had 3 kPa to 7 kPa higher MAP at notches 7 and 8 versus the double-powered consist.

4.4.3 Steady-State Exhaust Gas and PM Concentrations

The steady-state notch-average exhaust concentrations of CO_2, CO, HC, NO and PM measured using an Axion PEMS are summarized in Table 4-15. The steady-state notch-average CO_2 concentrations for the double-powered consist varied from 0.53 vol % at low idle to 5.92 vol % at notch 8 typically increased with notch position. The notch-average steady-state CO_2 concentrations varied from 0.68 vol % at low idle to 7.03 vol % at notch 7 for the single-powered consist and typically increased with notch position. The average CO_2 concentration at notch 8 was 6.08 vol % for the single-powered consist. Notch-average CO_2 concentrations were not statistically significantly different for double- versus single-powered consists for each notch position. Though not statistically significant, notch-average CO_2 concentrations for a given notch position were 2 to 6 percent lower for double- versus single-powered consists implying a higher air to fuel ratio and a lower fuel flow rate. The measurements were repeatable for a given notch position based on the inter-trip CV of 0.11 or lower. The CV was typically higher for notches 3 or lower compared to notches 4 and higher. However, notch-average CO_2 emission rates were also low for notches 3 or lower compared to notches 4 through 8.

Notch-average CO concentrations were typically below the detection limit of the Axion PEMS for most notches and trips. The inter-trip CV for a given notch position was typically higher for notches with low emission rates and that was based on average concentrations below the detection limit of the PEMS. For notches 7 and 8, for which measured notch-average CO concentrations were typically above the detection limit, measurements were repeatable based on inter-trip CV of 0.11 or lower. For low idle through notch 1, CO concentrations were the same, within the precision of the measurements, for a given notch position for double- versus single-powered consist. For notches 2 through 8, differences in CO concentrations for double- versus single-powered were not statistically significant. Notch-average HC concentrations were below the detection limit of the Axion PEMS for all notch positions and all one-way trips. No trend in Notch-average HC concentrations was observed for double- versus single-powered consist.

The steady-state notch-average NO concentrations for the double-powered consist varied between 160 ppm at low idle and 1,368 ppm at notch 6. Notch-average NO concentrations for the single-powered consist between 180 ppm at high idle and 1,439 ppm at notch 6. Notch-average NO concentration typically increased with notch position from high idle through notch 6 for each consist. Notch-average NO concentrations were repeatable for a given notch position and operation based on an inter-trip CV of 0.10 or lower for both consists, except at notch 1.

TABLE 4-15. Steady-State Notch-Average Concentrations for Locomotive NC 1984 for Over-the-Rail Measurements of Push/Pull Train Consists Conducted between June 18 and June 20, 2019: (a) Double-powered; and (b) Single-powered.

(a) Double-powered Push/Pull Consist

Throttle Notch Position	CO_2 concentration (vol %)		CO concentration (vol %)		HC concentration (ppm)		NO concentration (ppm)		PM concentration (mg/m^3)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	0.56	0.06	*0.002*	-[b]	*7*	*0.40*	170	0.08	11.5	0.09
High Idle	0.63	0.08	*0.001*	*0.87*	*8*	*0.27*	180	0.06	9.9	0.03
Dynamic Brake	0.74	0.07	*0.001*	*1.41*	*7*	*0.54*	179	0.08	10.4	0.01
1	0.71	0.09	*0.001*	*0.11*	*5*	*0.81*	236	0.14	9.8	0.06
2	2.35	0.03	*0.001*	*1.73*	*4*	*0.71*	643	0.07	10.2	0.02
3	3.59	0.01	*0.001*	*1.73*	*4*	*0.27*	1089	0.04	11.6	0.05
4	3.90	0.02	*0.003*	*0.57*	*4*	*0.50*	1110	0.08	12.7	0.04
5	4.52	0.02	*0.002*	*0.69*	*6*	*0.37*	1279	0.06	10.7	0.09
6	5.31	0.06	0.008	0.48	*3*	*0.75*	1308	0.05	13.1	0.06
7	3.40	-[b]	-	-[b]	*2*	-[b]	915	-[b]	19.6	-[b]
8	5.92	0.01	0.052	0.06	*4*	*0.53*	1094	0.09	14.9	0.01

(b) Single-powered Push/Pull Consist

Throttle Notch Position	CO_2 concentration (vol %)		CO concentration (vol %)		HC concentration (ppm)		NO concentration (ppm)		PM concentration (mg/m^3)	
	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	0.71	0.05	*0.001*	*1.41*	*4*	*0.35*	201	0.02	10.0	0.14
High Idle	0.66	0.03	*0.001*	*0.87*	*5*	*0.40*	183	0.03	9.6	0.17
Dynamic Brake	0.86	0.00[c]	*0.001*	*0.00*[c]	*5*	*0.16*	176	0.05	7.9	0.18
1	0.83	0.09	*0.001*	*0.43*	*5*	*0.45*	261	0.15	9.6	0.16
2	2.41	0.11	*0.002*	*0.65*	*5*	*0.12*	647	0.08	10.2	0.12
3	3.46	0.06	*0.003*	*0.78*	*3*	*0.00*[c]	979	0.07	11.0	0.14
4	4.05	0.03	*0.004*	*0.43*	*5*	*0.20*	1081	0.06	10.9	0.10
5	4.63	0.07	*0.003*	*0.75*	*7*	*0.57*	1248	0.10	10.4	0.14
6	5.72	0.01	0.010	0.32	*4*	*0.50*	1370	0.04	11.2	0.12
7	6.87	0.03	0.064	0.13	*4*	*0.35*	1230	0.04	17.2	0.12
8	6.08	0.02	0.046	0.05	*3*	*0.33*	1123	0.03	13.6	0.09

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips*
[b] *No CV because of only one measured trip with steady-state data*
[c] *CV greater than zero but less than 0.005.*
The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

Notch 1 had the inter-trip CV of 0.15 and 0.14 for double- and single-powered consists, respectively. However, the measured average NO concentrations were low for notch 1 compared to higher notch positions. Measured notch-average NO concentrations were within 100 ppm for a given notch potion for the double- versus single-powered consist, except at notch 7. However, the differences were not statistically significant. The large difference for notch 7 was an artifact of having relatively few seconds of steady-state data.

The steady-state notch-average PM concentrations for the double-powered consist varied from 10 $\mu g/m^3$ at high idle to 20 $\mu g/m^3$ at notch 8. The steady-state notch-average PM concentrations for the single-powered consist varied between 7 $\mu g/m^3$ at dynamic brake and 19 $\mu g/m^3$ at notch 7. Notch-average PM concentrations typically increased with notch position from high idle through notch 8, except at notch 7. Measured concentrations at notch 7 were typically based on a limited amount of steady-state data, typically 10 seconds or fewer, and therefore have larger random sampling error compared to other notches.

4.4.4 Steady-State Fuel Use and Emission Rates

The steady-state notch-average engine output, fuel use rate and emission rates of CO_2, CO, HC, NO_x and PM are summarized in Table 4-16. The net engine power output increased monotonically from notch 1 through notch 8.

The notch-average fuel use rate increased with increasing notch position for both double- and single-powered consists. Notch-average fuel use rates for a given notch position for low idle, high idle and notches 1 through 5 were within 4 percent for the double- versus single-powered consists. Notch-average fuel use rates for a given notch position for notches 6 through 8 were 5 percent to 10 percent lower for the double- versus single-powered consists. Measured CO_2 exhaust concentrations for these notch positions were typically 2 to 6 percent lower for the double- versus single-powered consists, resulting in a lower fuel flow rate for double-powered consist. At notch 8, the MAP for the double-powered consist was 4 percent lower compared to the single-powered consist, whereas RPM and IAT were within 0.5 percent of each other. As a result, the mass air flow rate at notch 8 for the double-powered consist was 5 percent lower compared to the single-powered consist, which resulted in a lower fuel use rate at notch 8. Notch-average fuel use rates were highly repeatable at a given notch position for both the double- and single-powered consists, as indicated by the inter-trip CV of 0.08 or lower. Notch-average CO_2 emission rates have the same trend as fuel use rate. Notch-average CO_2 emission rates were also repeatable.

The notch-average CO emission rates for low idle through notch 6 were typically based on CO concentrations below the detection limit of Axion PEMS. Although the CV for inter-trip variability in these rates was as high as 1.73, these emission rates were low. CO emission rates at notch 8 were highly repeatable for the double- and single-powered consists with an inter-trip CV of 0.07 and 0.05, respectively. Notch-average HC emission rates were based on average HC concentrations below the detection limit of the PEMS for all notches and all trips, resulting in large variability. However, emission rates were low.

TABLE 4-16. Steady-State Notch-Average Engine Output, Fuel Use and Emission Rates for Locomotive NC 1871 for Over-the-Rail Measurements of Push/Pull Train Consists Conducted between June 18 and June 20, 2019: (a) Double-powered; and (b) Single-powered.

(a) Double-Powered Push/Pull Consist

Throttle Notch Position	Engine Output (hp)	Fuel Use Rate (g/s)		CO_2 Emission Rate (g/s)		CO Emission Rate (g/s)		HC Emission Rate[b] (g/s)		NO_x Emission Rate[c] (g/s)		PM Emission Rate[d] (g/s)	
		Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	9[e]	2.0	-[g]	7	-[g]	0.0	-[g]	0.0	-[g]	0.2	-[g]	0.0	-[g]
High Idle	9[e]	3.0	0.00[f]	9	0.07	0.0	0.87	0.1	1.00	0.3	0.00[f]	0.0	0.00[f]
Dynamic Brake	9[e]	4.5	0.16	14	0.05	0.0	1.41	0.2	0.71	0.4	0.20	0.1	0.13
1	130	3.0	0.00[f]	10	0.06	0.0	0.00[f]	0.1	0.00[f]	0.4	0.20	0.1	0.28
2	310	14.3	0.04	44	0.03	0.0	1.73	0.4	0.96	1.3	0.08	0.1	0.17
3	675	28.0	0.00[f]	88	0.01	0.0	1.73	0.1	0.00[f]	2.9	0.05	0.1	0.18
4	1050	45.3	0.01	141	0.01	0.1	0.57	0.3	1.08	4.4	0.08	0.1	0.27
5	1450	55.0	0.02	172	0.02	0.0	0.87	0.1	0.43	5.4	0.07	0.2	0.26
6	2000	77.0	0.06	240	0.06	0.2	0.47	0.3	1.45	6.5	0.03	0.1	0.22
7	2700	57.0	-[g]	179	-[g]	2.2	-[g]	0.1	-[g]	5.3	-[g]	0.2	-[g]
8	3000	104.0	0.02	322	0.02	1.8	0.05	0.5	1.18	6.2	0.02	0.3	0.05

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips.*
[b] *HC measured with Axion PEMS were multiplied with a correction factor shown in Table D-4(b) in Appendix D to obtain THC.*
[c] *NO measured with Axion PEMS were been multiplied with a correction factor shown in Table D-4(a) in Appendix D to obtain* NO_x.
[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*
[e] *Assumed from prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).*
[f] *CV greater than zero but less than 0.005.*
[g] *No CV because of only one measured trip with steady-state data*
The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

Table 4-16 Continued on next page.

Table 4-16 Continued from previous page.

(b) Single-Powered Push/Pull Consist

Throttle Notch Position	Engine Output (hp)	Fuel Use Rate (g/s)		CO_2 Emission Rate (g/s)		CO Emission Rate (g/s)		HC Emission Rate[b] (g/s)		NO_x Emission Rate[c] (g/s)		PM Emission Rate[d] (g/s)	
		Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]	Avg	CV[a]
Low Idle	9[e]	3.0	-[g]	6	-[g]	0.0	-[g]	0.0	-[g]	0.3	-[g]	0.0	-[g]
High Idle	9[e]	3.0	0.00[f]	9	0.00[f]	0.0	0.87	0.3	1.41	0.3	0.00[f]	0.0	0.47
Dynamic Brake	9[e]	7.0	0.20	21	0.03	0.0	0.47	2.4	1.41	0.4	-	0.1	0.13
1	130	3.7	0.16	12	0.10	0.0	0.43	0.1	1.73	0.4	0.25	0.0	0.16
2	310	14.7	0.10	46	0.09	0.0	0.78	0.4	1.73	1.4	0.04	0.0	0.25
3	675	27.7	0.02	86	0.04	0.0	0.87	0.4	1.73	2.7	0.04	0.1	0.18
4	1050	47.3	0.03	147	0.04	0.1	0.41	0.5	1.36	4.3	0.07	0.1	0.18
5	1450	56.7	0.04	177	0.04	0.1	0.70	0.6	1.44	5.2	0.08	0.1	0.18
6	2000	83.7	0.01	260	0.01	0.3	0.28	0.8	1.52	6.9	0.04	0.1	0.20
7	2700	114.5	0.03	356	0.03	2.1	0.14	0.1	1.41	6.8	0.04	0.2	0.14
8	3000	109.7	0.05	339	0.05	1.6	0.07	1.2	1.59	6.9	0.05	0.1	0.31

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of one-way trips.*
[b] *HC measured with Axion PEMS were multiplied with a correction factor shown in Table D-4(b) in Appendix D to obtain THC.*
[c] *NO measured with Axion PEMS were been multiplied with a correction factor shown in Table D-4(a) in Appendix D to obtain NO_x.*
[d] *PM emission rates estimated with Axion measurements were multiplied by a factor of 5 to account for total PM.*
[e] *Assumed from prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).*
[f] *CV greater than zero but less than 0.005.*
[g] *No CV because of only one measured trip with steady-state data*
The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.

The notch-average NO_x emission rates increased monotonically from idle through notch 7 for both the double- and single-powered consists. NO_x emission rates for notches 6 through 8 were 5 percent to 10 percent lower for the double- versus single-powered consists. Notch-average NO_x emission rates were repeatable at a given notch position for both the double- and single-powered consists based on inter-trip CV of 0.09 or lower except for dynamic brake and notch 1, which have low NO_x emission rates. The inter-trip CV for a given notch position was 0.16 or lower for each position and for the double- and single-powered consists.

The notch-average PM emission rates increased monotonically from idle through notch 7 for both the double- and single-powered consists. For a given notch position for notches low idle through notch 6, notch-average PM emission rates were within 5 percent of each other for the double- versus single-powered consists. For notch 8, PM emission rates for the double-powered consist were 60 percent higher than for the single-powered consist. The inter-trip CV for a given notch position for the double-powered consist was 0.20 or lower for 7 of the 11 notch positions. The inter-trip CV for the single-powered consist was 0.20 or lower for 5 of the 11 notch positions.

4.5 Comparison among Measurements

In this section RY and OTR measurements for a given locomotive are compared to each other to assess differences in steady-state FUER. A measurement is defined as the average of multiple RY replicates measured in a given day, or the average of multiple one-way trips measured OTR for a given consist during a given multi-day period. Measurements of locomotive NC 1871 and NC 1984 are compared in Section 4.5.1 and 4.5.2, respectively.

4.5.1 NC 1871

The PME of locomotive NC 1871 was measured at a rail yard during December 2017 and June 2019, and for OTR measurements during September 2018 and March 2019. During the September 2018 measurement, five one-way trips were measured for the double-powered push/pull consist. Three one-way tips for both the double- and single-powered consists were measured during March 2019 measurements.

For OTR measurements, the engine activity variables and FUER are typically repeatable as indicated by low inter-trip CVs. However, typically very few or no steady-state data are available for notch 7, leading to variations in estimates of engine activity variables and FUER. The notch-average engine activity variables for each of these measurements are given in Figure 4-1. Notch-average engine RPM for a given notch position of a measurement was within 3 RPM of the corresponding notch-average engine RPM for other measurements for each notch position. Therefore, the notch-average RPM for a given notch position was similar for RY versus OTR measurements.

IAT is affected by ambient temperature and notch position. Given varying ambient conditions between the five measurements, it was expected that IAT would vary. However, on an absolute basis, the notch-average IAT for a given notch position of a measurement was within 2 to 10 percent of the corresponding notch-average IAT for other measurements for each notch position.

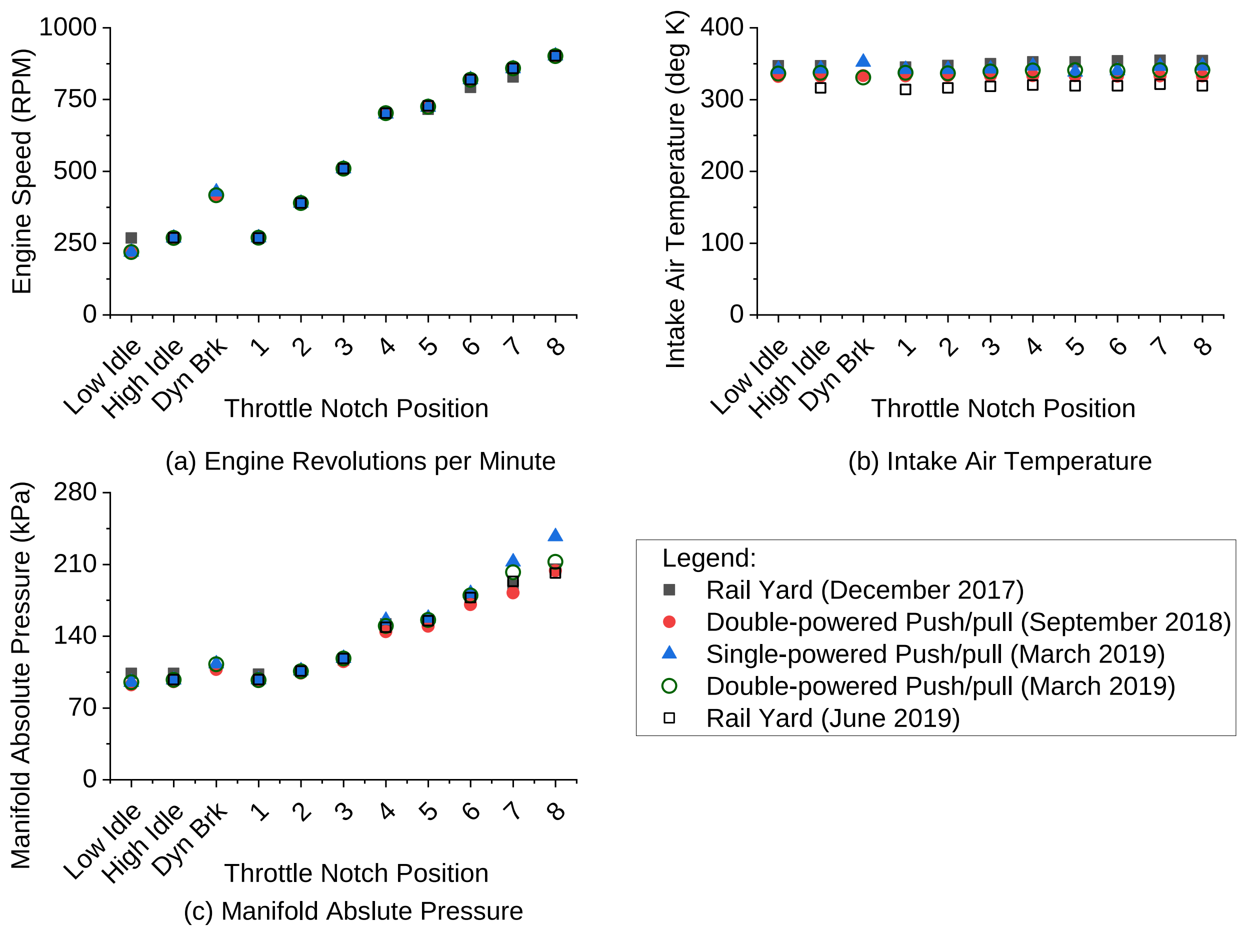


FIGURE 4-1. Comparison of Steady-State Notch-Average Engine Activity Variables for the Prime Mover Engine of Locomotive NC 1871 Between Rail Yard, Double- and Single-powered Push/Pull Over-the-Rail Measurements: (a) Engine Revolutions per Minute; (b) Intake Air Temperature; and (c) Manifold Absolute Pressure.

The notch-average MAP for a given notch position of a measurement was within 3 kPa of the corresponding notch-average MAP for other measurements for idle through notch 6. Therefore, the notch-average MAP for these positions was similar for RY versus OTR measurements. However, for notches 7 and 8, the average MAP for single-powered consist was 10 to 20 kPa higher for the same notch position compared to RY measurements and double-powered consist. This difference is consistent given that MAP was highly repeatable among replicates in the rail yard and among one-way trips over-the-rail.

The mass per time-based notch-average fuel use rates and FSEO for RY and OTR measurements are compared in Figure 4-2. For low idle through notch 3, the notch-average fuel rate for a given notch position of a measurement was within 5 percent of the corresponding notch-average fuel use rate for other measurements. For each notch position, except at notch 7, the average fuel use rate for a given notch position was typically the highest for the December 2017 RY measurement and the lowest for June 2019 RY measurement. As explained in the Section 3.4 these differences were due to differences in the notch-average IAT and CO_2 exhaust concentrations.

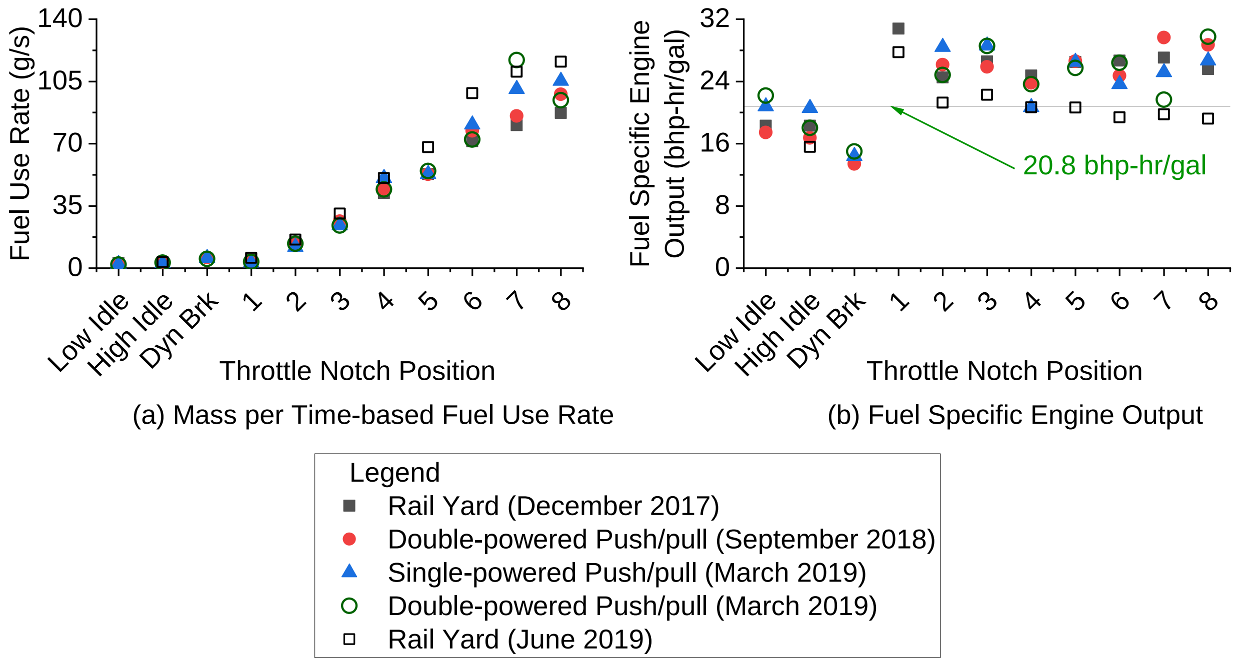


FIGURE 4-2. Comparison of Steady-State Notch-Average Fuel Use Rates for the Prime Mover Engine of Locomotive NC 1871 Between Rail Yard, Double- and Single-powered Push/Pull Over-the-Rail Measurements: (a) Mass per Time-based Fuel Use Rate; and (b) Fuel Specific Engine Output.

For double- versus single-powered consists, given in Figure 4-2(a), notch-average fuel use rates for each notch position were within 6 percent of each other. For notches 7 and 8, the average fuel use rates for the double-powered consist were 3 to 7 percent lower than for the single-powered consist because of 4 to 8 percent lower notch-average MAP for the double- versus single-powered consist.

Notch-average FSEOs, given in Figure 4-2(b), for five measurements are compared with the EPA benchmark FSEO. Notch-average FSEO for low idle, high idle and dynamic brake were typically at or below the EPA benchmark FSEO, except for low idle measured for the double-powered consist during March 2019. For notches 1 and higher, FSEO was typically equal to or greater than the EPA benchmark FSEO, except for notches 6 through 8 for the June 2019 RY measurement. Each measurement was conducted on a rebuilt locomotive. Rebuilt locomotive engines may be more fuel-efficient than the EPA benchmark measurement. Notch-average FSEOs for RY versus OTR measurements at notch 8 were lower. As discussed before, PMEs operate at reduced engine output at notches 7 and 8, leading to lower FESOs. FSEOs at notch 7 for OTR measurements were based on small sample sizes leading to large random variations.

The time-based notch-average CO_2, CO, HC, NO_x, and PM emission rates for the five measurements are illustrated in Figure 4-3. Time-based CO_2 emission rates had similar relative trends as time-based fuel use rates. The notch-average CO emission rates were based on notch-average CO concentrations below the detection limit of the Axion PEMS for low idle through notch 5, except for the double-powered September 2018 OTR and the single-powered March 2019 OTR measurements. For each measurement, average CO emission rates were 1.5 g/s or lower. The

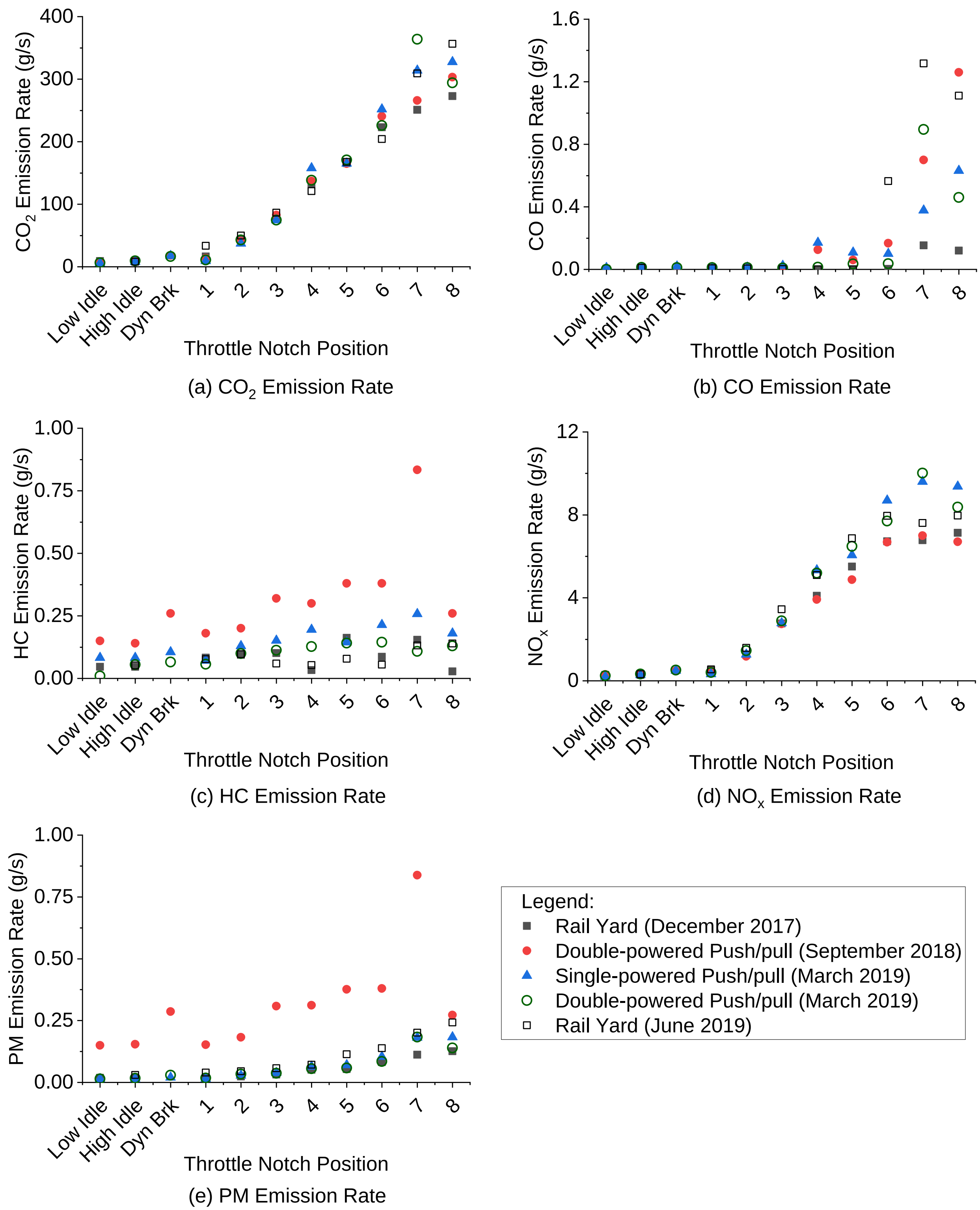


FIGURE 4-3. Comparison of Steady-State Notch-Average Time-Based Emission Rates for the Prime Mover Engine of Locomotive NC 1871 Between Rail Yard, Double- and Single-powered Push/Pull Over-the-Rail Measurements: (a) CO_2 Emission Rate; (b) CO Emission Rate; (c) HC Emission Rate; (d) NO_x Emission Rate; and (e) PM Emission Rate.

notch-average HC emission rates were typically based on notch-average HC concentrations below the detection limit of the Axion PEMS for all measurements, except for the double-powered consist measured on September 2018. For each measurement, average HC emission rates were 0.8 g/s or lower. Thus, CO and HC emission rates for the five measurements were low.

The notch-average NO_x emission rates for a given notch position were within 7 percent of each other for each of the five measurements for low idle through notch 3. For notches 4 and higher, the December 2017 RY and September 2018 double-powered OTR measurements had the lowest NO_x emission rates, whereas, the single-powered March 2019 OTR measurement typically had the highest NO_x emission rates because of higher notch-average MAP versus other measurements. The notch-average PM emission rates for idle through notch 6 were within 10 percent of each other for a given measurement, except for the double-powered OTR measurement in September 2018. For each notch position, average PM emission rates for the double-powered OTR measurement in September 2018were 3-10 times higher versus other measurements. However, at notch 8, the average PM emission rates for each of the five measurements were within 50 percent of each other. These differences were largely due to differences in notch-average IAT and MAP.

The observed differences in the measured notch-average FUER arise due to differences in notch-average IAT and MAP for the double- versus single-powered consists. For RY versus OTR measurements, differences in FUER are because of differences in measured exhaust concentrations and differences in the net engine power output at notches 7 and 8. RY measurements are more repeatable due to controlled steady-state operation and are, therefore, suitable to benchmark locomotives and to evaluate the effects of modifications such as engine rebuilds, alternate fuels, and exhaust after-treatment systems. OTR measurements are less repeatable versus RY measurements because they are subject to transients that are affected by operator behavior but provide FUER representative of actual operation. Furthermore, OTR measurements can be used to evaluate differences in FUER for different train consists.

4.5.2 NC 1984

The PME of locomotive NC 1984 was measured at a rail yard in January 2018, and for OTR measurements during June 2018 and June 2019. Only the double-powered consist was measured during the June 2018 measurements. Three one-way tips each for the double- and single-powered consists were measured during the June 2019 OTR measurement. The notch-average engine activity variables for each of these measurements are given in Figure 4-4.

The notch-average engine RPM for a given notch position of a measurement was within 3 RPM of the corresponding notch-average engine RPM for other measurements for each notch position, except for dynamic brake. Therefore, the notch-average RPM for a given notch position were similar to each other for RY versus OTR measurements, except for dynamic brake. The dynamic brake can be initiated from any throttle notch positions and therefore is variable. IAT is affected by ambient temperature and notch position. The notch-average IAT for a given notch position of a measurement was within 5 degree Kelvin of the corresponding notch-average IAT for other measurements for each notch position, except for the double-powered consist measured during June 2018. During the June 2018 measurement, the notch-average IAT for each notch position was 30 to 40 K lower than the corresponding notch-average IAT for other measurements of NC 1871.

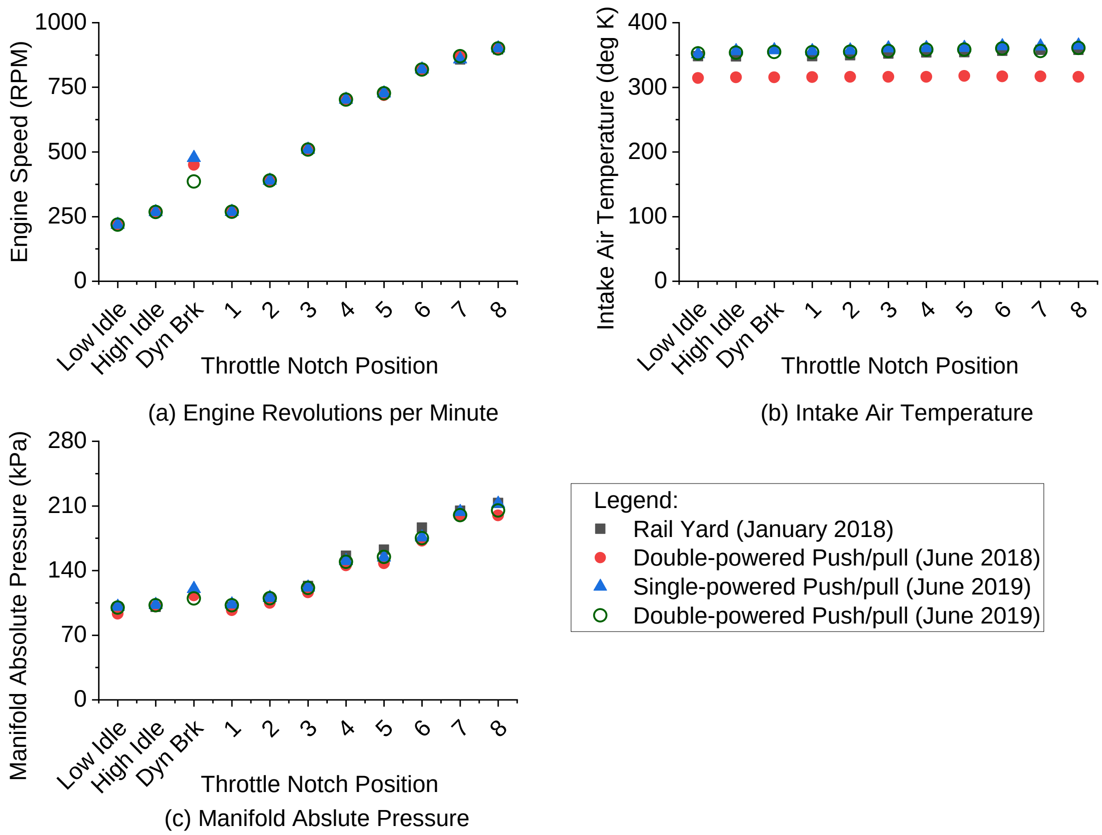
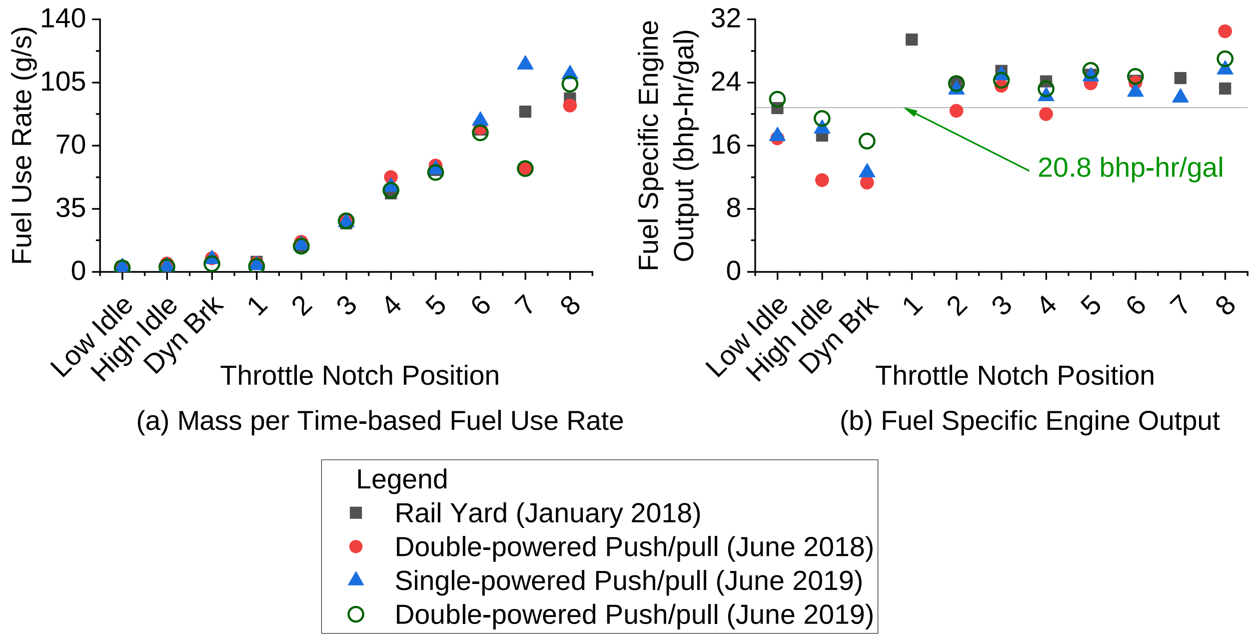


FIGURE 4-4. Comparison of Steady-State Notch-Average Engine Activity Variables for the Prime Mover Engine of Locomotive NC 1984 Between Rail Yard, Double- and Single-powered Push/Pull Over-the-Rail Measurements: (a) Engine Revolutions per Minute; (b) Intake Air Temperature; and (c) Manifold Absolute Pressure.

The notch-average MAP for a given notch position of a measurement was within 5 kPa of the corresponding notch-average MAP for other measurements for idle through notch 6. Therefore, the notch-average MAP for these positions was similar to each other for RY versus OTR measurements. However, for notches 7 and 8, the average MAP for the double-powered consist was 7 and 12 kPa lower than for the same notch position for RY measurement and the single-powered consist. This difference is consistent given that MAP was highly repeatable among replicates in the rail yard and among one-way trips over-the-rail. Differences in the average MAP for the double- versus single-powered consists for notches 7 and 8 were also measured for locomotive NC 1871.

The mass per time-based notch-average fuel use rates for RY and OTR measurements are compared in Figure 4-5(a). The notch-average fuel use rates for a given notch position for a measurement were within 6 percent of the corresponding notch-average fuel use rate for other measurements for low idle through notch 6. The large differences in the average fuel use rates at notch 7 among the four measurements were due to artifact of fewer measured steady-state data at notch 7 for OTR measurements. At notch 8, the average fuel use rate was the highest for the single-powered consist due to higher MAP versus the double-powered and higher net engine output versus RY measurement. However, the average fuel use rate differed by 7 percent or lower among the four measurements.



(a) Mass per Time-based Fuel Use Rate

(b) Fuel Specific Engine Output

FIGURE 4-5. Comparison of Steady-State Notch-Average Fuel Use Rates for the Prime Mover Engine of Locomotive NC 1984 Between Rail Yard, Double- and Single-powered Push/Pull Over-the-Rail Measurements: (a) Mass per Time-based Fuel Use Rate; and (b) Fuel Specific Engine Output.

Notch-average FSEOs among the four measurements of locomotives NC 1984 are compared to the EPA benchmark FSEO and each other in Figure 4-6(b). Notch-average FSEOs for most notch positions for each measurement were typically higher than the EPA benchmark FSEO, except for low idle, high idle and dynamic brake. Thus, the PME was typically more fuel-efficient than the EPA benchmark PME. For low idle, high idle and dynamic brake, average FSEOs different among the measurements but these are based on low fuel use rates relative to other notch positions. For notches 1 through 7, average FSEOs for a given notch position were approximately similar to each other among the four measurements. At notch 8, average FSEO was the highest for the double-powered consist measurement of June 2019 versus other measurements. For this measurement, average MAP and CO_2 concentrations at notch 8 were 3 percent and 17 percent lower, respectively, versus other measurements. In contrast, average IAT was 14 percent lower. Therefore, average FSEO at notch 8 was 12 percent higher versus other measurements.

The time-based notch-average CO_2, CO, HC, NO_x, and PM emission rates for the four measurements are illustrated in Figure 4-6. The notch-average CO_2 emission rates had the same relative trends as the notch-average fuel use rates. The notch-average CO and HC emission rates were typically based on notch-average CO and HC concentrations below the detection limit of the Axion PEMS. Thus, these latter rates were low.

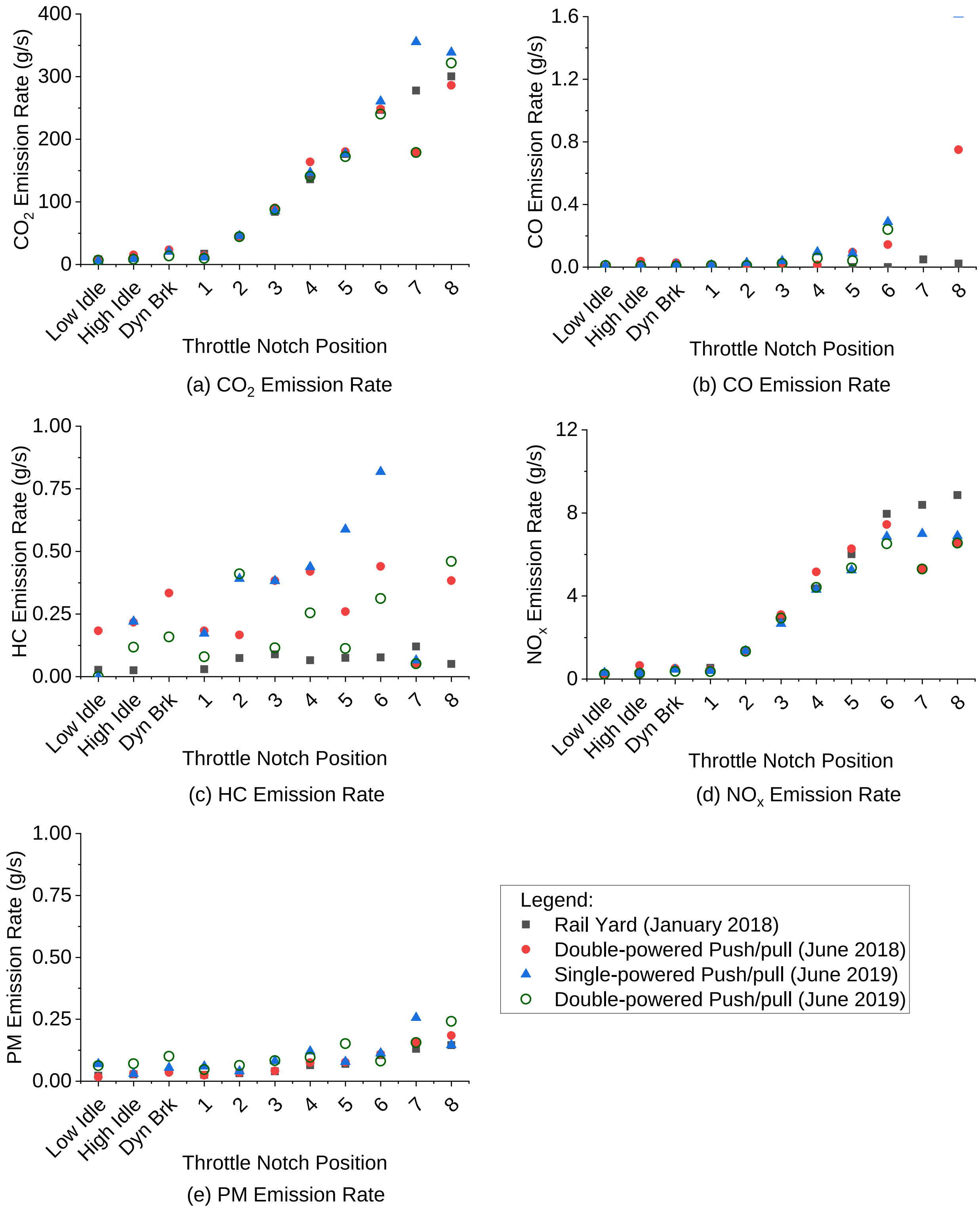


FIGURE 4-6. Comparison of Steady-State Notch-Average Time-Based Emission Rates for the Prime Mover Engine of Locomotive NC 1984 Between Rail Yard, Double- and Single-powered Push/Pull Over-the-Rail Measurements: (a) CO_2 Emission Rate; (b) CO Emission Rate; (c) HC Emission Rate; (d) NO_x Emission Rate; and (e) PM Emission Rate.

The notch-average NO_x emission rates for a given notch position for an RY replicate were within 6 percent of the notch-average rate for the corresponding notch position of OTR measurements for low idle through notch 4. For notches 5 through 8, the average NO_x emission rates were the highest for the RY measurement. For these notch positions, OTR-based NO_x emission rates were 2 to 50 percent lower versus RY-based notch-average rates. These differences were mostly due to measured notch-average NO concentrations that were 4 to 45 percent lower compared to RY measurements.

The notch-average PM emission rates for a given notch position of RY measurement was within 12 percent of the corresponding notch-average PM emission rate of OTR measurements for each notch position. Therefore, PM emission rates were approximately similar for RY versus OTR measurements and for the double- versus single-powered consists.

4.6 Comparison of Trip Fuel Use and Emissions: Steady-State versus Transients

In this section, the effect of transients on TFUE are quantified for the double- and single-powered consists. The key questions addressed in this section include: (1) are TFUE different for transient versus steady-state?; and (2) if so, are the differences similar for double- versus single-powered consists?

To quantify the differences, TFUE for steady-state versus transients were compared. To identify the most accurate approach to estimate TFUE, estimated PME trip fuel use based on alternative methods was benchmarked to the actual estimated trip PME fuel use. TFUE and estimated actual PME trip fuel use were estimated for the double- and single-powered consists of locomotives NC 1871 and NC 1984 based on the methods given in Section 2.6.4. Some of the approaches are sensitive to the percentage of missing data as explained in Section 2.6.4.

The proportion of time- and distance-based missing data and the estimated trip PME fuel consumption for both consists for NC 1871 and NC 1984 are given in Table 4-17. Fourteen one-way trips out of 23 met the data completeness criteria of having less than 5 percent missing data based on time and distance. PME trip fuel use was estimated for each of the one-way trips. The actual trip total fuel use was available for 17 out of 23 one-way trips. For the 6 one-way trips measured on locomotive NC 1871 during August 2018, the locomotive activity data recorder malfunctioned and provided implausible readings; therefore, actual trip total fuel use was not available for those trips.

On average, the estimated actual PME trip fuel use for the double-powered consist was 96 gal and ranged between 63 gal and 143 gal. On average, the estimated actual PME trip fuel consumption for single-powered consists was 197 gal and ranged between 180 gal and 240 gal.

TFUE based on the 5 approaches are presented in Figure 4.7. In Figure 4.7(a), trip PME fuel use estimated based on the 5 approaches are compared to the estimated actual trip PME fuel use. As discussed in Section 2.6.4, TFUE based on the steady rates and steady cycle (SRSC) approach are expected to be underestimated, whereas TFUE based on the steady rates actual cycle (SRAC) approach are expected to be overestimated. Of the five approaches, the estimated trip fuel use was the lowest for the SRSC and highest for the SRAC approaches for any given trip. The SRSC approach underestimated trip total fuel use on average by 38 percent and 60 percent for trips with complete data and incomplete data, respectively. The SRAC approach overestimated trip total fuel use by 40 percent and 44 percent for trips with complete data and incomplete data, respectively. Fuel use estimates based on these two approaches differed from each other by a factor of 3. The locomotives operated at steady-state for an average of only 35 percent of the trip duration. Thus, steady-state based approaches are not a suitable basis for estimating actual TFUEs based on OTR operation.

TABLE 4-17. Missing Data by Time and Distance, and Estimated Trip PME Fuel Consumption for the Double- and Single-powered Train Consist Over-the-rail Measurements of Locomotives NC 1871 and NC 1984.

Locomotive	Consist	Measurement Period	Trip	ID	Missing Data (%)[a]		Estimated PME Trip Fuel Use (gal)[b]
					by Time	by Distance	
NC 1871	Double-powered	Aug-2018	1	NC 1871 DP1	5.7	7.2	-[c]
			2	NC 1871 DP2	1.2	1.9	-[c]
			3	NC 1871 DP3	0.0	0.6	-[c]
			4	NC 1871 DP4	1.1	1.7	-[c]
			5	NC 1871 DP5	0.3	1.1	-[c]
		Jan-Feb 2019	6	NC 1871 DP6	0.3	0.9	120
			7	NC 1871 DP7	0.2	1.0	80
			8	NC 1871 DP8	0.8	1.3	70
	Single-powered	Aug-2018	1	NC 1871 SP1	4.2	4.4	-[c]
		Jan-Feb 2019	2	NC 1871 SP2	0.9	1.8	182
			3	NC 1871 SP3	0.3	1.3	182
			4	NC 1871 SP4	1.3	2.3	180
NC 1984	Double-powered	Jun-2018	1	NC 1984 DP1	3.0	4.0	111
			2	NC 1984 DP2	6.8	6.9	101
			3	NC 1984 DP3	18.6	22.1	92
			4	NC 1984 DP4	4.8	13.2	143
			5	NC 1984 DP5	29.2	29.9	82
		Jun-2019	6	NC 1984 DP6	26.7	30.0	91
			7	NC 1984 DP7	26.6	22.9	63
			8	NC 1984 DP8	2.8	6.4	109
	Single-powered	Jun-2019	1	NC 1984 SP1	1.4	2.3	190
			2	NC 1984 SP2	1.6	2.8	240
			3	NC 1984 SP3	36.1	33.1	210

[a] *Missing data by time and distance are as per Section 2.6.4.*
[b] *The estimated trip PME fuel consumption was inferred from the difference of the locomotive activity data recorder fuel display and estimated HEP engine fuel use based on Equation 2-10 of Section 2.6.4.*
[c] *The estimated PME fuel consumption for these trips was implausible based on values such as 20 gal or lower, or even negative for every one-way trip. Thus, for August 2018 measurements, the displayed fuel use was assumed to be erroneous.*

The biases for the SRSC and SRAC approaches were larger for double-powered versus single-powered consists. Compared to the single-powered consists, the double-power consists had more frequent notch transitions but lower time duration in a notch. For short durations in a notch position, steady-state may not be reached, or might be reached only for a short time leading to a large proportion of time in transients versus at steady-state. On average, transients comprised 60 percent and 30 percent of trip duration for the double-and single-powered consists, respectively.

Based on the trips with complete data, on average, SRCT, SOTR, and TRAC based PME fuel use were 7 percent, 9 percent, and 10 percent higher, respectively than the estimated actual PME fuel use. The estimated fuel use based on these three approaches was within 20 gal of the estimated PME fuel use. Hence the results for the three approaches are more accurate than those based on SRSC and SRAC approaches. When trips with incomplete data were included, on average SRCT, SOTR and TRAC based PME fuel use was 11 percent lower, 12 percent lower and 10 percent higher, respectively than the estimated actual PME fuel use. For each approach, the errors are approximately comparable to the imprecision of the estimated actual PME fuel use even for trips with incomplete data. Thus, these three approaches are robust to incomplete data. Each approach had similar biases for double- versus single-powered consists. The SRCT and TRAC approaches had the most number of trips with estimated fuel use within 10 percent of the estimated PME fuel use. The SRCT approach overestimated fuel use for trips with complete data but underestimated for trips with incomplete data. In contrast, the TRAC approach had the same average bias of 10 percent for trips with complete data versus incomplete data. The TRAC approach was insensitive to trips with complete or incomplete data, provided accurate estimates for the most number of trips and accounted for the entire trip duration. Therefore, the TRAC approach was found to be the most suitable approach for estimating trip PME fuel use.

In Figures 4.7(b), (c), (e) and (f), trip PME emissions of CO_2, CO, NO_x and PM, respectively had the same relative trends as the estimated trip PME fuel use for the five approaches because emission rates of these species increase monotonically with notch position, similar to the fuel use rate. Therefore, the biases associated with each approach for emissions were similar to the biases associated with fuel use for the corresponding approach. However, HC emission rates did not increased monotonically with the notch position for the measured locomotives leading to approximately similar notch-average HC emission rates for several notches. Since transitions occasionally occur between notches with similar HC emission rates, steady-state and transient-based HC emission rates may not differ substantially from each other leading to less bias for steady-state versus transients for HC emissions. Therefore, any approach is suitable for estimating trip HC emissions.

On average, locomotives operate at steady-state for 35 percent of the trip duration but contribute between 38% and 60% to the trip fuel use and emissions. Average rates are higher for steady-state operation versus transient operation. Therefore, TFUEs based on steady-state operation extrapolated for the entire trip duration will be overestimated. For trips with complete data, the SOTR and TRAC approaches provide the most accurate estimates of TFUEs. For trips with incomplete data, the TRAC approach is the most suitable approach. Thus, the TRAC approach is robust.

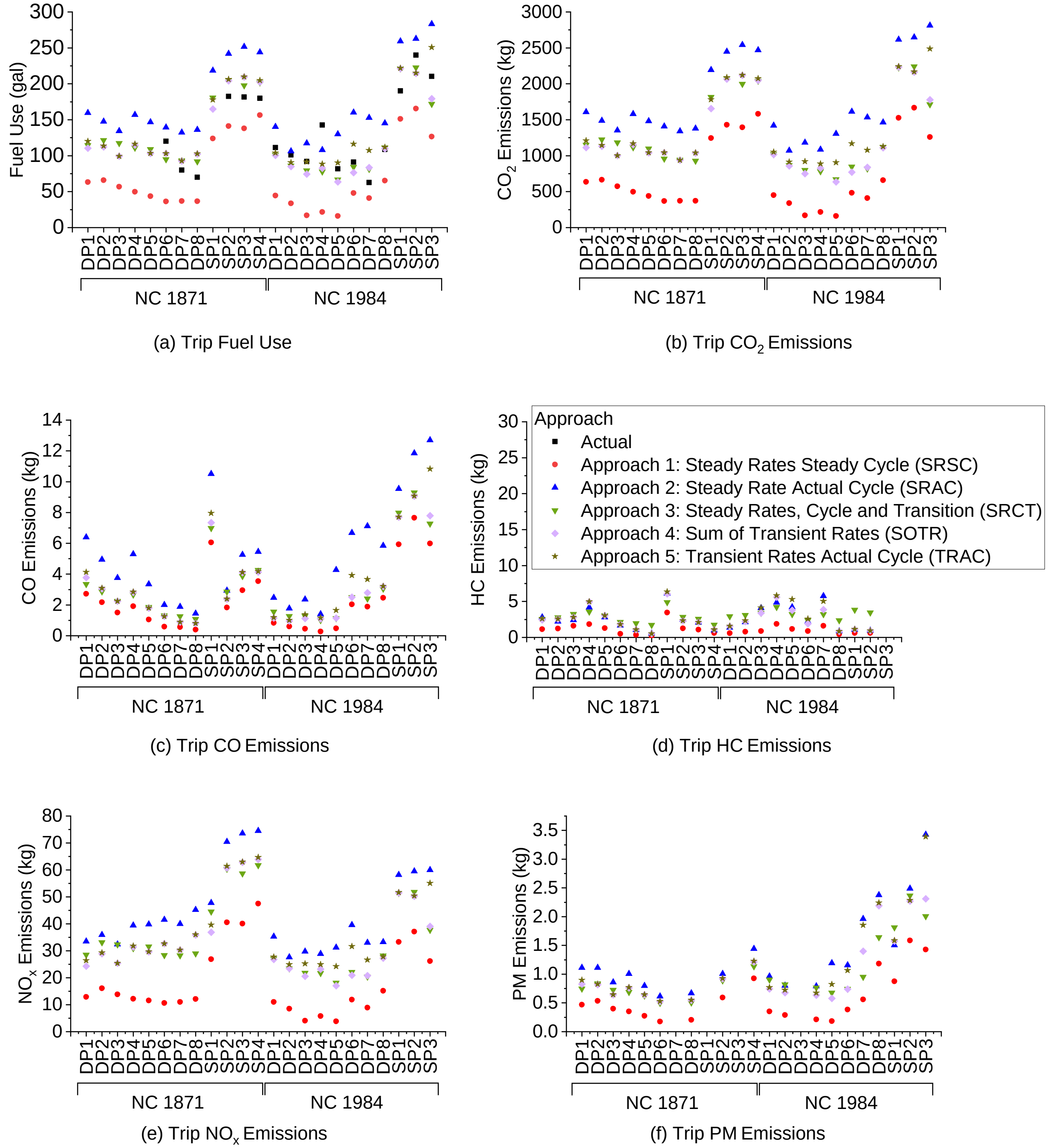


FIGURE 4-7. Comparison of Trip Prime Mover Engine Fuel Use and Emissions for the Double- and Single-Powered Consist Over-the-rail Measurements of Locomotives NC 1871 and NC 1984 for 5 Approaches: (a) Fuel Use; (b) CO_2 Emissions; (c) CO Emissions; (d) HC Emissions; (e) NO_x Emissions; and (f) PM Emissions.

Only Actual Trip PME Fuel Use was Measured. On the x-axis of each figure, DP and SP refer to the double- and single-powered consists, respectively. The number indicates the trip number (See Table 4-17). NC 1871 DP1, NC 1984 DP2 to NC 1984 DP8 and SP3 had more than 5 percent missing data.

4.7 Comparison of Trip Fuel Use and Emissions: Double- versus Single-powered Consists

In this section, TFUE were estimated for the double-versus single-powered consists conducted on NC 1871 and NC 1984 to quantify if the average trip totals for fuel use and emissions different for the double-versus single- powered consists. TFUEs were estimated based on the TRAC approach.

More time delays were typically encountered for the double- versus single-powered consists. However, these delays were not due to the consist. These delays were because of rail maintenance or heavy rail traffic. Therefore, to have a consistent comparison for the trade-offs of the double-versus single-powered consists, the trip durations for both were made to be equal. The difference between the average trip duration for the double- and single-powered consists was estimated. This time difference added to each trip of the double-powered consist such that the average trip duration for the two consists was the same. Both locomotives in the consist were assumed to be operating at low idle during the estimated incremental delay period. This assumption was made because such delays are typically associated with additional idling time. Results are given in Table 4-18.

Measured for locomotive NC 1871, the double-powered consist had 18 to 154 percent lower train total TFUEs versus the single-powered consist for fuel use and emissions of CO_2, CO, HC, NO_x and PM. Measured for locomotive NC 1984, train total TFUE for the double-powered consist had 1 to 41 percent lower trip total fuel use and emissions of CO_2, CO, and NO_x. However, HC and PM emissions were 76 and 17 percent higher, respectively for the double-powered consists. Thus, the differences between consists in TFUE may be different for different locomotives operated in a consist. Based on measurements of two locomotives, double-powered push/pull consist has a 19% lower trip average fuel consumption and CO_2 emissions versus single-powered push/pull consist. Trip average CO and NO_x emissions were 62 percent and 9 percent lower, respectively. In contrast, trip average HC and PM emissions were 40 percent and 3 percent higher. The double-powered push/pull consist is preferred in terms of fuel savings and emissions reductions emissions of CO_2, CO, and NO_x with trade-offs of higher HC and PM emissions versus the single-powered consist.

Higher HC and PM emissions can be mitigated by switching to B20 biodiesel fuel for the double-powered consists. Overall, the double-powered consist is a better choice for both locomotives in terms of fuel savings and reducing emissions of CO_2, CO, and NO_x. However, given the variability in HC and PM emissions for the two consists, more locomotives should be compared to estimate the fleet average trade-offs of the double-versus single-powered consists.

4.8 Benchmarking Among Locomotives and Standards

Locomotive FUER depend on exhaust flow rate and exhaust concentrations. Exhaust flow rate depends on air flow rate and fuel/air ratio. Fuel flow rate depends on the air flow rate and fuel/air ratio. The fuel/air ratio can be inferred from exhaust composition. Air flow rate depends on RPM, MAP, and IAT. Thus, variability in RPM, MAP, and IAT for a given notch position among locomotives can lead to inter-locomotive variability in air flow rate and, ultimately, in fuel use and emission rates. Therefore, the inter-locomotive variability in RPM, MAP, and IAT is identified to help explain inter-locomotive variability in fuel use and emission rates. Differences in FUER may also arise based on how the fuel injection is governed. Electronically-governed PMEs provide more precise timing of fuel injection and help reduce FUER versus mechanically-governed fuel injection (EPA 1998).

In this section, steady-state notch-average engine activity variables including engine output, RPM, IAT, and MAP, FUER and CAER based on OTR measurements for the NCDOT locomotives are benchmarked to each other and to RY measurements. Notch-average engine output and engine activity variables, FUER and CAER for locomotives other than NC 1871 and NC 1984 were taken from prior work (Frey *et al.*, 2016; Graver and Frey, 2013). For any locomotive with more than one OTR measurement for a consist, results from the most recent measurement were used. All of the locomotives except for NC 1792 were measured after a rebuild. Locomotives NC 1859, NC 1871 and NC 1984 were measured twice: for these, the results of the most recent measurements for each consist are presented. Locomotive NC 1792 was taken out-of-service after a rebuild before OTR measurements could be conducted. Therefore, the results of NC 1792 are based on pre-rebuild OTR measurements.

The engine activity variables for a given locomotive based on OTR measurements are compared to other locomotives and to RY measurements in Section 4.8.1. In Sections 4.8.2 and 4.8.3, the steady-state based notch-average FUER based on OTR measurements are compared for each locomotive consist and are benchmarked to the EPA reported data for the same model PMEs. In Section 4.8.4, steady-state notch-average FUER are weighted to the EPA line-haul duty cycle and to three real-world average Piedmont duty-cycles to estimate CAER and benchmark to the EPA line-haul duty cycle-based emission standards.

TABLE 4-18. Train Total Fuel Use and Emissions for an Entire Train with Equal Duration Trips for Double- versus Single-powered Train Consists based on Transient Data for Over-the-rail Measurements of Locomotives NC 1871 and NC 1984 Conducted during January-February 2019 and June 2019, respectively.

Train Total[a]	Locomotive NC 1871			Locomotive NC 1984		
	Double-powered	Single-powered	Percent Difference with respect to Double-powered Consist (%)	Double-powered	Single-powered	Percent Difference with respect to Double-powered Consist (%)
Fuel Use (kg)	514	661	-29	642	718	-12
CO_2 (kg)	1602	2057	-28	1928	2140	-11
CO (g)	1300	3300	-154	5600	7900	-41
HC (g)	2400	3200	-33	4900	1200	76
NO_x (kg)	54	64	-18	52	52	-1
PM (g)	1000	1300	-30	2300	1900	17

[a] *The train total fuel use and emissions (TFUEs) for each locomotive and consist were estimated based on Approach 5: transient rates and actual cycles (TRAC) approach.*

4.8.1 Steady-State Engine Activity Variables

This section evaluates inter-locomotive variability in engine activity variables, which leads to inter-locomotive variability in FUER. Steady-state notch-average engine activity variables, including net engine output, RPM, IAT, and MAP for each of the NCDOT locomotives, are given in Table 4-19. All of the PMEs have a rated power output of 3000 hp. The notch-average net engine output increased monotonically with notch position for each PME. For each PME, engine power output displayed by the locomotive activity recorder at idle position(s) and during dynamic brake was zero. However, engine power output was assumed to be 9 hp based on prior dynamometer measurements of one EMD 12-710 PME which the same model of PME in all F59PH and F59PHI locomotives. Engine output at idle and dynamic brake for the GP40 locomotive was assumed to be 20 hp based on a prior dynamometer measurement (Graver and Frey, 2013).

The power output for a given notch position is the same among locomotives in most cases. For a given notch position, the power output is the same for the GP40, F59PHI, and mechanically-governed F59PH locomotives. Compared to other locomotives, the power output for the electronically governed F59PH locomotives is 40 to 60 hp lower in notches 1 and 2, and 50 to 400 hp higher in notches 4 through 6. However, all of the locomotives have the same power output in notches 7 and 8. Differences in notch power output between the electronically governed F59PH locomotives and other locomotives contribute to differences in cycle-average rates on a per hp-hr basis. For each of the locomotives, the OTR-based notch-average engine output for a given notch position was the same as the RY-based notch-average engine output for the same notch position of the same locomotive, except for notches 7 and 8. For notches 7 and 8, the engine output for OTR measurements was higher than for RY measurements, as explained in Section 4.5.

Notch-average engine air flow rate (g/s) is proportional to notch-average RPM and MAP and inversely proportional to notch-average IAT. Therefore, differences in the values of these variables lead to differences in notch-average air flow rate. Such differences contribute to inter-locomotive variability in FUER.

The notch-average engine RPM for a given notch position was generally within 3 percent within, but not between, each of the following four locomotive groups: (1) F59PHI; (2) F59PH with mechanically governed fuel injection; and (3) F59PH locomotives with electronically governed fuel injection, except for NC 1893; and (4) GP40. The notch-average RPM differed between locomotive groups by more than 3 percent particularly for idle, dynamic brake and notches 1 through 6. At notch 7, all locomotives, except for the electronically-governed F59PH locomotives, had RPM within 3 percent of each other. At notch 8, all locomotives had RPM within 3 percent of each other. For each of the locomotives, the OTR-based notch-average RPM was comparable to the RY-based notch-average RPM for a given notch position of the same locomotive.

The notch-average IAT varies based on notch position and ambient temperature. The highest and the lowest notch-average IAT for OTR measurements for a given locomotive typically differed by 15 K. IAT was typically the lowest at idle and highest at notch 8 for each locomotive. For adjacent notch positions, typically the difference was less than 2 K. The notch-average IATs for OTR measurements differed from the notch-average IATs for RY measurements for the same locomotive because of differences in ambient temperatures.

TABLE 4-19. Steady-State Notch-average Engine Activity Variables for the Most Recent Over-the-rail Measurement of the Prime Mover Engines of NCDOT-owned Locomotives: (a) Net Engine Output; (b) Engine Revolutions per Minute; (c) Intake Air Temperature; and (d) Manifold Absolute Pressure.

Model	GP40	F59PHI		F59PH								
Fuel Injection	Mech-anical	Electronic		Mechanical					Electronic			
Locomotive	NC 1792	NC 1755	NC 1797	NC 1810	NC 1859		NC 1869	NC 1893	NC 1871		NC 1984	
Consist[a]	Single					DP-T[a]	Single		SP-PP[a]	DP-PP[a]	SP-PP[a]	DP-PP[a]
Notch Position	Net Engine Output (hp)											
Low Idle	20[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]
High Idle	20[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]
DB[b]	20[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]	9[c]
1	190	190	190	190	190	190	190	190	130	130	130	130
2	350	350	350	350	350	350	350	350	310	310	310	310
3	675	675	675	675	675	675	675	675	675	675	675	675
4	1000	1000	1000	1000	1000	1000	1000	1000	1050	1050	1050	1050
5	1300	1300	1300	1300	1300	1300	1300	1300	1450	1450	1450	1450
6	1600	1600	1600	1600	1600	1600	1600	1600	2000	2000	2000	2000
7	2700	2700	2700	2700	2700	2700	2700	2700	2700	2700	2700	2700
8	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
	Engine Revolutions per Minute (RPM)											
Low Idle	297	343	343	238	237	238	370	198	219	219	219	219
High Idle	297	343	343	384	369	370	370	349	268	268	268	268
DB[b]	536	343	343	389	386	385	370	368	428	417	477	386
1	323	342	343	379	369	370	370	349	268	268	268	268
2	381	342	343	380	369	368	369	347	389	389	389	389
3	500	489	490	484	491	492	492	489	509	509	509	509
4	566	651	651	557	564	564	564	568	700	702	703	702
5	657	748	750	651	651	652	653	651	723	725	727	727
6	725	749	750	725	728	729	731	731	819	819	819	818
7	826	818	819	823	819	821	821	825	858	858	859	870
8	899	903	903	905	902	902	904	907	902	901	901	901

Table 4-19 Continued on next page.

Table 4-19 Continued from previous page.

Model	GP40	F59PHI		F59PH								
Fuel Injection	Mech-anical	Electronic		Mechanical					Electronic			
Locomotive	NC 1792	NC 1755	NC 1797	NC 1810	NC 1859		NC 1869	NC 1893	NC 1871		NC 1984	
Consist[a]	Single					DP-T[a]	Single		SP-PP[a]	DP-PP[a]	SP-PP[a]	DP-PP[a]
Notch Position	Intake Air Temperature (K)											
Low Idle	284	319	320	339	343	349	308	338	342	336	352	353
High Idle	284	319	320	342	348	350	307	342	342	337	356	354
DB[b]	286	319	320	341	348	349	307	341	352	331	358	355
1	284	319	321	341	349	349	307	341	342	337	356	354
2	284	320	321	342	347	349	307	342	342	336	357	355
3	284	320	321	342	348	346	308	342	342	339	360	356
4	283	321	321	343	349	350	308	343	346	340	361	358
5	282	319	321	344	350	349	308	344	338	341	361	358
6	282	322	321	344	350	350	308	344	340	340	364	360
7	288	322	322	346	350	351	308	351	346	341	364	356
8	286	324	322	346	352	349	308	346	346	341	365	361
Manifold Absolute Pressure (kPa)												
Low Idle	103	110	105	98	100	98	101	102	95	95	101	100
High Idle	104	109	106	108	108	106	109	110	97	97	103	102
DB[b]	128	109	106	108	109	108	110	111	113	112	120	110
1	106	109	106	109	110	106	110	110	98	97	103	102
2	110	110	106	109	110	106	110	111	106	106	111	110
3	125	124	120	119	122	119	121	123	118	118	122	121
4	132	149	144	129	132	129	129	135	155	150	150	149
5	147	170	164	146	146	144	143	147	158	156	154	155
6	161	172	165	158	160	159	157	163	182	180	176	175
7	188	197	185	194	179	192	176	199	212	202	203	200
8	213	234	216	241	227	214	218	239	237	212	212	205

[a] *Abbreviations for consist: (1) DP-T: Double-powered tandem; (2) DP-PP: Double-powered push/pull; and (3) SP-PP: Single-powered push/pull*

[b] *DB = Dynamic Brake*

[c] *The locomotive activity recorder screen displays zero output at idle. Therefore, output was assumed from prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).*

The notch-average MAP for a given notch position for a given locomotive was within 5 kPa of that measured in the RY, except for single-powered push/pull consists at notches 7 and 8. The average MAP for notches 7 and 8 was 5 kPa to 20 kPa higher for the double- versus single-powered consists. Differences in MAP proportionately affect FUER. Given that notch-average engine activity variables differ among the same model PMEs and across difference model PMEs, notch-average FUER are expected to vary among locomotives for a given notch position. The inter-locomotive variability in FUER is discussed in the next section.

4.8.2 Steady-State Fuel Use Rates

In this section, steady-state fuel use rates based on OTR measurements are compared among different locomotives to EPA reported data for the same model PMEs. The FSEO for each locomotive is compared to EPA reported data. Steady-state based notch-average fuel use rates were weighted to the percent total time in each notch position corresponding to a duty cycle to estimate FSEO, as explained in Section 2.6. The steady-state notch-average fuel use rates versus notch position and notch average output and FSEO based on OTR measurements of the PMEs operated on ULSD for each of the NCDOT locomotives are given in Figures 4-8(a), 4-8(b) and 4-8(c), respectively.

For each of the locomotives, and on average, the steady-state notch-average fuel use rates increased monotonically with increasing notch position, as indicated in Figure 4-8(a). Dynamic brake can be initiated from any notch position leading to variability in average fuel use rate at dynamic brake. Although on average the fuel use rate in notch 7 was higher than in notch 6 and lower than that in notch 8, there were some exceptions to this trend for individual locomotives. These exceptions occurred because of artifacts of small sample sizes during steady-state operation. For low idle through notch 3, the notch-average fuel use rates for a given notch position of a locomotive were within 5 percent of the corresponding notch-average fuel use rates of other locomotives. These differences were larger for notches 4 thorough 8 and were the highest at notch 8, mainly due to differences in notch-average MAP as explained in Section 4.8.1. In general, especially at notch 8, fuel use rates were the highest, among all locomotives, for NC 1792, followed by single-operated mechanically-governed F59PH locomotives. Fuel use rates were similar for F59PHIs and the single-powered push/pull consist of electronically-governed F59PH locomotives. The double-tandem consist for NC 1859 and the double-powered push/pull consists of NC 1871 and NC 1984 typically had the lowest fuel use rates, especially at notch 8, as explained in Section 4.5.

Measured notch-average fuel use rate rates were compared with notch-average fuel use rates reported by the EPA based on engine dynamometer measurements for EMD 16-645E3 and EMD 12-710G3A PMEs (EPA, 1998). These are similar to the engine models of the GP40 and the other measured locomotives, respectively. Notch-average mass per time-based fuel use rates for EMD 16-645E3 and EMD 12-710G3A PMEs are given in Tables D-16 and D-17 of Appendix D, respectively. For locomotive NC 1792, notch-average fuel use rates were within 3 to 10 percent of the EPA reported fuel use rates for EMD 16-645E3 PMEs. Typically for each notch position, OTR-based notch-average fuel use rates for the EMD 12-710G3A PMEs were 1 to 25 percent lower than those reported by EPA for EMD 12-710G3A PMEs. At notch 8, the differences were less than 8 percent. The measured and reported notch-average rates are consistent. Thus, the measured locomotives typically had fuel use rates similar to or somewhat lower than the EPA reported rates. The lower rates could be related to the effect of engine rebuilds which can increase fuel efficiency.

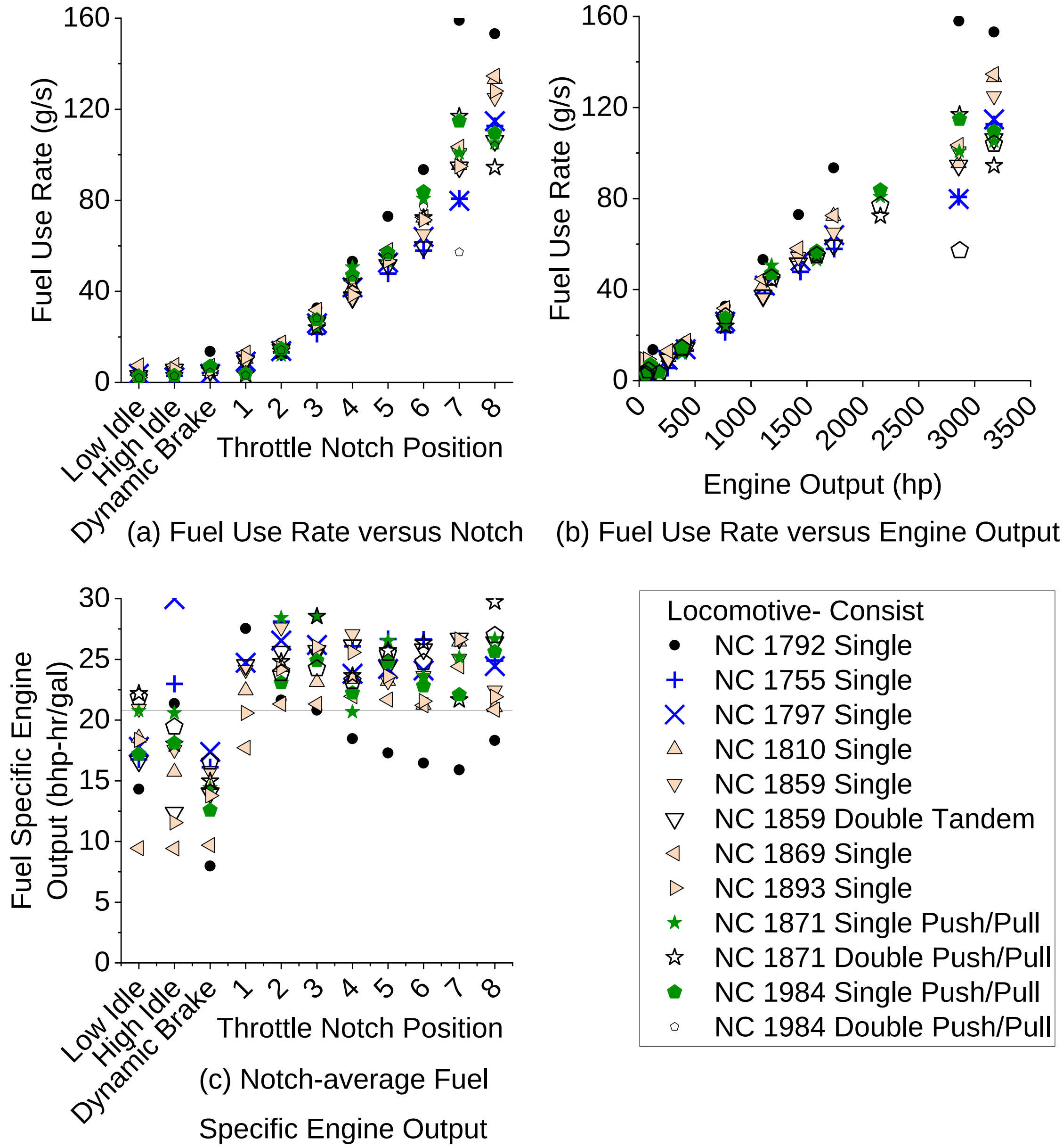


FIGURE 4-8. Steady-State based Notch-average Fuel Use Rates and Fuel Specific Engine Output for the Most Recent Over-the-rail Measurement of the Prime Mover Engines of all NCDOT Locomotives Operated on Ultra-low Sulfur Diesel: (a) Notch-average Fuel Use Rate versus Notch Position; (b) Notch-average Fuel Use Rate versus Engine Output; and (c) Notch-average Fuel Specific Engine Output.

Given the variability in engine activity variables among locomotives for a given notch position, fuel use rates versus engine output are compared. A plot of fuel use rate versus engine output given in Figure 4-8(b) indicates that notch-average fuel use rates vary approximately linearly with engine output of 2000 hp or lower. Each of the locomotives have approximately similar fuel consumption to provide a power output of up to 2000 hp with the exception of NC 1792. Fuel use rates for NC 1792 were measured before the locomotive was rebuild. The fuel consumption of NC 1792 decreased after the rebuild based on RY measurements. However, OTR measurements could not be conducted for NC 1792 after the rebuild because the locomotive was destroyed in a grade crossing accident prior to a scheduled post-rebuild OTR measurement. Fuel use rates differed for outputs greater than 2000 hp among locomotives. The differences among locomotives were highest for 3200 hp output, corresponding to notch 8. At higher output, locomotives with electronically-governed fuel injection had lower fuel use rate per unit output versus locomotives with mechanically-governed fuel-efficient. Notch 8 has the highest fuel use rate and the operators typically spend between 25 percent and 50 percent of the trip duration in notch 8. Differences in FUER at notch 8 among locomotives may lead to substantial differences in CAERs and TFUEs. A locomotive with a lower average fuel use rate at notch 8 will typically have lower trip fuel use versus other locomotives.

FSEO is a normalized indicator of fuel consumption rate that can be compared to a benchmark value. FSEO is proportional to engine efficiency as explained in Section 2.6.3. The notch-average FSEOs are given in Figure 4-8(c). The PMEs had lower engine efficiencies at idle and during dynamic brake compared to the EPA benchmark. The observed OTR based FSEOs for notches 1 and higher were typically higher than the EPA benchmark FSEO for mid-1990 locomotives. Compared to RY measurements, locomotives were more energy-efficient for OTR measurements.

The cycle-average FSEO given in Figure 4-9 were estimated based on the EPA line-haul duty cycle and the corresponding real-world Piedmont duty cycle: single operation; single-powered push/pull and double-powered push-pull consists. The method to estimate cycle-average FSEO and the Piedmont duty cycles are given in Section 2.6. The double-powered consists of NC 1871 and NC 1984 had the highest FSEOs followed by double-tandem measurement of NC 1859 for each duty cycle. All of the locomotives, except for NC 1792 and NC 1869, had higher FSEOs for than the EPA benchmark FSEO. Although slightly lower than the benchmark value, the FSEO of NC 1869 was between 20.0 and 20.8 bhp-hr/gal; therefore, it was not substantially different than the benchmark value. NC 1792 was expected to have lower FSEO because NC 1792 was measured many years after a prior PME rebuild; therefore, the relatively low FSEO may have been related to engine wear.

The results here indicate that the NCDOT locomotives are typically more fuel-efficient than the EPA benchmark. The inter-locomotive variability in the fuel use rates indicates the potential to reduce fuel consumption for NCDOT passenger rail operations by operating more fuel-efficient locomotives more frequently than other less fuel-efficient locomotives. For example, locomotives NC 1871 and NC 1984 typically have the highest cycle-average FSEOs based on single- and double-powered push/pull consists. In contrast, locomotives NC 1810, NC 1869, and NC 1893 have lower FSEO based on single-locomotive consists. Although, these numbers are not directly comparable, because the consists differ, and because a given locomotive is typically more efficient fuel-efficient in a double-locomotive consist, the results are indicative that overall fuel use should be reduced for Piedmont train operations by preferentially running more fuel-efficient locomotives more frequently.

4.8.3 Steady-State Emission Rates

Notch-average mass per time-based CO_2, CO, HC, NO_x, and PM emission rates based on OTR measurements of the PMEs operated on ULSD for each of the NCDOT locomotives are given in Figure 4-10. The emission rates were estimated for steady-state operation as explained in Section 2.6. Notch-average mass per engine output-based emissions rates of CO, HC, NO_x, and PM for EMD 16-645E3 and EMD 12-710G3A PMEs reported by the EPA are given in Tables D-16 and D-17 of Appendix D, respectively. These reported rates were converted to mass per time-based rates using the reported engine output.

The measured notch-average CO_2 emission rates had the same relative trend as fuel use rates. The measured notch-average CO emission rates were typically based on CO concentrations below the detection limit of the Axion PEMS for low idle through notch 5, similar to RY measurements. Therefore, CO emission rates for these locomotives were low at low notch positions. The highest average CO emission rate was 2 g/s for both OTR and RY measurements at notch 8 and was 0.7 g/s on average at notch 8. The EPA reported CO emission rate at notch 8 for EMD 16-645E3 and EMD 12-710G3A PMEs are 1.6 g/s and 1.2 g/s, respectively. Thus, the measured and reported rates were consistent.

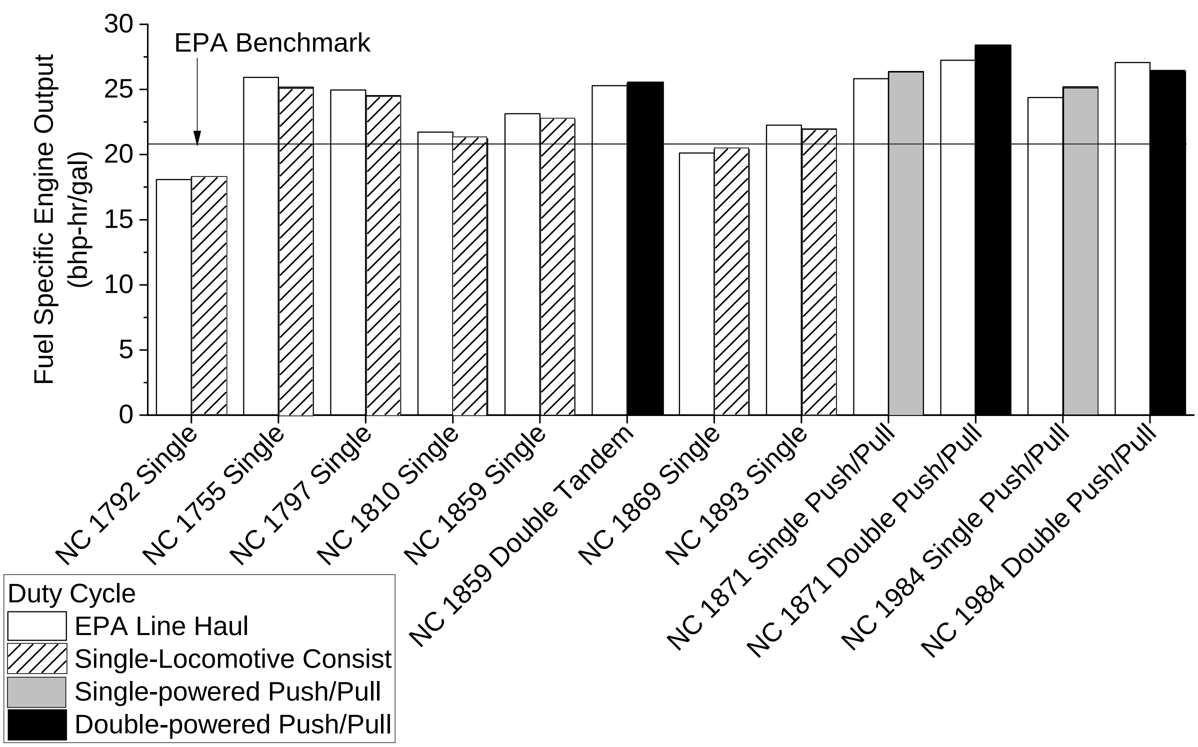


FIGURE 4-9. The EPA Line-Haul and Piedmont Duty Cycles based Fuel Specific Engine Output Estimated based on Steady-State Fuel Use Rates for the Most Recent Over-the-rail Measurement of the Prime Mover Engines of all NCDOT Locomotives Operated on Ultra-low Sulfur Diesel.

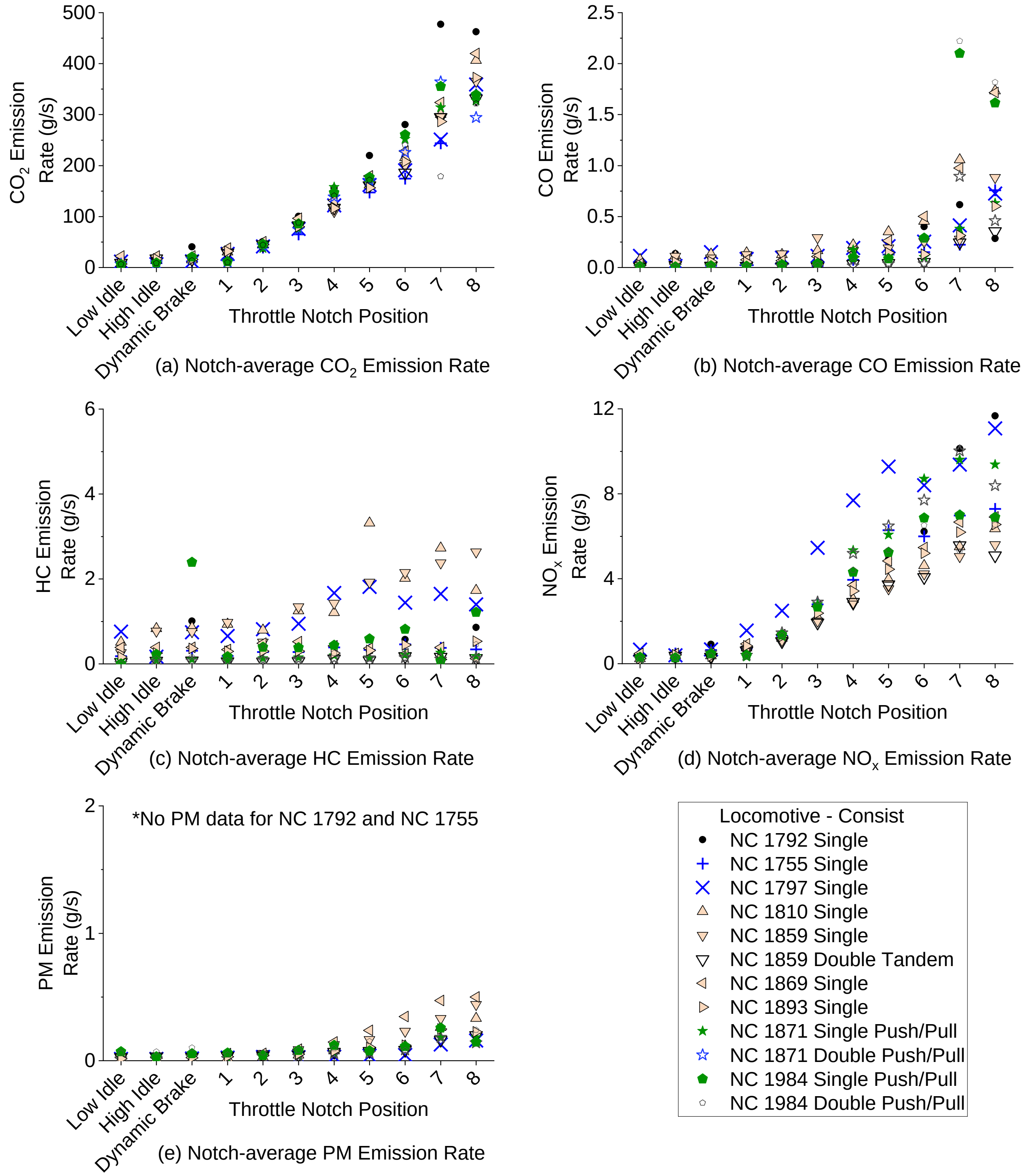


FIGURE 4-10. Steady-State Notch-Average Emission Rates for the Most Recent Over-the-rail Measurement of the Prime Mover Engines of all NCDOT Locomotives Operated on Ultra-low Sulfur Diesel: (a) CO_2 Emission Rate; (b) CO Emission Rate; (c) HC Emission Rate; (d) NO_x Emission Rate; and (e) PM Emission Rate.

The measured notch-average HC emission rates were typically based on HC concentrations below the detection limit of the Axion PEMS for most of the notch positions. The notch-average HC emission rates were 4 g/s or lower for each of the OTR measurements and 0.5 g/s or lower for 8 of the 12 OTR locomotive measurements. The EPA reported HC emission rate for EMD 16-645E3 and EMD 12-710G3A PMEs at notch 8 are 0.3 g/s and 0.1 g/s, respectively. Measured notch-average HC emission rates were typically several orders of magnitude higher compared to the EPA reported data. For most NCDOT locomotives and PME notch positions, the measured exhaust concentrations were below the gas analyzer detection limit. Therefore, the differences in HC emission rates compared to the EPA reported rates are not significant.

The measured notch-average NO_x emission rates for a given notch position were the lowest for mechanically-governed F59PH locomotives and the highest for F59PHI and electronically-governed F59PH locomotives for each notch position. The EPA-reported NO_x emission rate at notch 8 for EMD 16-645E3 and EMD 12-710G3A PMEs are 10.3 g/s and 8.5 g/s, respectively. NO_x emission rates at notch 8 were 8.5 g/s or lower for 8 of the 12 locomotive-consist measurements. Therefore, the measured NO_x emission rates are approximately similar to the EPA reported emission rates, indicating agreement with the EPA reported data.

In contrast to the inter-locomotive trend for measured NO_x emission rates, the notch-average PM emission rates for a given notch position were the highest for mechanically-governed F59PH locomotives and the lowest for F59PHI and electronically-governed F59PH locomotives for each notch position. No PM data were available for NC 1792 and NC 1755. The EPA-reported PM emission rate at notch 8 for EMD 16-645E3 and EMD 12-710G3A PMEs are 0.23 g/s and 0.20 g/s, respectively. The average PM emission rates at notch 8 were 0.4 g/s or lower for each of the locomotives and 0.21 g/s on average for all locomotives. Therefore, PM emission rates measured here indicate good agreement with the EPA reported data.

4.8.4 Cycle-Average Emission Rates and Emission Standards

To compare with the standards, CAER based on the EPA line-haul duty cycle and the corresponding Piedmont duty-cycle were estimated based on OTR measurements for CO_2, CO, HC, NO_x and PM for all locomotives and consists. Steady-state based notch-average FUER were weighted to the percent total time in each notch position corresponding to a duty cycle to estimate CAER based on the Steady-Rates Actual Cycle Approach (SRAC) given in Section 2.6.

The EPA has set emission standards for CO, HC, $NO_{x,}$ and PM. Although the EPA has not set emission standards for CO_2 emissions from locomotive engines, a typical CO_2 emission rate can be inferred from the EPA benchmark fuel specific engine output of 20.8 bhp-hr/gal. CO_2 emission rate corresponding the EPA benchmark FSEO was inferred by assuming 100% conversion of C in fuel to CO_2, and 87 wt% carbon content in the fuel. The inferred CO_2 emission rate corresponding the EPA benchmark FSEO was 480 g/bhp-hr. Thus, cycle average CO_2 emission rates for the NCDOT locomotives are compared to an inferred benchmark value.

The PMEs of the locomotives are certified to the Tier 0+ standard. A description of the emissions standards, applicability, and CAER corresponding to each standard are given in Appendix C. CAER are given in Figure 4-11. Cycle-average CO_2 emission rates are given in Figure 4-11(a).

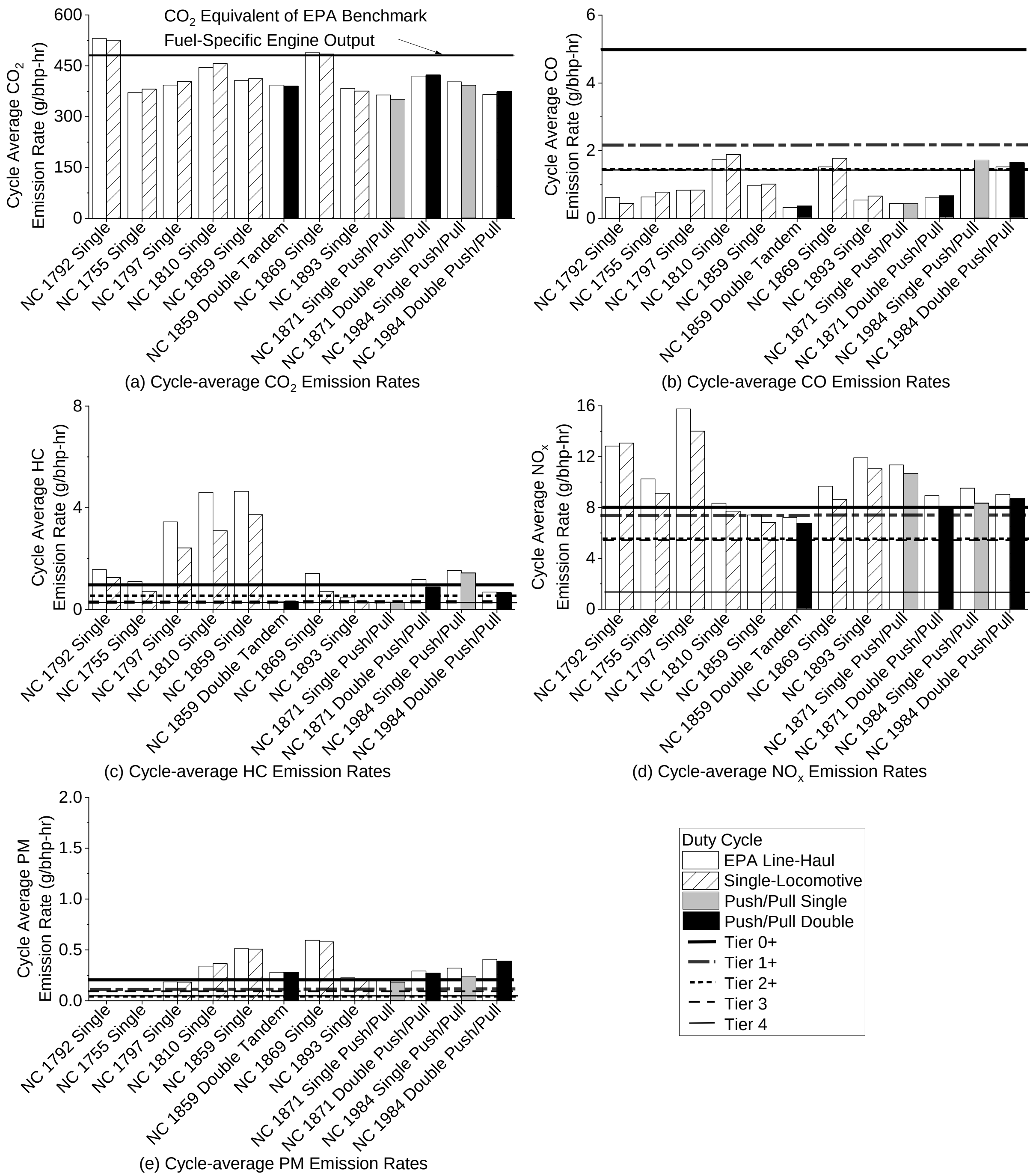


FIGURE 4-11. The EPA Line-haul and Piedmont Duty Cycle based Average Emission Rates Estimated based on Steady-State Emission Rates for the Most Recent Over-the-rail Measurement of the Prime Mover Engines of all NCDOT Locomotives Operated on Ultra-Low Sulfur Diesel: (a) CO_2 Emission Rate; (b) CO Emission Rate; (c) HC Emission Rate; (d) NO_x Emission Rate; and (e) PM Emission Rate. CO_2 emission rate corresponding the EPA benchmark FSEO was inferred by assuming 100% conversion of C in fuel to CO_2, and 87 wt% carbon content in the fuel.

Cycle-average CO_2 emission rates for the four duty-cycles for a given locomotive consist were within 2 percent of each other. Therefore, cycle-average CO_2 emission rates were approximately the same for different duty cycles. The trend in cycle-average CO_2 emission rates is inverse to the trend of cycle-average FSEOs. Therefore, more efficient engines have lower CO_2 emission rates.

Cycle-average CO emission rates given in Figure 4-11(b) varied from 0.5 g/bhp-hr for the double-tandem NC 1859 to 2.0 g/bhp-hr for the double-powered push/pull consist of locomotive NC 1859. There is large inter-locomotive variability in cycle-average CO emission rates. The EPA reported line-haul duty cycle based CO emission rates of 1.85 g/bhp-hr and 1.09 g/bhp-hr for EMD 16-645E3 and EMD 12-710 PMEs, respectively (EPA, 1998). Thus, the range of inter-engine variability in cycle-average CO emission rates for the NCDOT locomotive fleet encloses, and is of similar magnitude as, numbers for similar engines reported by EPA. Cycle-average CO emission duty cycles were lower than the level of the Tier 4 standard for locomotives NC 1792, NC 1755, NC 1797, NC 1859, NC 1871 and NC 1893. Cycle-average CO emission rates for each of the duty cycles were lower than the level of the Tier 2+ standard for locomotives NC 1810, NC 1896 and NC 1984.

Cycle-average HC emission rates in Figure 4-11(c) varied from 0.2 g/bhp-hr to 4.5 g/bhp-hr leading to large inter-locomotive variability. The EPA reported line-haul duty cycle based HC emission rate of 0.48 g/bhp-hr and 0.15 g/bhp-hr for EMD 16-645E3 and EMD 12-710 PMEs, respectively (EPA, 1998). Only the recently acquired F59PH locomotives with electronic fuel injection had HC emission rates at or below the EPA reported HC emission rates. Cycle-average HC emission rates for four of the 12 measured locomotive consists were lower than the level of the Tier 0+ standard for each duty cycle. For a given locomotive consist, typically the cycle-average HC emission rates were the highest for the EPA line-haul duty cycle and the lowest for the single and single-powered push/pull duty cycles.

Cycle-average NO_x emission rates in Figure 4-11(d) varied from 6.1 g/bhp-hr to 15.8 g/bhp-hr, and were 10.2 g/bhp-hr on average. Average cycle-average NO_x emission rates were approximately comparable to the EPA line-haul duty cycle-average NO_x emission rate of 10.6 g/bhp-hr for the EMD 12-710 PMEs (EPA, 1998). The cycle-average NO_x emission rates were at or below the level of the Tier 1+ standard for each duty cycle for two of the 12 measured locomotive consists. For every other locomotive, the cycle-average NO_x emission rates were higher than the level of the Tier 0+ standard for at least one duty cycle.

Cycle-average PM emission rates in Figure 4-11(e) varied from 0.2 g/bhp-hr to 0.6 g/bhp-hr and was 0.3 g/bhp-hr on average for all locomotives. The EPA line-haul duty cycle based PM emission rate is 0.23 g/bhp-hr for EMD 12-710 PMEs (EPA, 1998). Thus, measured rates were of similar magnitude as the EPA reported data. The cycle-average PM emission rate for locomotives NC 1792 and NC 1755 were not measured. The cycle-average PM emission rates were higher than the level of the Tier 0+ standard for 7 of the 10 measured locomotive consists. The remaining three locomotive consists had the cycle-average PM emission rates were higher than the level of the Tier 2+ standard but lower than the level of the Tier 1+ standard.

Based on prior measurements of three NCDOT locomotives, switching from ULSD to B20 lowered cycle-average HC and PM emission rates by 54 percent and 34 percent, respectively.

Assuming that these reductions could be achieved for each locomotive in the NCDOT fleet, a switch from ULSD to B20 fleet-wide might increase the number of locomotives with cycle average HC emission rates at or below the level of the Tier 0+ standard from 3 to 5. Likewise, the number of locomotives with cycle average PM emission rates at or below the level of the Tier 0+ standard would increase from 3 to 7.

Prior work on one of the NCDOT locomotive demonstrated that a retrofitted blended exhaust after treatment system (BATS) was able to achieve a reduction of 70 percent in cycle average rates. Assuming that the same reduction could be achieved for each locomotive in the NCDOT fleet, a retrofitted BATS fleet-wide might increase the number of locomotives with cycle average NO_x emission rates at or below the level of the Tier 0+ standard from 2 to 8.

Chapter 5. Predicting Fuel Use and Emission Rates

This chapter focuses on the development of a method for predicting locomotive fuel use and emission rates (FUER) based on any train trajectory and train consist for locomotives operated on Ultra-Low Sulfur Diesel (ULSD) and biodiesel blend B20. Locomotive FUER are directly proportional to the tractive effort of the locomotive (AREMA, 2013; Hay, 1982; Profillidis, 2014). Locomotive FUER vary spatially due to differences in speed, acceleration, grade and curvature along a railroad route (Hay, 1982; Profillidis, 2014). Therefore, some locations may have higher emissions than others, leading to emissions hotspots. Spatially resolved emission rates are needed to accurately quantify the source contribution of railroad sector emissions, air pollution exposure and health impacts (Bergin *et al.*, 2009, 2012; Gould and Niemeier, 2009, 2011; Lioy and Smith, 2013). Spatially resolved models are useful to evaluate impacts of train trajectory changes based on modifications to infrastructure such as track re-alignment on fuel use and emissions. Federal funding of infrastructure changes typically requires demonstration of emission reductions along a route (40 CFR 93, 1993).

Spatial variability in diesel locomotive FUER is due to variability in the prime mover engine (PME) operation along a route. The load on the Head End Power (HEP) engine is dependent on the number of passenger cars and, therefore, is typically constant for a given train consist (Frey and Hu, 2015). Therefore, FUER of the HEP engine are typically constant for a given train consist. As discussed in Section 2.6.4, the measured HEP engine load and fuel use rate for NC 1984 was approximately constant during each of 6 one-way trips.

Section 5.1 describes resistive forces, key variables affecting the magnitude and direction of resistive forces, and estimation of locomotive power demand (LPD) based on these variables. Section 5.2 describes the methods to collect over-the-rail (OTR) data and to estimate key variables affecting LPD. The calibration, validation, and application of the LPD model are given in Section 5.3.

5.1 Background

This section describes the resistive forces opposing train motion. This section also describes the estimation of tractive effort, quantified here as LPD, from the resistive forces.

5.1.1 Resistive Forces

The motion of a train is opposed by several resistive forces, including: (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 (Hay, 1982; Profillidis, 2014). The higher the magnitude of resistive forces, the higher is the required tractive effort and, thus, the higher will be the FUER for a locomotive.

Starting resistance is typically encountered when 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:

$$R_{s,t} = \begin{cases} 18\frac{lbs}{ton} & if\ v_{t-1} = 0\ and\ v_t > 0 \\ 0 & otherwise \end{cases} \tag{5-1}$$

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. Since the weight per unit axle may be different for the locomotive versus passenger cars, the journal resistance should be estimated separately for the locomotive and passenger cars. The journal resistance is estimated as (AREMA, 2013; Hay, 1982; Profillidis, 2014):

$$R_{j,t} = \left(0.6 + \frac{20}{\mathrm{w}}\right) \tag{5-2}$$

Where,

$R_{j,t}$	=	journal resistance (*lbs/ton*)
w	=	weight of locomotive per axle (w_l) or passenger car per axle (w_p) (*tons/axle)*

Flange resistance includes flange friction between the track and wheel flange, and oscillation (swaying and concussion). Flange resistance varies directly with train speed. The coefficient of proportionality between flange resistance and train speed is the flange resistance coefficient. Flange resistance is estimated as (Hay, 1982; Mittal, 1977; Profillidis, 2014):

$$R_{f,t} = B \times v_t \tag{5-3}$$

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 train speed. Train air resistance is the sum of air resistance for each locomotive and each passenger car. Since the drag is different for the lead locomotive versus trailing locomotives and passenger cars, the drag resistance should be estimated separately for each. For a train consist with multiple locomotives, the front and sides of the lead locomotive are fully exposed to the atmosphere. In contrast, for the trailing locomotive(s), the sides are fully exposed, similar to passenger cars. Thus, for estimating drag, any trailing locomotive(s) is assumed to be similar to passenger cars. Air resistance of locomotive or a passenger car for speeds up to 60 mph is estimated as (Hay, 1982; Mittal, 1977; Profillidis, 2014):

$$R_{d,t} = \frac{C_d \times F \times {v_t}^2}{w \times n} \tag{5-4}$$

Where,

$R_{d,t}$	=	air resistance for a locomotive or a passenger car 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). See Table 5-1 for typical values.
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)

For speeds greater than 60 mph, more complex and data-intensive calculations than Equation 5-4 are sometimes used to estimate air resistance more accurately. For example, estimation of the drag coefficient requires a streamline design factor, the value of which is based on the combination of shapes of different exterior parts of a locomotive or a passenger car. However, the data for such calculations may not be available. Hence, most studies only use Equation 5-4 as an estimate for air resistance to simplify the calculations for train speeds typically up to 100 mph (Drish, 1992; Kim *et al.*, 2006; Lukaszewicz, 2009). The drag coefficient for locomotives, freight cars, and passenger cars is given in Table 5-1.

Wind resistance ($R_{w,t}$) occurs due to the wind blowing over the tracks and can be accounted for by incorporating wind speed into Equation 5-4. However, 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. Therefore, wind speed is set to 0 and only air resistance is considered as a source of drag. Drag resistance, including air and wind resistance for a locomotive or a passenger car, is estimated as:

$$R_{w,t} = \frac{C_d \times F \times (v_t + v_w)^2}{w \times n} \qquad (5\text{-}5)$$

TABLE 5-1. 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/ft^2-mph^2)
Lead Locomotive	0.0024
Streamlined Lead Locomotive	0.0017
Freight cars	0.0005
Trailing Locomotive(s) and Passenger cars	0.00034[a]

[a] *The passenger car is always behind the locomotive. Thus, only a part of the full frontal area of the passenger car leads to the drag resistance. Therefore, a passenger car and a locomotive with similar frontal areas do not create the same drag. The drag coefficient for passenger cars is 7 to 10 times lower than that of locomotives with similar frontal areas. Therefore, the effect of reduced exposed or effective frontal area is included in the drag coefficient of the passenger car. For a train consist with more than one locomotive, drag resistance is based on the leading locomotive. All trailing locomotive(s) and passenger cars are quantified in the same way as passenger cars because trailing units are not completely exposed to the atmosphere.*

Where,

$R_{w,t}$	=	drag resistance for trains with directly opposing wind at time *t* (*lbs/ton*)
$v_{w,t}$	=	wind speed opposite to train motion at time *t* (*mph*)

Curve resistance is encountered on a horizontal curve. Curve resistance occurs due to the longitudinal and transverse sliding between the wheel and rail on a curve and the increased friction on the surface of the flange and inner rail because of the effect of lateral forces (Hay, 1982; Profillidis, 2014). Curve resistance is directly proportional to the degree of curve, also known as track curvature. The degree of a curve is the angle subtended by a 100-ft chord at the center of a curve. Curve resistance per unit train weight is estimated as (AREMA, 2013):

$$R_{c,t} = D \times d_t \tag{5-6}$$

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*)

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 is defined as the change in elevation per unit length of the horizontal projection of the track on a level surface. However, for small relative grades typically observed on railroad tracks, the horizontal projection of the track on a level surface is approximately equal to the track length. Grade was estimated based on the change in elevation per unit track length. The error in estimated grade based on this assumption for a 2 percent grade, which is the maximum observed grade on the Piedmont route, is 0.02 percent. Therefore, the error in the grade estimates based on track length rather than projected length on a level surface is negligible. The grade resistance per unit train weight is estimated as (AREMA, 2013; Hay, 1982; Profillidis, 2014):

$$R_{x,t} = E \times x_t \tag{5-7}$$

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, which results 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 acceleration resistance per unit train weight is estimated as:

$$R_{a,t} = G \times a_t \tag{5-8}$$

Where,

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

a_t = train acceleration at time t (m/s^2)

5.1.2 Traction Resistance

The resistances associated with train movement are called traction resistance. Traction resistance includes starting, journal, flange, air, wind, curve, grade and acceleration resistances. Journal, flange and air resistance are always present during train movement. The American Railway Engineering and Maintenance-of-way Association (AREMA) recommended multiplying the journal, flange and air resistance by a factor of 0.85 to account for improved train and rail designs (AREMA, 2013). 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 curves and grades, respectively. Acceleration resistance is only present during train acceleration. The traction resistance is estimated as:

$$R_{T,t} = R_{s,t} + (R_j + R_{f,t} + R_{w,t}) \times I + R_{c,t} + R_{x,t} + R_{a,t} \quad (5\text{-}9)$$

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

5.1.3 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 inside the locomotive cab. 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 was used to account for internal resistance (Hay, 1982; Mittal, 1977; Profillidis, 2014). Lighting, heating and space conditioning for passenger cars is provided by the HEP engine. The HEP engine typically operates at a constant load for a given train consist throughout the trip leading to constant FUER along a route. Therefore, HEP engine FUER is not included here in the model. However, the HEP engine FUER is included in the train total fuel use and emissions estimation as detailed later.

5.1.4 Gross Resistance

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

$$R_{g,t} = \frac{R_{T,t}}{\eta} \quad (5\text{-}10)$$

Where,

$R_{g,t}$ = gross 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 5-9,

$$R_{g,t} = \frac{R_{s,t} + (R_j + R_{f,t} + R_{w,t}) \times I + R_{c,t} + R_{x,t} + R_{a,t}}{\eta} \tag{5-11}$$

Ignoring wind resistance and substituting the expressions for $R_{j,t}$, $R_{f,t}$, $R_{d,t}$, $R_{c,t}$, $R_{x,t}$ and $R_{a,t}$, from Equations 5-2, 5-3, 5-4, 5-5, 5-6 and 5-7, respectively, Equation 5-11 becomes:

$$R_{g,t} = \frac{R_s + \left(\left(0.6 + \frac{20}{w}\right) + Bv_t + \frac{C_d \times F}{w \times n} v_t^2\right) \times I + Dd_t + Ex_t + Ga_t}{\eta} \tag{5-12}$$

Equation 5-12 is applicable for the lead locomotive, trailing locomotive(s), or passenger cars. However, the parameters w, F, C_d, and n may differ among lead locomotive, trailing locomotives, and passenger cars. Therefore, the gross train resistance must be estimated for each separately. Each of the locomotive owned by the NCDOT has the same corresponding value for w, F, and n, which is obtained from the locomotive manual. C_d differs among locomotive based on the shape of the frontal cross-section and the position of locomotive in a consist. The locomotives owned by NCDOT have two distinct shapes of the frontal cross-section. The F59PHI locomotives have a more aerodynamic frontal cross-section versus F59PH locomotives. If the lead locomotive is an F59PH, C_d equal to 0.0024 *lbs/ft*^{2}*-mph*^{2} is used for estimating drag resistance (Table 5-1). For a lead F59PHI locomotive, C_d equal to 0.0017 *lbs/ft*^{2}*-mph*^{2} is used for estimating drag resistance (Table 5-1).

Passenger cars are not fully exposed to the atmosphere. Therefore, the drag resistance is lower versus lead locomotive, as indicated by a relatively lower C_d of 0.00034 *lbs/ft*^{2}*-mph*^{2} for passenger cars (Table 5-1). Since trailing locomotive(s) are also not fully exposed to the atmosphere, they are assumed to have the same drag coefficient as a passenger car. Parameters w, F, and n corresponding to trailing locomotive(s) or passenger cars are used.

The gross train resistance for a train consist is estimated as the sum of resistances for the lead locomotive, trailing locomotive(s), and passenger cars:

$$R_{g,t} = \frac{\left[R_{s,t} + \left\{\left(0.6 + \frac{20}{w_l} + Bv_t + \frac{C_{d,l} F_l}{w_l\, n_l} v_t^2\right) + \mathrm{N}\left(0.6 + \frac{20}{w_l} + Bv_t + \frac{C_{d,p} F_l}{w_l\, n_l} v_t^2\right) + \mathrm{P}\left(0.6 + \frac{20}{w_p} + Bv_t + \frac{C_{d,p} F_p}{w_p\, n_p} v_t^2\right)\right\} \times \left(\frac{I}{1+P+N}\right) + Dd_t + Ex_t + Ga_t\right]}{\eta} \tag{5-13}$$

Where,

N	=	number of locomotives per train other than the lead locomotive
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 lead locomotive from Table 5-1 (*lbs/ft*^{2}*-mph*^{2})
$C_{d,p}$	=	drag coefficient for trailing locomotive(s) and passenger cars from table 5-1 (*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, η and v_w are constant. These coefficients, independent of the train system, are shown in Table 5-2. The coefficients $N, \mathrm{w}_l, n_l, C_{d,l}, F_l, P, \mathrm{w}_p, n_p, C_{d,p}$ 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 on board a train. However, the weight of each passenger car at full seating capacity versus an empty passenger car differs only by 7 percent for the passenger cars used on the Amtrak Piedmont train (Rastogi and Frey, 2018a). Therefore, differences in passenger car weight related to passenger load were neglected. The coefficients $N, \mathrm{w}_l, n_l, C_{d,l}, F_l, P, \mathrm{w}_p, n_p, C_{d,p}$ and F_p for the Amtrak Piedmont train are shown in Table 5-3. Train speed and acceleration are dependent on train operation and are referred to as "train activity." Rail grade and track curvature depend on track geometry and alignment.

5.1.5 Locomotive Power Demand

For the Piedmont train, one or two locomotives are used to 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. Taking into account unit conversions, LPD for each second of train operation is (Profillidis, 2014):

$$LPD_t = 0.00377 \times R_{g,t} \times v_t \times W \tag{5-14}$$

Where,

LPD_t	=	locomotive power demand at time *t* (*kW*)
W	=	total train weight (*tons*)

$R_{g,t}$ is estimated using Equation 5-13. Train weight is estimated as:

$$\mathrm{W} = w_l \times n_l \times (1 + N) + w_p \times n_p \times P \tag{5-15}$$

TABLE 5-2. 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-s^2/ton-m*
η	Locomotive efficiency factor	0.82
$v_{w,t}$	Wind speed	Typically assumed zero

TABLE 5-3. Train Resistance Equation Parameters for the Amtrak Piedmont Passenger Rail Service.

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-mph^2*)[c]	0.0024 (F59PH) 0.0017 (F59PHI)
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*)[b]	17.5 (Empty) 18.8 (Full Capacity)
n_p	Number of axles per passenger car	4
$C_{d,p}$	Trailing locomotive(s) or passenger car drag coefficient (*lbs/ft^2-mph^2*)	0.00034
F_p	Passenger car frontal cross-sectional area (*ft^2*)	142

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

[b] *The weight of an empty passenger car used on the Piedmont rail route is 70 tons. Assuming an average weight of 70 kgs per person (Gbologah et al., 2014), the weight of a passenger car with a seating capacity of 66 persons fully occupied by passengers is 75 tons. To simplify calculations, the weight of an empty passenger car was used.*

[c] *F59PHI locomotives have more aerodynamic frontal cross-section compared to F59PH locomotives. Therefore, two different values of drag coefficients are used.*

5.2 Modeling Fuel Use and Emission Rates

This section describes the data used for model calibration and validation. Methods to estimate track geometry are described for grade and curvature. These data were time-aligned and screened for errors. A model is calibrated and validated to predict 1 Hz FUER based on train activity and track geometry.

5.2.1 Train Data Used for Model Calibration and Validation

The data for model calibration and validation includes over-the-rail (OTR) measurements conducted during the current project period and OTR measurements from prior work (Frey *et al.*, 2016; Frey and Rastogi, 2018; Graver *et al.*, 2016; Graver and Frey, 2015). The procedures for data collection, time alignment, quality assurance and estimation of FUER are described in Sections 2.3 through 2.6. The LPD model is calibrated and validated based on OTR data from prior work including single-consist measurements of NC 1797, NC 1810, NC 1859 and NC 1893, double-tandem measurements of NC 1859 operated on ULSD (Frey *et al.*, 2016; Frey and Rastogi, 2018; Graver and Frey, 2015), and single-consist measurements of NC 1797, NC 1810 and NC 1859 operated on B20 biodiesel fuel (Frey *et al.*, 2016). Data for the double- and single-powered push/pull consists of locomotives NC 1871 and NC 1984 are based on recent work as reported in Chapter 4. Data from locomotives NC 1792, NC 1755 and NC 1869 were not used because only two or fewer one-way trips were measured for these locomotives. RY measurements do not account for the effect of train speed and acceleration, or track grade and curvature. Therefore, RY data are not relevant to LPD model calibration and validation and are not used.

5.2.2 Track Geometry

Track grade and curvature were inferred from prior GPS measurements for eight locomotives operated on ULSD and biodiesel blends (Boroujeni and Frey, 2014; Frey and Rastogi, 2018; Rastogi and Frey, 2018b). GPS receivers record position and elevation data. However, each recorded position is subject to random errors. The typical horizontal position precision of a low-cost GPS receiver is ± 9 feet or more. The vertical precision of altimeter measurements is ±1 m. The imprecision of the position and elevation data can be compensated for by a large sample size of data. A method to estimate road grade using low-cost GPS receivers with barometric altimeters has previously been demonstrated (Boroujeni and Frey, 2014; Frey and Rastogi, 2018).

Position and elevation data were collected at 1 Hz using Garmin 76CSx and Garmin Oregon 500 receivers. The GPS receivers were installed near the window in the locomotive cab. Grade and curve radii estimates were found to be independent of the position of the GPS receivers with respect to rail elevation and the centerline of the track. Grade is based on relative changes in elevation. The estimated grade is unaffected by the location of the GPS receiver within the train as long as the position is the same throughout the trip. On curves, the inner rail has a shorter radius than the outer rail. However, the difference between the two radii was less than the precision of the GPS receivers. Thus, the positioning of receivers with respect to the centerline is an insignificant source of error. It was also assumed that the longitudinal grade is approximately similar regardless of the superelevation of the track. Although the latter is an approximation, differences in elevation of just a few inches are smaller than the precision of the GPS receivers.

Segment length was selected to be long enough to include sufficient 1 Hz data 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 (Boroujeni and Frey, 2014; Frey and Rastogi, 2018; Rastogi and Frey, 2018b). Yazdani et *al*. (2013) found a distance of 0.1 miles to be appropriate for quantifying road grade based on GPS data (Boroujeni and Frey, 2014). However, for railroad tracks, elevation changes are typically more gradual than for roads. Therefore, a segment length of 0.25 mile is used here. The number of GPS data points in a segment depends upon train speed. For example, for the Piedmont route which has a speed limit of 79 mph, at least 11 data points were recorded at 1 Hz for a 0.25-mile segment per GPS receiver.

Typically, 4 to 10 GPS receivers fitted with barometric altimeters were used per one-way trip. Any receiver that lost signal or that could not record data for some part of a trip was excluded from further analysis. Data from 180 GPS measurements were used. Each GPS measurement represents one GPS receiver that recorded 1 Hz data for a complete one-way trip. The 173-mile rail route was divided into 692 0.25-mile segments. Grade estimation is based on relative changes in elevation. The barometric pressure varies from run-to-run depending on weather conditions. Thus, while the change in elevation along a segment is repeatable, the recorded absolute barometric pressure may vary on average from one run to another. Because grade is based on relative changes in elevation, it is not necessary to know the actual absolute elevation. However, statistical precision of grade estimates from multiple GPS runs was improved by vertically aligning data points from each run to an arbitrary average reference elevation for each segment.

Rail grade was quantified for non-overlapping adjacent equal-length track segments based on a method developed by Boroujeni and Frey (2014) for road segments (Boroujeni and Frey, 2014). This method included the following steps: (1) projecting position-elevation data from 180 GPS measurements onto the segmented line representing the location of the track using ArcGIS (ESRI, 2004); (2) combining 1 Hz measurements from multiple GPS measurements into a single dataset; (3) aligning each GPS measurement to have the same average elevation for each track segment to improve statistical precision of grade estimates; (4) using Geographic Information System (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. In prior work, rail grade estimated using GPS receivers was compared with track design drawings available for a 40-mile section of the route and with grade estimated based on Light Detection and Ranging (LIDAR)-based Digital Elevation Models (DEMs) (Rastogi and Frey, 2018b). The GPS-based grade estimates were generally accurate compared to these other data sources. The GPS-based grade estimates were compared with the grade from the track design drawings. Based on the design drawings for a 40-mile section of the route, the grade varied between -2 percent and 2 percent. The grade in the track design drawings was for segments typically 0.5 mile or longer. The GPS-based grade estimates were on average within ± 0.3 percent absolute versus track drawings. The grade estimated based on GPS data for the entire Piedmont route varied between -1.9 percent and 1.9 percent. Therefore, the GPS-based grade estimates are accurate.

Track curvature was estimated based on circular regression of GPS position data and the GIS-based track shapefile for each segment (Rastogi and Frey, 2018b). Track curvature estimated using GPS data and the GIS shapefile were compared to design drawings for 0.25-mile track segments of the Piedmont route. The track design drawings were labelled with curvature in degrees for a 40-mile section of the route for every 0.1-mile track segment at a resolution of 0.5 degrees. Thus, every 0.25-mile segment on the Piedmont route comprised three 0.1-mile track segments corresponding to track design drawings. To enable consistent comparison, an average curvature of three 0.1-mile track segments was compared with the overlapping 0.25-mile track segment. Based on average track curvature inferred from track design drawings, curvature varied between 0.0 degree and 4.0 degrees. The GPS-based curvature estimates were on average within ± 0.2 degrees versus track drawings. Curvature estimated based on GPS data for the entire Piedmont route varied between 0 degree and 4.3 degrees. Thus, the range of curvature included in the design drawings is representative of curvatures for the entire route.

For a given track segment, curvature estimated based on the GIS shapefile was within ± 0.1 degrees of curvature estimated based on GPS data. The GIS-based curvature estimates were on average within ± 0.2 degrees versus track drawings. Therefore, curvature estimated from either GPS data or the GIS shapefile are comparable and suitable for estimating curvature for segments for which design drawings are not available. Here, track curvature was estimated based on GPS data.

5.2.3 Modeling Locomotive Power Demand

Locomotive power demand was estimated using Equation 5-14 for each second of OTR data for each locomotive, consist, and fuel. Although the throttle notch setting can be changed nearly instantaneously, within a second, the PME operation takes some time to respond. The change in engine RPM, MAP, and IAT during the transition period from one notch setting to another is gradual over a period of typically 5 to 30 seconds depending on the difference of engine output between the two levels (Graver and Frey, 2015). For example, a transition from notch 1 to notch 8 will have a larger duration compared to a transition from notch 1 to notch 5. Thus, LPD_t is affected by LPD from the current and past seconds. To account for this transition, an n-second backward moving average LPD ($LPD_{n,t}$) was used instead of instantaneous LPD_t. $\overline{LPD}_{n,t}$ is defined as an average of the LPD at time *t*, and the LPD_t in the past (*n-1*) seconds:

$$\overline{LPD}_{n,t} = \frac{1}{n}\sum_{i=0}^{n-1} LPD_{t-i} \tag{5-16}$$

Where,

$\overline{LPD}_{n,t}$	=	average of the locomotive power demand at time *t* and the past (*n-1*) seconds
n	=	backward moving average period (*s*)

The appropriate averaging period to select for model calibration was not known *a priori*. Therefore, to identify a suitable averaging period for model specification, *n* was varied from 1 to 100 and Pearson's correlation coefficient was estimated between fuel use rate and moving average $\overline{LPD}_{n,t}$. The averaging period that led to the highest correlation between 1 Hz $\overline{LPD}_{n,t}$ and 1 Hz fuel use rate was selected as the basis for model specification.

Based on observations from RY and OTR measurements of typically monotonically increasing measured trends in steady-state FUER versus throttle notch position and engine horsepower, FUER were hypothesized to increase monotonically and linearly with positive $\overline{LPD}_{n,t}$. Based on OTR measurements, negative $\overline{LPD}_{n,t}$ was typically encountered on downhill gradients, when the train was decelerating, or both. Since there was no engine power demand for negative $\overline{LPD}_{n,t}$, the PME was typically operated at idle in such cases. Thus, the FUER in such cases were equivalent to idle FUER. The relationship between 1 Hz FUER and $\overline{LPD}_{n,t}$ is hypothesized as:

$$m_{s,L,C,F,t} = \begin{cases} m_{s,\mathrm{idle},L,C,F} + PC_{s,L,C,F} \times \overline{LPD}_{n,t} \left({}^{kW}/_{s}\right) & \overline{LPD}_{n,t} > 0 \\ m_{s,idle,L,C,F}, & \overline{LPD}_{n,t} \leq 0 \end{cases} \tag{5-17}$$

Where,

$m_{s,L,C,F,i,t}$	=	Empirical 1 Hz fuel use or emission rate of species *s* for locomotive *L* and consist *C* operated on fuel *F* at time *t* (*g/s*)
$m_{s,idle,L,C,F}$	=	Idle fuel use or emission rate of species *s* for locomotive *L* and consist *C* operated on fuel *F*, assumed to be constant irrespective of time (*g/s*)
$PC_{s,L,C,F}$	=	Proportionality constant for species *s* for locomotive *L* and consist *C* operated on fuel *F* (*g/kW*)
s	=	Index for species. *s* ϵ {fuel use rate, emission rate of CO_2, CO, HC, NO_x or PM}
L	=	Index for locomotive. *L* ϵ {NC 1797, NC 1810, NC 1859, NC 1893, NC 1871 and NC 1984}
C	=	Index for train consist. *C* ϵ {single, single-powered push/pull and double-powered push/pull}

F = Index for fuel. $F \in$ {ULSD and B20}

5.2.3.1. *Model Calibration*

The model was calibrated for all possible leave-one-out (LOO) cross-validation combinations of one-way trips for each locomotive, consist, and fuel. For a locomotive, consist, and fuel with *T* one-way trips, *(T-1)* one-way trips were used to estimate $PC_{s,L,C,F}$. The left out one-way trip was used for validation, as explained in the next section. For example, if there were six one-way trips for a given locomotive, consist, and fuel, six models were calibrated. Each of the models was calibrated to five of the trips and validated with the left-out trip. For each LOO cross-validation case, $PC_{s,L,C,F,T\neq i}$ was calibrated based on linear regression:

$$m_{s,L,C,F,t,T\neq i} - m_{s,idle,L,C,F} = PC_{s,L,C,F,T\neq i} \times \overline{LPD}_{n,t} \left({kW}/{s}\right) + \epsilon_t,\ \overline{LPD}_{n,t} > 0 \qquad (5\text{-}18)$$

Where,

$m_{s,L,C,F,t,T\neq i}$	=	Empirical 1 Hz fuel use or emission rate of species *s* for locomotive *L* and consist *C* operated on fuel *F* at time *t* for all one-way trips but the i^{th} one-way trip (*g/s*)
$PC_{s,L,C,F,T\neq i}$	=	Calibrated proportionality constant for species *s* for a given LOO cross-validation case of locomotive *L* and consist *C* operated on fuel *F* or all one-way trips but the i^{th} one-way trip (*g/kW*)
z	=	Index for moving average period. Ranges from 0 to (*n-1*).
ϵ_t	=	Residual error. $\epsilon_t \sim_{iid} N(0,\sigma^2)$

Since FUER and LPD are autocorrelated, the error term of the linear regression is also autocorrelated. The error term in Equation 5-18 would be biased and not independent and identically distributed if the autocorrelation among the residual errors is not accounted for. Therefore, a lagged error term was added in Equation 5-18. The lagged error term with an order *q* is the weighted average of error in the current second and past (*q-1*) seconds. The lagged error term is estimated as (Box *et al.*, 2015):

$$\epsilon_t = \sum_{z=1}^{q} \theta_z \times \epsilon_{t-z} + \omega_t \qquad (5\text{-}19)$$

Where,

θ_z	=	weighting parameter of the lagged error term at lag *z* seconds. The parameter ranges between -1 and 1. The weighting parameters are estimated based on Equation 5-21 and are given in Appendix F.
z	=	lag. Ranges from 1 for the error in the past second to *q* for the error in the past q^{th} second.
q	=	Order of the lagged error term. The moving average period until which the errors are correlated.
ω_t	=	White noise. $\omega_t \sim_{iid} N(0,\sigma^2)$

The order of lagged error term and weighting parameters in Equation 5-19 are estimated based on the Auto Regressive Integrated Moving Average (ARIMA) approach for time series analysis with autocorrelated errors (Box *et al.*, 2015). With the inclusion of lagged error term, the residual errors are similar to white noise.

The ARIMA models are calibrated based on the past (known) observations of a time series. The calibrated model could be used to make forecasts for the remainder part (unknown) of the time series. Model calibration includes estimation of the order and weighting parameter(s) of the lagged error term based on past data. The order of the lagged error term is equal to the lag at which the autocorrelation coefficient drops to zero (Box *et al.*, 2015). The autocorrelation coefficient at lag z is estimated as:

$$\rho_z = \frac{\sum_{t=z+1}^{T}(\epsilon_t - \bar{\epsilon})(\epsilon_{t-z} - \bar{\epsilon})}{\sum_{t=z+1}^{T}(\epsilon_t - \bar{\epsilon})^2} \quad (5\text{-}20)$$

Where,

ρ_z	=	Autocorrelation coefficient among lagged error terms at lag z. The coefficient ranges between -1 and 1.
$\bar{\epsilon}$	=	Average residual error

The weighting parameter(s) of the lagged error term are estimated based on the relationship with autocorrelation at lag z as:

$$\rho_z = \frac{-\theta_z + \theta_1\theta_{z+1} + \theta_2\theta_{z+2} + \ldots + \theta_{q-z}\theta_q}{1 + \theta_1^2 + \theta_2^2 + \ldots + \theta_q^2} \quad (5\text{-}21)$$

ARIMA models rely on past data to forecast future values. Thus, these models are useful for describing observed data. However, for a new trajectory, FUER and lagged error terms will be unknown. Thus, although ARIMA models are statistically more robust versus simple linear regression (Equation 5-18), ARIMA models are not useful for predicting FUER for a new trajectory. Therefore, a simple linear regression without the lagged error term is demonstrated for model calibration, validation and application. Given that the model is calibrated without lagged error term, the proportionality constant and the model performance will differ from the model with lagged error terms. Differences in calibrated model parameters without versus with the lagged error terms could potentially lead to bias in model predictions for the case in which a model without lagged error terms is used for prediction. Therefore, the models with and without the lagged error term are compared. As will be shown later, the models without the lagged error term, which are useful for prediction, perform similarly to those with lagged error terms.

Calibrated models with and without lagged error terms were evaluated based on the 95% confidence interval of the proportionality constant, calibrated model R-squared (R^2) and the p-value of the proportionality constant. A narrower versus wider 95% confidence indicates a more precise estimate of $PC_{s,L,C,F,T\neq i}$. R^2 is a goodness-of-fit measure. R^2 is the proportion of the variance in the dependent variable that is predictable from the independent variable(s). R^2 ranges between 0 and 1. Higher R^2 indicates that the model explains a larger proportion of variance in the dependent variable and better precision compared to lower R^2. In this work, models with R^2 higher than 0.70 are referred to as high precision models. Models with R^2 between 0.50 and 0.70 are referred to as medium precision models and models with R^2 less than 0.50 are referred to as low precision models. The p-value tests the null hypothesis that the estimated $PC_{s,L,C,F,T\neq i}$ is equal to zero. A p-value lower than 0.05 indicates that the estimated $PC_{s,L,C,F,T\neq i}$ is statistically significantly different from zero.

The multiple cross-validated models for a given locomotive, consist, and fuel were deemed to be robust to the choice of calibration trips if $PC_{s,L,C,F,T\neq i}$ for each LOO cross-validation case was within 10 percent of the mean $PC_{s,L,C,F,T\neq i}$ based on the average of all LOO cross-validation cases. In such a case, one model was calibrated to all of the one-way trips for a given locomotive, consist, and fuel and was used as the final model.

5.2.3.2. Model Validation

The model was validated with and without lagged error terms for 1 Hz FUER and for trip fuel use and emissions (TFUE) for the validation trips for each LOO cross-validation case. For a given LOO cross-validation case, 1 Hz FUER for the left-out one-way trip were modeled as:

$$m_{s,L,C,F,t,T=i}^{modeled} = m_{s,\mathrm{idle},L,C,F} + PC_{s,L,C,F,T\neq i} \times \overline{LPD}_{n,t} \left({kW}/{s} \right) + \epsilon_t, \qquad \overline{LPD}_{n,t} > 0 \qquad (5\text{-}22)$$

Where,

$m_{s,L,C,F,t,T=i}^{modeled}$ = Modeled 1 Hz fuel use or emission rate of species *s* for locomotive *L* and consist *C* operated on fuel *F* at time *t* for the i^{th} one-way trip predicted based on $PC_{s,L,C,F,T\neq i}$ calibrated to all one-way trips but the i^{th} one-way trip (*g/s*)

To quantify model accuracy, a linear regression without intercept was fit for FUER predicted with the calibrated model versus the empirical FUER. The model accuracy is indicated by a slope close to one and precision is indicated by R^2 close to one. The 95% confidence interval and the p-value of slope are the indicators of the estimated slope.

To determine model accuracy for TFUE of a given locomotive, consist, and fuel, linear regression with the intercept set to zero was fit for modeled versus empirical TFUE. Empirical TFUE were estimated based on Equation 2-15. Modeled TFUE for each one-way trip was estimated as:

$$SOMR_{s,L,C,F,i}^{modeled} = \sum_{t_{L,C,F,i,0}}^{t_{L,C,F,i,n}} m_{s,L,C,F,t,T=i}^{modeled} \qquad (5\text{-}23)$$

Where,

$SOMR_{s,L,C,F,i}^{modeled}$ = Modeled trip fuel use or emissions of species *s* for locomotive *L* and consist *C* operated on fuel *F* for the i^{th} one-way trip estimated as the sum of modeled 1 Hz rates *(g)*.

5.2.4 Train Total Fuel Use and Emissions

The train total FUER are estimated based on the sum of FUERs of the PME and the HEP engine. For a given consist, the HEP engine operates at a constant load. Because the HEP engine(s) operate at constant load, variability in TFUEs arises due to variability in the operation of PMEs. A method to estimate train total FUER and TFUEs based on the final LPD model, calibrated to all available trips, is demonstrated below for a given combination of locomotive(s), consist and fuels.

FUER for the PME are estimated based on Equation 5-18. FUER of the HEP engine corresponding to load *l* in hp for F59PHI and mechanically-governed F59PH locomotives were estimated in prior work based on RY measurements (Frey and Hu, 2015). FUER for HEP engines operated on ULSD and B20 are given in Tables F1 and F2, respectively, in Appendix F. FUER for the HEP engines of locomotives NC 1871 and NC 1984 have not been quantified yet. Therefore, FUER for these HEP engines were assumed to be the average FUER of the measured HEP engines.

For single locomotive consists, train FUER are estimated as the sum of PME FUER and HEP engine FUER. For train consists with multiple locomotives, the PME and HEP engine of the same locomotive operate independently of each other. For Piedmont rail service, operators powered one or both PMEs. However, the HEP engine of only one locomotive was powered during the entire trip. Train FUER for tandem and double-powered consists were estimated as the sum of modeled FUER for the PME of each locomotive and the HEP engine FUER of one locomotive. The power demand was assumed to be equally shared amongst each locomotive. Train FUER for the single-powered consist were estimated as the sum of modeled FUER for the PME of the powered locomotive, idle FUER for the PME of other locomotives, and the HEP engine FUER of one locomotive.

The train total FUER for single, tandem, single-powered, and double-powered consists are estimated as:

$$m_{s,\mathrm{t},L_1,L_2,C,F,i}^{train} = \begin{cases} \begin{array}{c} m_{s,idle,L_1,C,F,i} + (\lambda_{C_1} - 1) \times m_{s,idle,L_2,C,F,i} + h_{L_1} \times m_{s,L_1,F,i}^{HEP} + \\ h_{L_2} \times m_{s,L_2,F,i}^{HEP} + \lambda_{C_2} \times \overline{LPD}_{n,t} \times (PC_{s,L_1,C,F} + (\lambda_{C_1} - 1) \times PC_{s,L_2,C,F}) \end{array}, & \overline{LPD}_{n,t} > 0 \\ m_{s,idle,L_1,C,F,i} + (\lambda_{C_1} - 1) \times m_{s,idle,L_2,C,F,i} + h_{L_1} \times m_{s,L_1,F,i}^{HEP} + h_{L_2} \times m_{s,L_2,F,i}^{HEP}, & \overline{LPD}_{n,t} \leq 0 \end{cases} \quad (5\text{-}24)$$

Where,

$m_{s,t,L_1,L_2,C,F,i}^{train}$	=	Train total fuel use or emission rate of species *s* at time *t* for a consist *C* including one or two locomotives and operated on fuel *F* (*g/s*).
$m_{s,idle,L_1,C,F,i}$	=	Idle fuel use or emission rate of species *s* for the prime mover engine of locomotive L_1 in consist *C* operated on fuel *F*, assumed to be constant regardless of time (*g/s*).
λ_{C_1}	=	Number of powered prime mover engines in the train consist. = 0 for single-powered and single consists, and 1 for double-powered and tandem consists.
$m_{s,idle,L_2,C,F,i}$	=	Idle fuel use or emission rate of species *s* for the prime mover engine of locomotive L_1 in consist *C* operated on fuel *F*, assumed to be constant regardless of time (g/s).
h_{L_1}	=	Index for the status of the HEP engine of locomotive L_1, = 1 if the HEP engine was ON and 0 if the HEP engine was OFF.
h_{L_2}	=	Index for the status of the HEP engine of locomotive L_2, = 1 if the HEP engine was ON and 0 if the HEP engine was OFF.

$m^{HEP}_{s,L_1,F,i}$	=	Fuel use or emission rate of species *s* for the HEP engine of the locomotive L_1 corresponding to load *l* and operated on fuel *F*, assumed to be constant regardless of time because HEP engine load is approximately constant for a given consist (*g/s*). (See Tables F1 through F2 for ULSD and B20, respectively, in Appendix F).
$m^{HEP}_{s,L_2,F,i}$	=	Fuel use or emission rate of species *s* for the HEP engine of the locomotive L_2 corresponding to load *l* and operated on fuel *F*, assumed to be constant regardless of time because HEP engine load is approximately constant for a given consist (*g/s*). (See Tables F1 through F2 for ULSD and B20, respectively, in Appendix F).
λ_{C_2}	=	Fraction of total tractive power provided by each prime mover engine. = 1 for single-powered and single consists, and 0.5 for double-powered and tandem consists.
$PC_{s,L_1,C,F}$	=	Proportionality constant for species *s* for the prime mover engine of locomotive L_1 and consist *C* operated on fuel *F* (*g/kW*).
$PC_{s,L_2,C,F}$	=	Proportionality constant for species *s* for the prime mover engine of locomotive L_2 and consist *C* operated on fuel *F* (*g/kW*).

5.3 Results and Discussion

For a given locomotive, consist, and fuel, key inputs to the LPD model include speed, acceleration, grade, and curvature. Thus, typical distributions of speed, acceleration, grade, and curvature for the Piedmont passenger rail are discussed. The LPD models are calibrated based on characteristics of the locomotives and passenger cars (Tables 5-2 and 5-3, respectively), and idle FUER of the PMEs (Table 5-4). The models are calibrated and validated without the lagged error terms (Equation 5-18). The typical distribution of the empirical fuel use rate is discussed. The most suitable backward moving average period to estimate LPD is determined. LPD model calibration, validation, and applications are discussed. The calibration and validation are demonstrated for single consist of NC 1859 operated on ULSD as an example, as shown in Section 5.3.5 and 5.3.6, respectively. For other combinations of locomotives, consists, and fuels, only the results of the final model are given. Calibration and validation of each LOO cross-validation case of other combinations of locomotives, consists, and fuels are given in Appendix F. Calibration and validation of each LOO cross-validation case for models with lagged error terms are discussed in Appendix F. An application of an LPD model to quantify the impact of trajectory and track infrastructure change on fuel use and emissions is demonstrated in Section 5.3.7.

5.3.1 Locomotive Speed and Acceleration

Train speed was measured, and acceleration was inferred from change in speed. As an example, train activity data for six one-way trips for a single-locomotive consist of locomotive NC 1859 operated on ULSD are summarized in Figure 5-1. The train was stopped for about 10 percent of the total time for an average one-way trip. 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. Similar distributions of speed were observed for other combinations of locomotives, consists, and fuels.

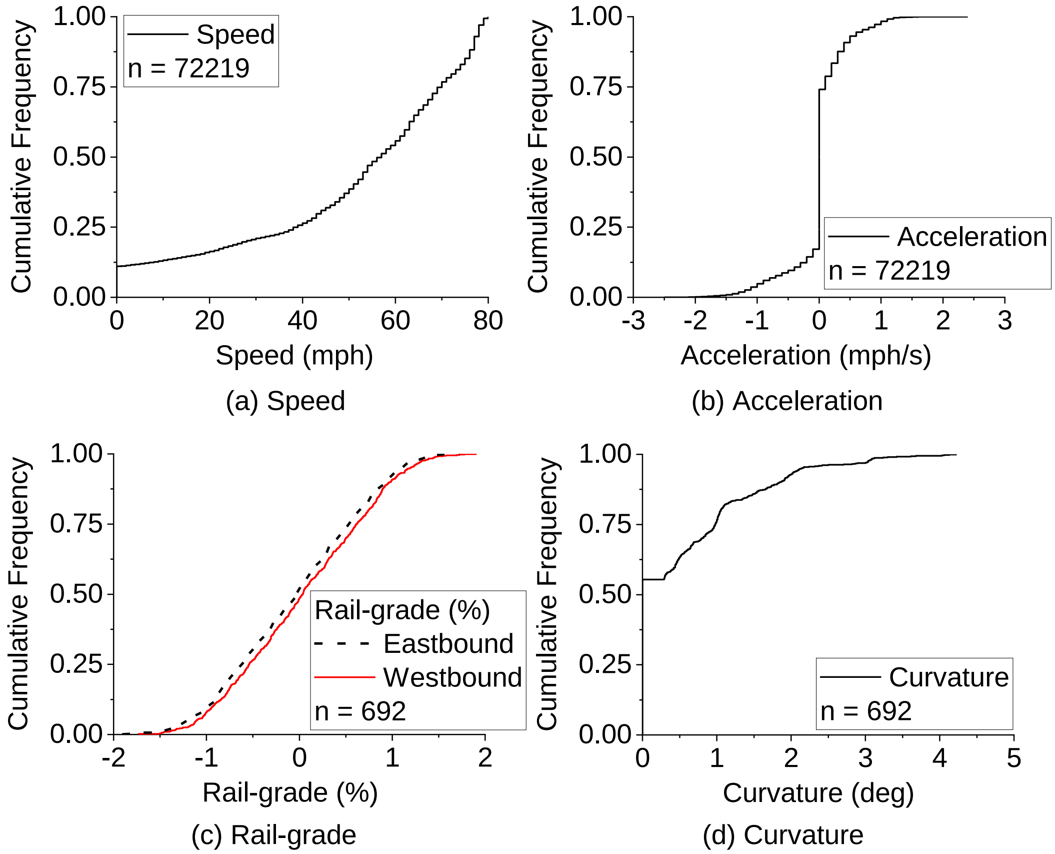


FIGURE 5-1. Cumulative Frequency Distributions based on Six One-way Trips on Single-Operated Locomotive NC 1859 between Raleigh, NC and Charlotte, NC for the Piedmont Passenger Rail Service: (a) Speed, (b) Acceleration, (c) Grade, and (d) Curvature. The Six One-way Trips Included 72,219 Seconds of Data and 692 measured Track Segments.

The acceleration varied between -2.3 mph/s and 2.3 mph/s. The train cruised at a constant speed or stopped (no acceleration) for about 50 percent of the average trip duration. At speeds greater than 50 mph, changes in speed were gradual or the train cruised at a constant speed for short periods of time (e.g., 25 seconds or less) before speed changed and the train cruised at a new speed. About 80 percent of the accelerations were between -0.5 mph/s and 0.5 mph/s. Similar distributions of acceleration were observed for other combinations of locomotives, consists, and fuels.

5.3.2 Rail grade and Curvature

The grade estimated from GPS data varied between -1.9 percent and 1.9 percent as indicated in Figure 5-1(c). The grade for a given track segment (Section 5.2.2) in a given travel direction is opposite in sign to the grade of the same segment in the opposite direction. Segment-average grade in either travel direction is given in Figure 5-1(c). On average, the grade in the westbound direction is higher versus grade in the eastbound direction because there is a net gain in elevation of 133 meters from Raleigh to Charlotte.

The segment-average curvature varied between 0.2 degrees and 4.3 degrees. Fifty percent of the segments did not have horizontal curvature. Curves with less than 1 degree of curvature accounted for about 25 percent of the track segments. Curves exceeding 2 degrees accounted for less than 10 percent of the track segments, as indicated in Figure 5-1(d). Track curvature does not vary with travel direction.

5.3.3 Empirical Fuel Use Rates

The variation in typical fuel use rates based on cumulative frequency distribution for six one-way trips on single operated locomotive NC 1859 is given in Figure 5-2. The fuel use rate varied between 1 g/s and 159 g/s. Fuel use rates less than 3.1 g/s typically correspond to locomotive idling and account for approximately 38 percent of the trip time but only 2 percent of the trip total fuel use. The average fuel use rate at idle was 2.9 g/s. Fuel use rates greater than 150 g/s typically correspond to the highest throttle notch position of the engine. The steep slopes in the plot at low (between 1 g/s and 4 g/s), and high (between 140 g/s and 159 g/s) fuel use rates indicate that a relatively large proportion of time is spent at these fuel use rates, or at the lowest and highest throttle notch positions, respectively. The two together account for about 55 percent of the total trip duration. A good model should be able to predict the same range of fuel use rates as empirical.

5.3.4 Backward Moving Average Period

To help select a suitable backward moving average period, the Pearson correlation coefficient was estimated between FUER versus $\overline{LPD}_{n,t}$ for each combination of locomotives, consists, and fuels. LPD was calculated for each second of data and $\overline{LPD}_{n,t}$ at 1 Hz for up to 100 seconds and at increments of 5 to 10 seconds thereafter through 100 seconds was calculated. The correlations are given in Figure 5-3. The Pearson correlation coefficient for each locomotive consist was between 0.3 and 0.8 for fuel use rates and emission rates of CO_2, NO_x, and PM, except for PM emission rates for the double- and single-power consists of NC 1871 and NC 1984. For these two locomotives, the notch-average PM emission rates did not differ substantially between adjacent positions as observed for other locomotives.

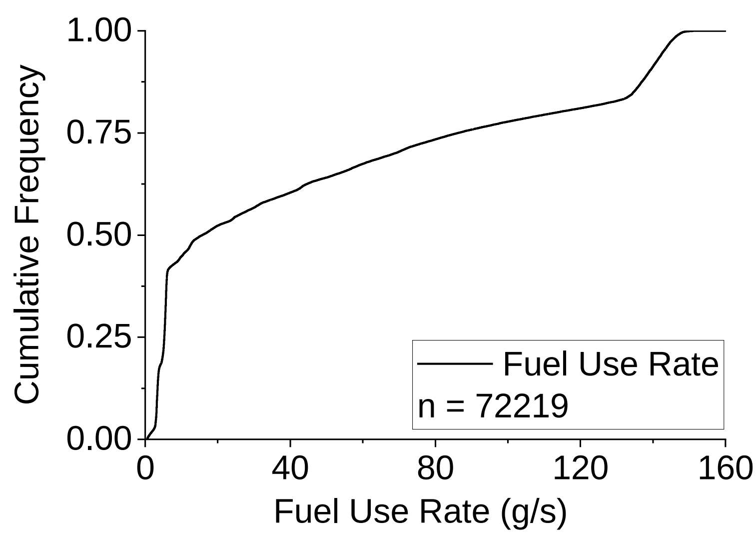


FIGURE 5-2. Cumulative Frequency Distributions of Fuel Use Rate Based on Six One-Way Trips on Single-Operated Locomotive NC 1859 Between Raleigh, NC and Charlotte, NC for the Piedmont Passenger Rail Service. The Six One-way Trips Included 72,219 Seconds of Data.

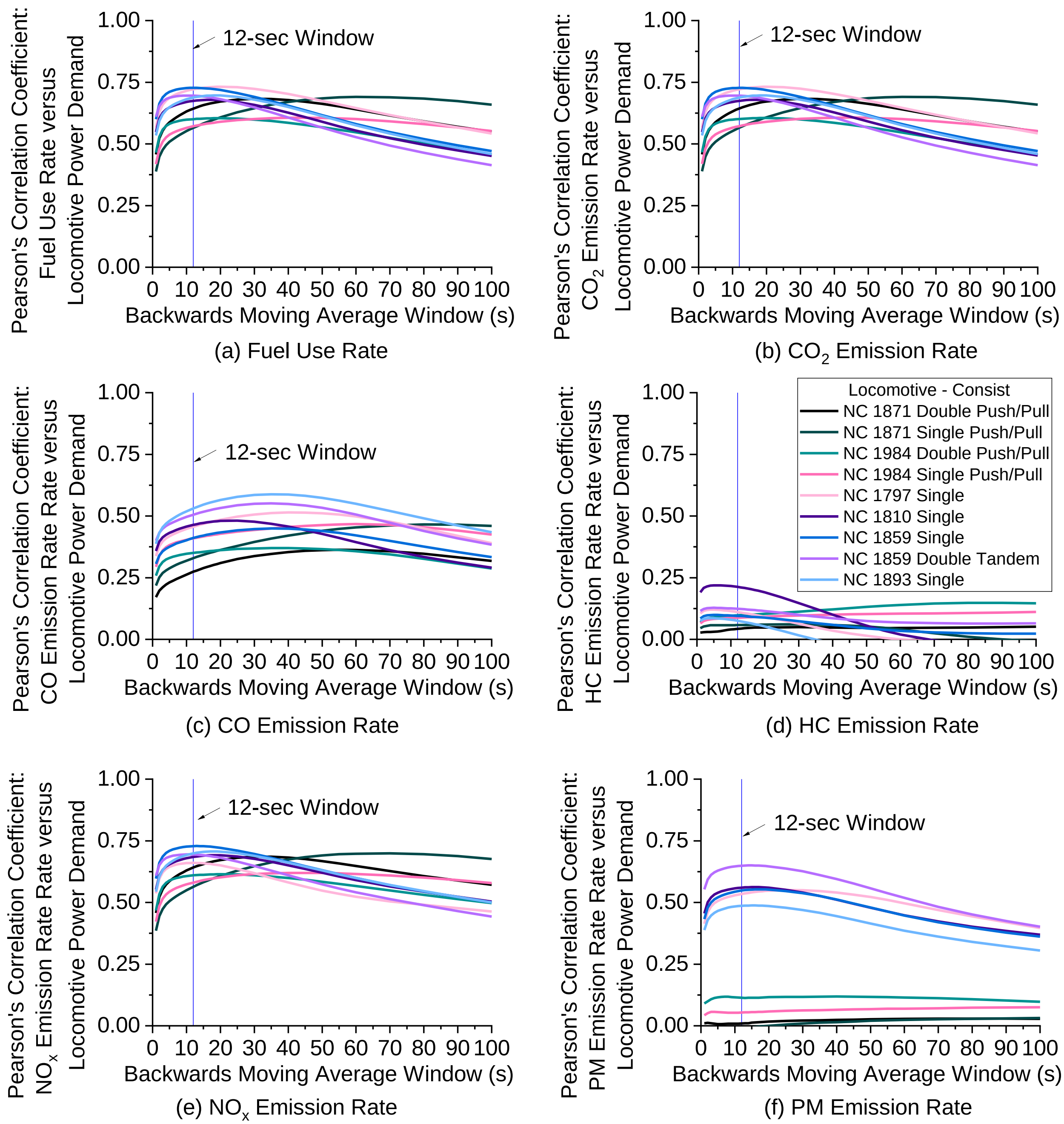


FIGURE 5-3. Pearson's Correlation Coefficient of Backwards Moving Average Locomotive Power Demand for All Train Consists with: (a) Fuel Use Rates; (b) CO_2 Emission Rates; (c) CO Emission Rates; (d) HC Emission Rates; (e) NO_x Emission Rates; and (f) PM Emission Rates. The legend for each figure panel is given in panel (d).

The Pearson correlation coefficient for CO emission rates varied between 0.2 and 0.6. HC emission rates were weakly correlated with LPD. As discussed in Section 4.8, HC emission rates do not differ substantially between adjacent notch positions leading to less variation in HC emission rates with LPD. CO and HC emission rates are low for diesel locomotives.

For fuel use rates and emission rates of CO_2, NO_x, and PM, the Pearson correlation coefficient increased sharply with the moving average period for the first 5 to 10 seconds. In most cases, the correlation coefficient peaked around a moving average period of 11 to 14 seconds and started to decrease gradually for longer moving average periods. On average for each combination of locomotive, consist and fuel, the Pearson correlation coefficient for fuel use rates and emission rates of CO_2, NO_x, and PM was the highest at 12 seconds. Therefore, a 12-second backward moving average period was found to be the most suitable basis for averaging LPD to predict FUER. The moving averaging time used for an independent variable does not have to be the same as the order of lagged error terms (Box *et al.*, 2015).

Differences in the trend of fuel use rate with respect to LPD are assessed based on instantaneous and backward moving average LPD. The differences are illustrated based on an example of a single-locomotive consist of NC 1859. The variation of fuel use rate with respect to LPD_t and $\overline{LPD}_{12,t}$ for six one-way trips on the single-operated locomotive, NC 1859 is shown in Figure 5-4. Power demand was binned into groups. The mean fuel use rate and the 95% confidence interval on the mean of fuel use rate were estimated for each group. Error bars in the figure indicate the 95% confidence interval of the mean fuel use rate for each group. For groups based on instantaneous LPD, mean fuel use rate is approximately constant at a low value for negative LPD_t and is larger for positive LPD_t.

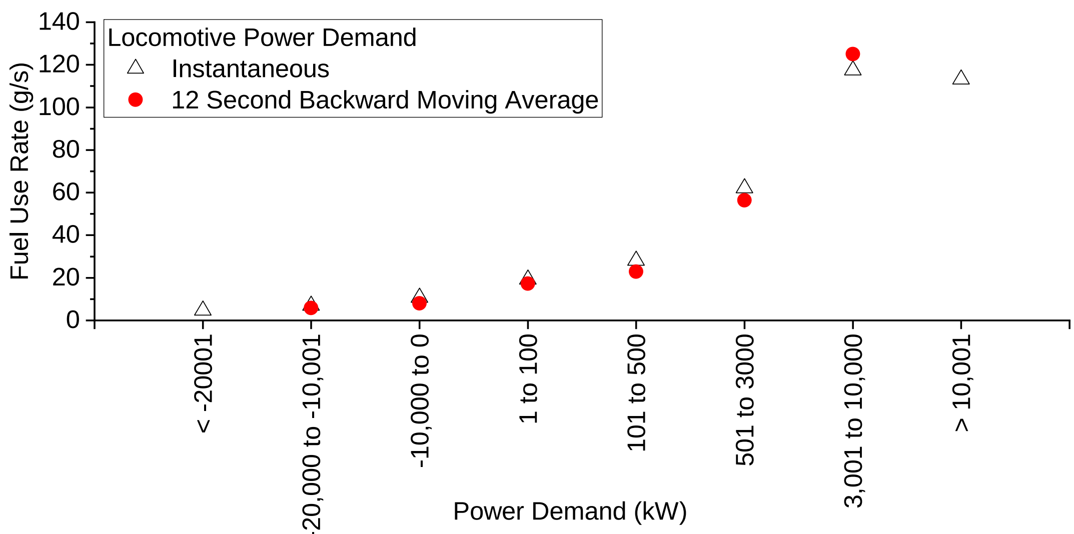


FIGURE 5-4. Comparison of the Relationship between Fuel Use Rate for Six One-Way Trips on Single Operated Locomotive NC 1859 versus Instantaneous Locomotive Power Demand-based Group versus 12-Second Backwards Moving Average Locomotive Power Demand-based Group. The Six One-way Trips Included 72,219 Seconds of Data. Not shown: 95% confidence intervals on averages were ± 5% of the mean or less.

However, fuel use rate increases monotonically with increasing positive LPD_t, except at the highest bin. For groups based on backward moving average LPD, fuel use rate increases monotonically with positive $\overline{LPD}_{12,t}$. A more continuous trend was observed in average fuel use rate with LPD for $\overline{LPD}_{12,t}$ versus LPD_t particularly for the bin from 3001 to 10000 LPD. The mean trend in 1 Hz fuel use rate ranged from idle fuel use rate to 105 g/s based on LPD_t. Whereas, the mean trend in fuel use rate for $\overline{LPD}_{12,t}$ ranged from idle fuel use rate to 130 g/s. Therefore, a wider range of the mean trend in fuel use rate can be explained based on $\overline{LPD}_{12,t}$ versus LPD_t.

Similar relative trends as for fuel use rate were observed for emission rates of CO_2, NO_x, and PM. Therefore, FUER based on $\overline{LPD}_{12,t}$ can explain a larger variability in empirical FUER versus LPD_t.

5.3.5 Model Calibration

In this section, models calibrated without the lagged error terms are evaluated for each combination of locomotive, consist, and fuel based on Equation 5-18. The models calibrated with the lagged error terms are evaluated in Appendix F. In total there are 12 combinations of locomotive, consist and fuel. For each combination of locomotive, consist and fuel, an LPD model was calibrated based on every measured one-way trip, except for one, using LOO cross-validation. As discussed in Section 5.2.1, locomotives NC 1792, NC 1755 and NC 1869 were excluded from analysis because of two or fewer measured one-way trips. The idle FUER for each locomotive, consist, and fuel, which are inputs to Equation 5-18, are given in Table 5-4. An example of model calibration without the error term based on each LOO cross-validation case of locomotive single consist locomotive NC 1859 operated on ULSD is given in the next section. Calibration and validation of models with and without lagged error terms for each LOO cross-validation case and for a model calibrated to all available trips for other locomotives, consists, and fuels are given in Appendix F. The model accuracy and precision with and without lagged error terms is evaluated.

TABLE 5-4. Steady-State Idle Fuel Use Rate and Emission Rates of CO_2, CO, HC, NO_x and PM for Each Locomotive, Consist and Fuel used in Locomotive Power Demand Model Calibration.

Locomotive	Consist	Idle Rate (g/s)					
		Fuel Use	CO_2	CO	HC	NO_x	PM
NC 1797	Single	7.4	23	0.091	0.60	0.95	0.015
NC 1810	Single	2.8	8.1	0.073	0.48	0.25	0.026
NC 1859	Single	3.3	10	0.016	0.07	0.34	0.033
NC 1859	Double Tandem	3.0	10	0.015	0.05	0.21	0.037
NC 1893	Single	2.7	8.2	0.014	0.06	0.22	-[a]
NC 1871	Double Push/Pull	3.0	9.3	0.018	0.07	0.33	0.028
NC 1871	Single Push/Pull	3.2	8.2	0.014	0.11	0.32	0.025
NC 1984	Double Push/Pull	3.1	9.7	0.075	0.12	0.33	0.044
NC 1984	Single Push/Pull	3.3	10	0.073	0.30	0.30	0.033

The idle FUER indicated here are used as input to Equation 5-18 as described in Section 5.2.3. The idle FUER are estimated for steady-state operation and assumed to be constant with time for a given combination of locomotive, consist, and fuel.

5.3.5.1. Locomotive NC 1859

Detailed examples of calibrated models without the lagged error terms for fuel use rate and emission rates of CO_2, CO, HC, NO_x and PM with respect to $\overline{LPD}_{12,t}$ are given in Table 5-5 for the single-locomotive consist OTR measurements of NC 1859 operated on ULSD. These examples include the estimated proportionality constant of Equation 5-18 as described in Section 5.2.3, along with diagnostic statistics. The diagnostic statistics indicate the precision of the proportionality constant based on the 95% confidence interval and the coefficient of determination. Results are given for the LOO cross-validation cases and for a "final" model without the lagged error term in which all trips are used for model calibration.

For fuel use rate, the proportionality constant without the lagged error terms varied over a narrow range of 0.030 g/kW to 0.032 g/kW among the six LOO cross-validation cases. Thus, the value of this constant is nearly insensitive to the choice of trips used for model calibration. Each cross-validated model has a narrow confidence interval on the proportionality constant, and coefficient of determination of 0.68 to 0.75. The p-value of the proportionality constant was below 0.05 for all of these cases. Each cross-validated model is of similar precision. Given that the model parameter value and diagnostic statistics are insensitive to the choice of trips used for model calibration, a "final" model was fit based on all of the available six one-way trips.

For CO_2 emission rate, the proportionality constant without the lagged error terms varied over a narrow range of 0.094 g/kW to 0.102 g/kW among the six LOO cross-validation cases. Similar to fuel use, the model parameter value and diagnostic statistics are insensitive to the choice of trips used for model calibration, a "final" model was fit based on all of the available six one-way trips. The results for each of the other pollutants, including CO, HC, NO_x, and PM, generally indicate precise estimates of the proportionality constants for each LOO cross-validation case, and for the final model calibrated to all of the available trips. The proportionality constants for each LOO cross-validation case for a given pollutant were typically within three percent of each other, which indicates that the value of this parameter is not sensitive to the choice of trips used for model calibration. Therefore, a final model was calibrated without lagged error terms for each pollutant to all of the available trips. The precision of the proportionality constants is indicated by narrow confidence intervals that are typically within ± 1 percent of the mean. The high precision of the proportionality constants in all cases, including those for HC emission rates for which the model coefficient of determination was very low (e.g., 0.05), is because of the large sample sizes of 1 Hz data used in model calibration. The sample size is approximately 60,000 data points for each LOO cross-validation case, and 70,000 for each final model.

Similar to NC 1859, the 1 Hz FUER models without the lagged error terms for other locomotives, consists, and fuels were insensitive to the choice of trips for fuel use rates and emissions rates of CO_2, CO, HC and NO_x and PM. Final models fit to each species for each locomotive, consist, and fuel are given in the next section. The calibrated model parameters for each LOO cross-validation case, and for the final model based on all trips of a locomotive and consist for ULSD and B20 biodiesel are given in Appendix F.

TABLE 5-5. Locomotive Power Demand Model Parameters Calibrated Without Lagged Error Term for the Single Consist of Locomotive NC 1859 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.032	[0.031, 0.033]	0.68
	1,3,4,5,6	2	0.032	[0.032, 0.032]	0.74
	1,2,4,5,6	3	0.032	[0.031, 0.033]	0.72
	1,2,3,5,6	4	0.030	[0.029, 0.031]	0.73
	1,2,3,4,6	5	0.031	[0.030, 0.032]	0.75
	1,2,3,4,5	6	0.031	[0.031, 0.031]	0.71
	Final Model		0.031	[0.030, 0.032]	0.72
CO_2 Emission Rate	2,3,4,5,6	1	0.094	[0.092, 0.096]	0.69
	1,3,4,5,6	2	0.098	[0.096, 0.101]	0.74
	1,2,4,5,6	3	0.098	[0.096, 0.100]	0.77
	1,2,3,5,6	4	0.102	[0.100, 0.105]	0.75
	1,2,3,4,6	5	0.100	[0.098, 0.102]	0.70
	1,2,3,4,5	6	0.100	[0.099, 0.101]	0.72
	Final Model		0.099	[0.097, 0.101]	0.73
CO Emission Rate	2,3,4,5,6	1	0.00012	[0.00010, 0.00013]	0.42
	1,3,4,5,6	2	0.00013	[0.00013, 0.00013]	0.45
	1,2,4,5,6	3	0.00012	[0.00010, 0.00013]	0.41
	1,2,3,5,6	4	0.00013	[0.00013, 0.00013]	0.43
	1,2,3,4,6	5	0.00012	[0.00012, 0.00012]	0.42
	1,2,3,4,5	6	0.00011	[0.00011, 0.00011]	0.40
	Final Model		0.00012	[0.00011, 0.00012]	0.42

The LPD model was calibrated based on Equation 5-18.

Table 5-5 Continued on next page.

Table 5-5 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.000042	[0.000038, 0.000047]	0.05
	1,3,4,5,6	2	0.000036	[0.000034, 0.000038]	0.05
	1,2,4,5,6	3	0.000036	[0.000032, 0.000039]	0.06
	1,2,3,5,6	4	0.000037	[0.000034, 0.000041]	0.05
	1,2,3,4,6	5	0.000039	[0.000035, 0.000042]	0.05
	1,2,3,4,5	6	0.000032	[0.000028, 0.000035]	0.03
	Final Model		0.000037	[0.000034, 0.00004]	0.05
NO_x Emission Rate	2,3,4,5,6	1	0.0018	[0.0018, 0.0018]	0.82
	1,3,4,5,6	2	0.0017	[0.0017, 0.0017]	0.77
	1,2,4,5,6	3	0.0016	[0.0016, 0.0016]	0.78
	1,2,3,5,6	4	0.0016	[0.0016, 0.0016]	0.80
	1,2,3,4,6	5	0.0017	[0.0017, 0.0017]	0.77
	1,2,3,4,5	6	0.0016	[0.0016, 0.0016]	0.77
	Final Model		0.0017	[0.0017, 0.0017]	0.78
PM Emission Rate	2,3,4,5,6	1	0.000052	[0.000052, 0.000052]	0.52
	1,3,4,5,6	2	0.000052	[0.000051, 0.000054]	0.54
	1,2,4,5,6	3	0.000051	[0.000050, 0.000052]	0.55
	1,2,3,5,6	4	0.000054	[0.000053, 0.000055]	0.53
	1,2,3,4,6	5	0.000052	[0.000050, 0.000053]	0.53
	1,2,3,4,5	6	0.000049	[0.000048, 0.000050]	0.52
	Final Model		0.000052	[0.000051, 0.000052]	0.53

Sample size of calibration trips varied from 59,745 to 60,373. The sample size for the final model was 72,219. The LPD model was calibrated based on Equation 5-18.

5.3.5.2. Other Locomotives, Consists, and Fuels

A model without the lagged error terms was fit to all available trips for each species for each locomotive, consist, and fuel. These models are given in Table 5-6. For fuel use rate and each pollutant emission rate, there is substantial variability in the proportionality constants among locomotives, consists, and fuels. However, the 95% confidence interval on the proportionality constant calibrated without the lagged error terms is typically within ± 10% indicating that these parameters are precisely estimated because of the large sample sizes of 32,214 to 65,634 for these models. The model R^2 for other locomotives, consists, and fuels for fuel use and emissions were similar to those for the single-locomotive consist of NC 1859 operated on ULSD.

On average for all locomotives, consists, and fuels, the model R^2 without the lagged error terms for fuel use and CO_2 emission rates was 0.74. The average R^2 for NO_x and PM emission rates was 0.72 and 0.62, respectively. Thus, the models for fuel use rate, and emission rates of CO_2, NO_x, and PM are generally highly correlated with empirical 1 Hz data, which demonstrates that the models are precise. However, the average R^2 for CO and HC emission rates was 0.36 and 0.08, respectively. Thus, in general, the models were more precise for fuel use and emission rates of CO_2, NO_x, and PM, and explain more variability in 1 Hz rates, than for CO and HC emission rates.

For a given pollutant, the model R^2 for fuel use and emission rates of CO_2, NO_x, and PM had a CV of 0.10 or lower among different combinations of locomotives, consists, and fuels. Therefore, all models typically had similar precision for model estimates of fuel use and emission rates of CO_2, NO_x, and PM. The CV for CO emission rates was 0.4 and HC emission rates was 0.8. Thus, the precision of model estimates of CO and HC emission rates varied among locomotives, consists, and fuels.

The trends in proportionality constants are not indicative of the trends in predicted FUER and TFUEs because the proportionality constants were calibrated based on non-idle data only. Thus, the proportionality constants are not directly related to FUER or TFUEs.

5.3.5.3. Calibration Model Sensitivity to Lagged Error Terms

The models for each combination of locomotive, consist, and fuel were calibrated with and without the lagged error terms. The calibrated proportionality constants and model R^2 are compared to assess the sensitivity of the LPD model to lagged error terms. For each combination of locomotive, consist, and fuel, the order of the lagged error term was 5 seconds and each of the weighting parameter was between 0.1 and 0.8. The estimation of order and weighting parameters is given in Appendix F. Since all of the weighting parameters were positive, the lagged error term was also typically positive. Because of the overall positive lagged error term added to the model, the proportionality constants calibrated for the model without lagged error terms are expected to be higher than the proportionality constants calibrated for the model with lagged error terms. The model calibrated with lagged error terms is expected to have higher model R^2 because of additional terms included in the model, which provide more degrees of freedom for model fitting.

TABLE 5-6. Final Locomotive Power Demand Model Parameters Calibrated Without the Lagged Error Term based on Every One-way Trip for Each Locomotive, Consist and Fuel for Fuel Use Rates and Emission Rates of CO_2, CO, HC, NO_x and PM.

Species	Locomotive	Consist	Fuel	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	NC 1859	Single	ULSD	0.031	[0.030, 0.032]	0.72
	NC 1797	Single	ULSD	0.036	[0.036, 0.037]	0.82
	NC 1810	Single	ULSD	0.030	[0.030, 0.031]	0.77
	NC 1859	Tandem	ULSD	0.029	[0.028, 0.029]	0.79
	NC 1893	Single	ULSD	0.027	[0.027, 0.027]	0.79
	NC 1871	DP[a]	ULSD	0.029	[0.028, 0.029]	0.73
	NC 1871	SP[a]	ULSD	0.034	[0.034, 0.035]	0.69
	NC 1984	DP[a]	ULSD	0.020	[0.020, 0.021]	0.63
	NC 1984	SP[a]	ULSD	0.030	[0.030, 0.031]	0.71
	NC 1810	Single	B20	0.038	[0.038, 0.039]	0.81
	NC 1797	Single	B20	0.030	[0.030, 0.031]	0.77
	NC 1859	Single	B20	0.044	[0.044, 0.045]	0.63
CO_2 Emission Rate	NC 1859	Single	ULSD	0.099	[0.097, 0.101]	0.73
	NC 1797	Single	ULSD	0.115	[0.114, 0.116]	0.82
	NC 1810	Single	ULSD	0.099	[0.098, 0.100]	0.79
	NC 1859	Tandem	ULSD	0.091	[0.090, 0.092]	0.79
	NC 1893	Single	ULSD	0.097	[0.096, 0.098]	0.79
	NC 1871	DP[a]	ULSD	0.093	[0.091, 0.094]	0.73
	NC 1871	SP[a]	ULSD	0.110	[0.108, 0.112]	0.70
	NC 1984	DP[a]	ULSD	0.064	[0.063, 0.066]	0.61
	NC 1984	SP[a]	ULSD	0.093	[0.091, 0.095]	0.72
	NC 1810	Single	B20	0.103	[0.102, 0.103]	0.79
	NC 1797	Single	B20	0.098	[0.097, 0.099]	0.78
	NC 1859	Single	B20	0.138	[0.137, 0.139]	0.63

The LPD model was calibrated based on Equation 5-18.

Table 5-6 Continued on the next page.

Table 5-6 Continued from the previous page.

Species	Locomotive	Consist	Fuel	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Goodness of Fit (R^2)
CO Emission Rate	NC 1859	Single	ULSD	0.00012	[0.00011, 0.00012]	0.43
	NC 1797	Single	ULSD	0.00015	[0.00015, 0.00016]	0.46
	NC 1810	Single	ULSD	0.00030	[0.00029, 0.00030]	0.48
	NC 1859	Tandem	ULSD	0.00011	[0.00010, 0.00011]	0.48
	NC 1893	Single	ULSD	0.00007	[0.00007, 0.00007]	0.60
	NC 1871	DP[a]	ULSD	0.00010	[0.00009, 0.00011]	0.15
	NC 1871	SP[a]	ULSD	0.00022	[0.00021, 0.00023]	0.32
	NC 1984	DP[a]	ULSD	0.00030	[0.00028, 0.00033]	0.24
	NC 1984	SP[a]	ULSD	0.00046	[0.00045, 0.00048]	0.44
	NC 1810	Single	B20	0.00044	[0.00043, 0.00045]	0.36
	NC 1797	Single	B20	0.00003	[0.00003, 0.00003]	0.26
	NC 1859	Single	B20	0.00010	[0.00010, 0.00010]	0.11
HC Emission Rate	NC 1859	Single	ULSD	0.00004	[0.00003, 0.00004]	0.05
	NC 1797	Single	ULSD	0.00013	[0.00012, 0.00014]	0.05
	NC 1810	Single	ULSD	0.00024	[0.00023, 0.00025]	0.23
	NC 1859	Tandem	ULSD	0.00003	[0.00003, 0.00003]	0.09
	NC 1893	Single	ULSD	0.00002	[0.00002, 0.00002]	0.07
	NC 1871	DP[a]	ULSD	0.00003	[0.00002, 0.00003]	0.12
	NC 1871	SP[a]	ULSD	0.00001	[0.00000, 0.00001]	0.01
	NC 1984	DP[a]	ULSD	0.00006	[0.00003, 0.00007]	0.01
	NC 1984	SP[a]	ULSD	0.00017	[0.00014, 0.00020]	0.03
	NC 1810	Single	B20	0.00003	[0.00003, 0.00003]	0.06
	NC 1797	Single	B20	0.00013	[0.00012, 0.00014]	0.13
	NC 1859	Single	B20	0.00021	[0.00020, 0.00021]	0.11

The LPD model was calibrated based on Equation 5-18.

Table 5-6 Continued on the next page.

Table 5-6 Continued from the previous page.

Species	Locomotive	Consist	Fuel	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Goodness of Fit (R^2)
NO_x Emission Rate	NC 1859	Single	ULSD	0.0017	[0.0017, 0.0017]	0.78
	NC 1797	Single	ULSD	0.0025	[0.0025, 0.0026]	0.69
	NC 1810	Single	ULSD	0.0012	[0.0012, 0.0012]	0.78
	NC 1859	Tandem	ULSD	0.0015	[0.0014, 0.0015]	0.75
	NC 1893	Single	ULSD	0.0014	[0.0014, 0.0014]	0.78
	NC 1871	DP[a]	ULSD	0.0028	[0.0027, 0.0028]	0.72
	NC 1871	SP[a]	ULSD	0.0032	[0.0031, 0.0033]	0.70
	NC 1984	DP[a]	ULSD	0.0015	[0.0015, 0.0016]	0.63
	NC 1984	SP[a]	ULSD	0.0020	[0.0020, 0.0021]	0.72
	NC 1810	Single	B20	0.0011	[0.0011, 0.0011]	0.78
	NC 1797	Single	B20	0.0023	[0.0023, 0.0023]	0.67
	NC 1859	Single	B20	0.0022	[0.0022, 0.0022]	0.67
PM Emission Rate	NC 1859	Single	ULSD	0.000052	[0.000051, 0.000052]	0.53
	NC 1797	Single	ULSD	0.000032	[0.000031, 0.000032]	0.58
	NC 1810	Single	ULSD	0.000072	[0.000070, 0.000073]	0.61
	NC 1859	Tandem	ULSD	0.000042	[0.000041, 0.000043]	0.72
	NC 1893	Single	ULSD	-[b]	-[b]	-[b]
	NC 1871	DP[a]	ULSD	0.000041	[0.000041, 0.000042]	0.63
	NC 1871	SP[a]	ULSD	0.000049	[0.000049, 0.000050]	0.63
	NC 1984	DP[a]	ULSD	0.000040	[0.000038, 0.000042]	0.58
	NC 1984	SP[a]	ULSD	0.000046	[0.000044, 0.000048]	0.64
	NC 1810	Single	B20	0.000054	[0.000053, 0.000054]	0.66
	NC 1797	Single	B20	0.000029	[0.000028, 0.000030]	0.71
	NC 1859	Single	B20	0.000048	[0.000047, 0.000049]	0.51

[a] *DP = double-powered consist; SP = single-powered consist.*

[b] *No valid data available for the select locomotive, consist and fuel*

The sample size of the final model varied from 32,214 to 65,634. The LPD model was calibrated based on Equation 5-18.

Example plots of calibrated proportionality constant and model R^2 for fuel use rate for each combination of locomotive, consist, and fuel are given in Figure 5-5. The calibrated proportionality constants for the model without the lagged term were 5 percent to 11 percent higher versus the model calibrated with lagged error term. The 95% confidence interval on the proportionality constant was also 7 percent to 13 percent wider for the model calibrated without lagged error term. The calibrated model R^2 for model without the lagged term was 7 percent to 12 percent lower. Therefore, calibrated models were more precise with lagged error terms versus without lagged error terms. For fuel use rate among the 12 combinations of locomotives, consists, and fuels, average model R^2 without the lagged error terms was greater than 0.70 for 9 combinations. However, for the models calibrated with the lagged error terms, average model R^2 was greater than 0.70 for 10 combinations. On average, model R^2 for fuel use rate was 6 percent lower for model without lagged error terms versus for the model with lagged error terms. For emission rates also, the differences in model R^2 were not substantial. Thus, the model performance was not substantially affected when the model was calibrated without versus without the lagged error terms.

5.3.6 Model Validation

The calibrated models without the lagged error terms based on LOO cross-validation case were validated based on the methods described in Section 5.2.3. The models were validated based on comparison of estimated versus predicted FUER at 1 Hz and estimated versus predicted TFUE for individual trips.

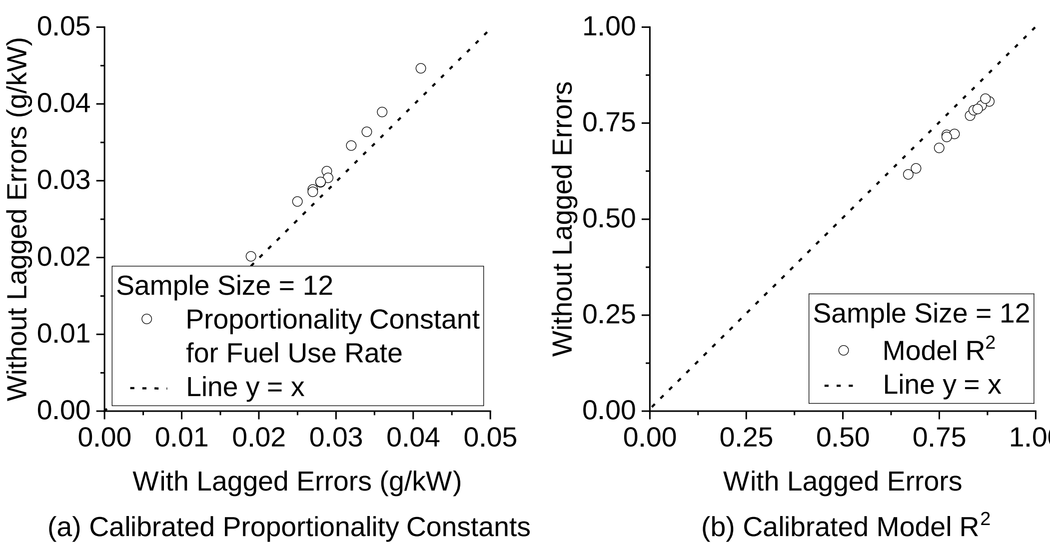


FIGURE 5-5. Comparison of Average Calibrated Proportionality Constant and Model Goodness-of-fit for Fuel Use Rate for Each Combination of Locomotive, Consist, and Fuel based on Locomotive Power Demand Model Calibrated With and Without Lagged Error Terms: (a) Calibrated Proportionality Constants; and (b) Calibrated Model Goodness-of-fit.

5.3.6.1. *One Hz Model Validation*

Validation parameters for model without the lagged error terms include the estimated slope of the parity plot between modeled versus empirical rates, along with diagnostic statistics. The diagnostic statistics indicate the precision of the slope based on the 95% confidence interval and the coefficient of determination.

5.3.6.2. *Locomotive NC 1859*

Model validation parameters without the lagged error terms for each LOO cross-validation case for fuel use rate and emission rates of CO_2, CO, HC, NO_x, and PM with respect to $\overline{LPD}_{12,t}$ are given in Table 5-7 for the single-locomotive consist OTR measurements of NC 1859 operated on ULSD. For fuel use rate, the parity slope varied over a narrow range of 0.89 to 1.12 among the six LOO cross-validation cases. The average slope for 6 trips was1.02. Thus, on average these models are accurate. Each cross-validated model has a narrow confidence interval on the parity slope, within ±5 percent of the parity slope. The model R^2 varied from 0.75 to 0.87. The p-value of the proportionality constant was below 0.05 for all of these cases. Thus, the models are precise. Each cross-validated model is of similar precision.

For CO_2 emission rate, the parity slope without the lagged error terms varied over a narrow range of 0.89 to 1.11 among the six LOO cross-validation cases. The model parameters and diagnostic statistics were similar to those for fuel use rate. The results for each of the other pollutants, including CO, NO_x, and PM generally indicated precise estimates of the slope for each LOO cross-validation case based on confidence intervals within ±7 percent of the parity slope. The high precision of the slope is because of large sample sizes, which typically ranged from 10,534 to 13,354 among each LOO cross-validation case. For HC emission rates, the confidence interval was within ±25 percent of the slope. However, the average slope for all available trips was1.09. Thus, on average over available trips, HC emission rates were accurate, even though they were imprecise compared to other pollutants.

The model R^2 for each LOO cross-validation case for fuel use and emission rates of CO_2 was 0.75 or higher, indicating high precision of the model calibrated without lagged error terms. The model R^2 for CO, NO_x and PM emission rates was moderate, ranging from 0.35 to 0.81. The model R^2 for HC emission rates was the lowest, typically less than 0.09. The model was least precise for HC emission rates, but still accurate overall. The lower precision for HC emission rates is expected since notch-average HC exhaust concentrations were typically below the gas analyzer detection limits for most notch positions for all locomotives. Thus, the 1 Hz empirical emission rate data for HC are more imprecise compared to any of the other pollutants.

5.3.6.3. *Other Locomotives, Consists, and Fuels*

For the remaining locomotives, consists, and fuels, the average validation parameters for models calibrated without lagged error terms based on each LOO cross-validation case are given in Table 5-8. Validation parameters for each LOO cross-validation case for each locomotive, consist, and fuel are given in Appendix F.

TABLE 5-7. Locomotive Power Demand Model Parameters Validated Without Lagged Error Term for the Single Consist of Locomotive NC 1859 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	1.12	[1.06, 1.19]	0.75
	1,3,4,5,6	2	1.08	[1.05, 1.11]	0.79
	1,2,4,5,6	3	1.06	[0.98, 1.14]	0.87
	1,2,3,5,6	4	0.91	[0.87, 0.95]	0.83
	1,2,3,4,6	5	1.07	[1.02, 1.11]	0.77
	1,2,3,4,5	6	0.89	[0.86, 0.93]	0.81
	Average		1.02	[0.97, 1.07]	0.80
CO_2 Emission Rate	2,3,4,5,6	1	1.11	[1.07, 1.16]	0.75
	1,3,4,5,6	2	1.10	[1.03, 1.13]	0.79
	1,2,4,5,6	3	1.04	[0.96, 1.16]	0.89
	1,2,3,5,6	4	0.89	[0.87, 0.97]	0.84
	1,2,3,4,6	5	1.07	[1.03, 1.09]	0.78
	1,2,3,4,5	6	0.90	[0.85, 0.93]	0.79
	Average		1.02	[0.96, 1.05]	0.81
CO Emission Rate	2,3,4,5,6	1	1.26	[1.09, 1.44]	0.39
	1,3,4,5,6	2	0.82	[0.71, 0.93]	0.38
	1,2,4,5,6	3	0.88	[0.79, 0.97]	0.37
	1,2,3,5,6	4	1.25	[1.18, 1.33]	0.49
	1,2,3,4,6	5	0.86	[0.71, 1.01]	0.39
	1,2,3,4,5	6	1.28	[1.11, 1.45]	0.35
	Average		1.06	[0.93, 1.19]	0.40

Table 5-7 Continued on next page.

Table 5-7 Continued from previous page.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	1.15	[0.86, 1.44]	0.05
	1,3,4,5,6	2	0.61	[0.33, 0.88]	0.05
	1,2,4,5,6	3	1.00	[0.62, 1.39]	0.05
	1,2,3,5,6	4	1.69	[1.37, 2.00]	0.05
	1,2,3,4,6	5	0.64	[0.33, 0.94]	0.04
	1,2,3,4,5	6	1.47	[1.27, 1.68]	0.04
	Average		1.09	[0.80, 1.39]	0.05
NO_x Emission Rate	2,3,4,5,6	1	1.06	[1.00, 1.11]	0.78
	1,3,4,5,6	2	1.14	[1.02, 1.27]	0.79
	1,2,4,5,6	3	1.17	[1.07, 1.26]	0.73
	1,2,3,5,6	4	1.00	[0.82, 1.19]	0.75
	1,2,3,4,6	5	1.11	[1.05, 1.17]	0.75
	1,2,3,4,5	6	1.19	[1.02, 1.36]	0.69
	Average		1.11	[1.00, 1.23]	0.75
PM Emission Rate	2,3,4,5,6	1	1.20	[1.06, 1.34]	0.50
	1,3,4,5,6	2	1.13	[1.05, 1.22]	0.50
	1,2,4,5,6	3	1.28	[1.19, 1.36]	0.52
	1,2,3,5,6	4	0.98	[0.87, 1.09]	0.55
	1,2,3,4,6	5	1.18	[1.12, 1.23]	0.46
	1,2,3,4,5	6	1.01	[0.97, 1.06]	0.50
	Average		1.13	[1.04, 1.22]	0.51

Sample size of the validation trip varied from 10,534 to 13,354. The LPD model was calibrated based on Equation 5-18.

TABLE 5-8. Locomotive Power Demand Model Average Parameters Validated without Lagged Error Terms based on Every One-way Trip for Each Locomotive, Consist and Fuel for Fuel Use Rates and Emission Rates of CO_2, CO, HC, NO_x and PM.

Species	Locomotive	Consist	Fuel	Slope	95 % Confidence Interval on Slope	Goodness of Fit (R^2)
Fuel Use Rate	NC 1859	Single	ULSD	1.02	[0.97, 1.07]	0.80
	NC 1797	Single	ULSD	1.08	[1.01, 1.15]	0.79
	NC 1810	Single	ULSD	0.97	[0.94, 1.01]	0.73
	NC 1859	Tandem	ULSD	1.03	[0.95, 1.12]	0.77
	NC 1893	Single	ULSD	0.92	[0.88, 0.95]	0.72
	NC 1871	DP[a]	ULSD	1.03	[0.93, 1.13]	0.81
	NC 1871	SP[a]	ULSD	1.01	[0.97, 1.05]	0.67
	NC 1984	DP[a]	ULSD	1.02	[0.93, 1.10]	0.62
	NC 1984	SP[a]	ULSD	1.08	[1.03, 1.14]	0.67
	NC 1810	Single	B20	1.03	[0.90, 1.15]	0.78
	NC 1797	Single	B20	1.11	[1.03, 1.18]	0.79
	NC 1859	Single	B20	0.99	[0.93, 1.09]	0.60
CO_2 Emission Rate	NC 1859	Single	ULSD	1.02	[0.96, 1.05]	0.81
	NC 1797	Single	ULSD	1.09	[1.02, 1.16]	0.79
	NC 1810	Single	ULSD	0.97	[0.94, 1.01]	0.73
	NC 1859	Tandem	ULSD	1.03	[0.94, 1.11]	0.77
	NC 1893	Single	ULSD	0.93	[0.87, 0.98]	0.72
	NC 1871	DP[a]	ULSD	1.03	[1.03, 1.14]	0.81
	NC 1871	SP[a]	ULSD	1.02	[1.03, 1.14]	0.66
	NC 1984	DP[a]	ULSD	1.02	[1.03, 1.14]	0.62
	NC 1984	SP[a]	ULSD	1.08	[1.03, 1.14]	0.67
	NC 1810	Single	B20	1.04	[0.91, 1.16]	0.78
	NC 1797	Single	B20	1.11	[1.04, 1.19]	0.79
	NC 1859	Single	B20	0.99	[0.93, 1.09]	0.61

The LPD model was calibrated based on Equation 5-18.

Table 5-8 Continued on the next page.

Table 5-8 Continued from the previous page.

Species	Locomotive	Consist	Fuel	Slope	95 % Confidence Interval on Slope	Goodness of Fit (R^2)
CO Emission Rate	NC 1859	Single	ULSD	1.07	[0.94, 1.19]	0.39
	NC 1797	Single	ULSD	0.94	[0.80, 1.07]	0.44
	NC 1810	Single	ULSD	1.16	[1.05, 1.27]	0.46
	NC 1859	Tandem	ULSD	1.16	[1.06, 1.26]	0.47
	NC 1893	Single	ULSD	1.24	[1.11, 1.37]	0.41
	NC 1871	DP[a]	ULSD	1.11	[1.00, 1.22]	0.34
	NC 1871	SP[a]	ULSD	1.13	[0.99, 1.28]	0.33
	NC 1984	DP[a]	ULSD	1.43	[1.30, 1.56]	0.23
	NC 1984	SP[a]	ULSD	1.17	[1.12, 1.23]	0.43
	NC 1810	Single	B20	0.94	[0.83, 1.05]	0.34
	NC 1797	Single	B20	1.18	[1.08, 1.27]	0.40
	NC 1859	Single	B20	1.07	[0.94, 1.20]	0.10
HC Emission Rate	NC 1859	Single	ULSD	1.09	[0.80, 1.39]	0.05
	NC 1797	Single	ULSD	0.92	[0.73, 1.11]	0.05
	NC 1810	Single	ULSD	1.06	[0.73, 1.40]	0.22
	NC 1859	Tandem	ULSD	1.08	[0.86, 1.30]	0.08
	NC 1893	Single	ULSD	1.11	[0.84, 1.38]	0.07
	NC 1871	DP[a]	ULSD	1.25	[1.02, 1.50]	0.13
	NC 1871	SP[a]	ULSD	0.87	[0.55, 1.19]	0.01
	NC 1984	DP[a]	ULSD	1.06	[0.77, 1.35]	0.01
	NC 1984	SP[a]	ULSD	0.73	[0.43, 1.03]	0.03
	NC 1810	Single	B20	1.27	[0.99, 1.55]	0.05
	NC 1797	Single	B20	1.37	[1.18, 1.57]	0.14
	NC 1859	Single	B20	1.04	[0.72, 1.36]	0.11

The LPD model was calibrated based on Equation 5-18.

Table 5-8 Continued on the next page.

Table 5-8 Continued from the previous page.

Species	Locomotive	Consist	Fuel	Slope	95 % Confidence Interval on Slope	Goodness of Fit (R^2)
NO_x Emission Rate	NC 1859	Single	ULSD	1.11	[1.00, 1.23]	0.75
	NC 1797	Single	ULSD	1.03	[0.95, 1.11]	0.66
	NC 1810	Single	ULSD	1.06	[0.97, 1.15]	0.75
	NC 1859	Tandem	ULSD	1.01	[0.91, 1.10]	0.75
	NC 1893	Single	ULSD	1.01	[0.84, 1.17]	0.73
	NC 1871	DP[a]	ULSD	0.99	[0.88, 1.10]	0.66
	NC 1871	SP[a]	ULSD	0.98	[0.95, 1.00]	0.65
	NC 1984	DP[a]	ULSD	1.05	[0.97, 1.14]	0.60
	NC 1984	SP[a]	ULSD	0.95	[0.91, 1.00]	0.70
	NC 1810	Single	B20	1.08	[0.96, 1.20]	0.73
	NC 1797	Single	B20	1.02	[0.92, 1.11]	0.63
	NC 1859	Single	B20	1.04	[0.93, 1.16]	0.65
PM Emission Rate	NC 1859	Single	ULSD	1.07	[1.04, 1.22]	0.51
	NC 1797	Single	ULSD	1.10	[0.97, 1.22]	0.55
	NC 1810	Single	ULSD	1.09	[1.02, 1.20]	0.62
	NC 1859	Tandem	ULSD	1.10	[1.00, 1.19]	0.72
	NC 1893	Single	ULSD	-[b]	-[b]	-[b]
	NC 1871	DP[a]	ULSD	0.99	[0.96, 1.02]	0.67
	NC 1871	SP[a]	ULSD	1.08	[0.95, 1.21]	0.66
	NC 1984	DP[a]	ULSD	1.07	[0.93, 1.21]	0.71
	NC 1984	SP[a]	ULSD	0.96	[0.92, 1.00]	0.59
	NC 1810	Single	B20	1.13	[1.03, 1.23]	0.64
	NC 1797	Single	B20	0.99	[0.91, 1.07]	0.67
	NC 1859	Single	B20	1.06	[1.01, 1.21]	0.48

[a] *DP = double-powered consist; SP = single-powered consist.*

[b] *No valid data available for the select locomotive, consist and fuel*

Sample size of the validation trip varied from 10,434 to 14,132. The LPD model was calibrated based on Equation 5-18.

For fuel use rate and each pollutant emission rate, there is variability in the parity slope without lagged error terms among all 12 combinations of locomotives, consists, and fuels as indicated in Figure 5-6. For fuel use rate, the average parity slope is 1.02 and ranges from 0.92 to 1.11 among the 12 locomotive, consist, and fuel combinations. Thus, given that the slopes are within ±10 percent of the ideal value of 1, except for one combination, the models are judged to be accurate. The results are similar for CO_2 with a mean parity slope of 1.03 and range of 0.93 to 1.11. For CO, the mean parity slope of 1.13 and range of 0.94 to 1.43 reflects that the models are accurate for only 4 locomotive, consist, and fuel combinations and, on average over all 12 combinations, are biased high. In future work, mean model bias can be corrected. For example, for NC 1984, double-powered, and ULSD, the parity slope is 1.43. The model predictions can be corrected with a factor of 1/1.43, or 0.70. The average parity slope for the HC models is 1.07, with a range of 0.73 to 1.37. For HC, six of the models are accurate, two of the models are biased low, and four of the models are biased high. Similar to CO, the HC models can be bias-corrected. For NO_x, the mean parity slope is 1.03 with a range of 0.95 to 1.11. Except for the NC 1859, single-locomotive, and ULSD model, for which the parity slope is 1.11, the NO_x emission rate models are accurate. For PM, nine of the models are accurate, while two are biased high. No valid PM emission rates for NC 1893, single-locomotive, and ULSD were available. The mean parity slope for PM is 1.06, with a range of 0.96 to 1.13. Thus, for NO_x and PM, most of the models are accurate, and for the few models that are biased high, their parity slopes do not exceed 1.13. Bias corrections can be applied in the future to each model as needed.

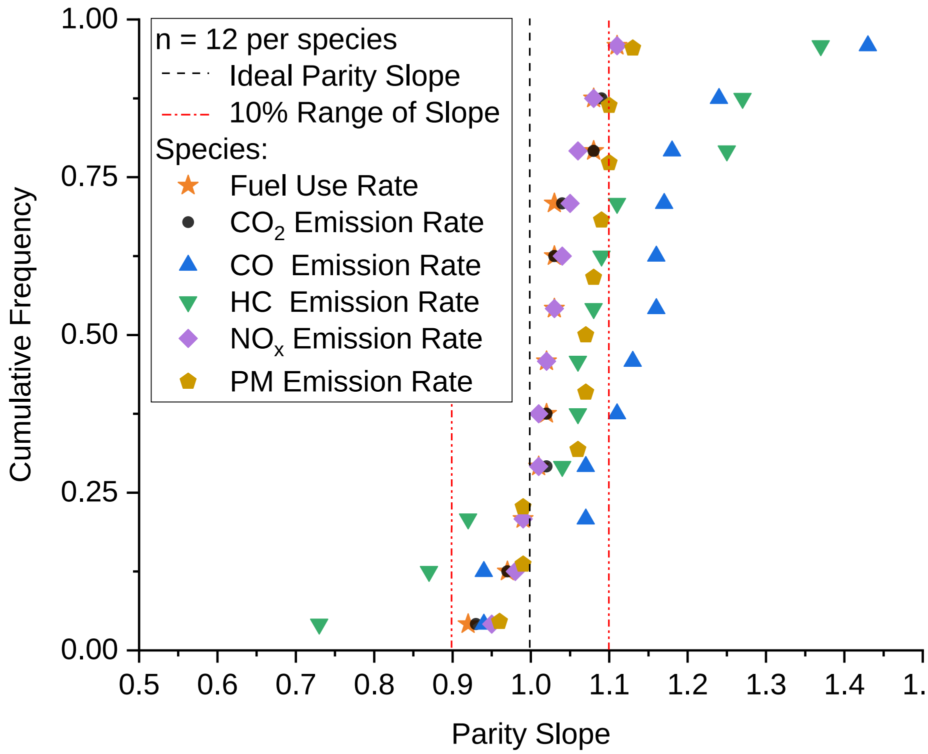


FIGURE 5-6. Cumulative Frequency Plot of Parity Slopes based on the Locomotive Power Demand Model Without Lagged Error Terms for All Combinations of Locomotive, Consist and Fuel for Fuel Use Rates and Emission Rates of CO_2, CO, HC, NO_x and PM. No valid data for PM Emission rates for the single-locomotive consist with NC 1893 operated on ULSD were available.

The 95% confidence interval on the parity slope was typically within ± 10%, except for HC. Therefore, the parity slopes for each model are precisely estimated because of the large sample sizes of 60,324 to 70,347 for these models.

The model R^2 without lagged error terms for all 12 combinations of locomotives, consists, and fuels for fuel use and emission rates of CO_2 was between 0.60 and 0.81. For NO_x and PM emission rates, the model R^2 was between 0.48 and 0.75. For CO emission rates, the model R^2 was between 0.10 and 0.44. For HC emission rates, the model R^2 was between 0.01 and 0.22. On average for all locomotives, consists, and fuels, the model R^2 for fuel use and CO_2 emission rates was 0.73. The average R^2 for NO_x and PM emission rates was 0.69 and 0.62, respectively. However, the average R^2 for CO emission rates was 0.36. The average R^2 for HC emission rates was 0.08. Thus, in general, the models were more precise for fuel use and emission rates of CO_2, $NO_{x,}$ and PM than for CO and HC emission rates.

For a given pollutant, the model R^2 for fuel use and emission rates of CO_2, $NO_{x,}$ and PM had a CV of 0.12 or lower among different combinations of locomotives, consists, and fuels. Therefore, all models without lagged error terms typically had similar precision for fuel use or emission rates of CO_2, $NO_{x,}$ and PM. The CV of model R^2 for CO emission rates was 0.5 and for HC emission rates was 0.8. Thus, the precision of model estimates of CO and HC emission rates varied among locomotives, consists, and fuels. The higher variability for CO and HC is expected given that for these pollutants the emission rates were low relative to the gas analyzer detection limit.

Example time-series plots of modeled, without lagged error terms, versus measured fuel use rate and emission rates of CO_2, CO, HC, NO_x and PM for one one-way trip on the single-operated locomotive NC 1859 operated on ULSD are illustrated in Figure 5-7. The peaks and troughs in the predicted rates coincide with peaks and troughs of empirical rates, respectively. Therefore, the power-demand model is able to appropriately respond to increases and decreases in the rates. For a given second of a trip, the predicted fuel use and emission rates were within ± 30 percent compared to estimated fuel use and emission rates. However, on average for an entire trip, the differences between 1 Hz predicted and estimated FUER were 3 percent or lower. This indicates that the random errors at 1 Hz compensate to some extent when averaged over a larger period of time such as trip duration.

5.3.6.4. Validation Sensitivity to Lagged Error Terms

In this section, the parity slope and model goodness-of-fit for the validation of fuel use rate are compared for the LPD model calibrated with and without lagged error terms in Figure 5-8. For either case, the average parity slopes were typically within 10 percent of the desired parity slope of 1. The parity slopes for the model without lagged error terms were 6 to 9 percent higher versus the model with lagged error terms. For the 12 combinations of locomotives, consists, and fuels, the average parity slope was within 10 percent of one for 10 combinations for the model without lagged error terms. For the model with lagged error terms, each of the 12 combinations had parity slopes within 10 percent of one. Thus, on average, the models with the error terms were more accurate than the models without the error term. However, the difference in accuracy was small, as indicated by six percent to nine percent difference in parity slope.

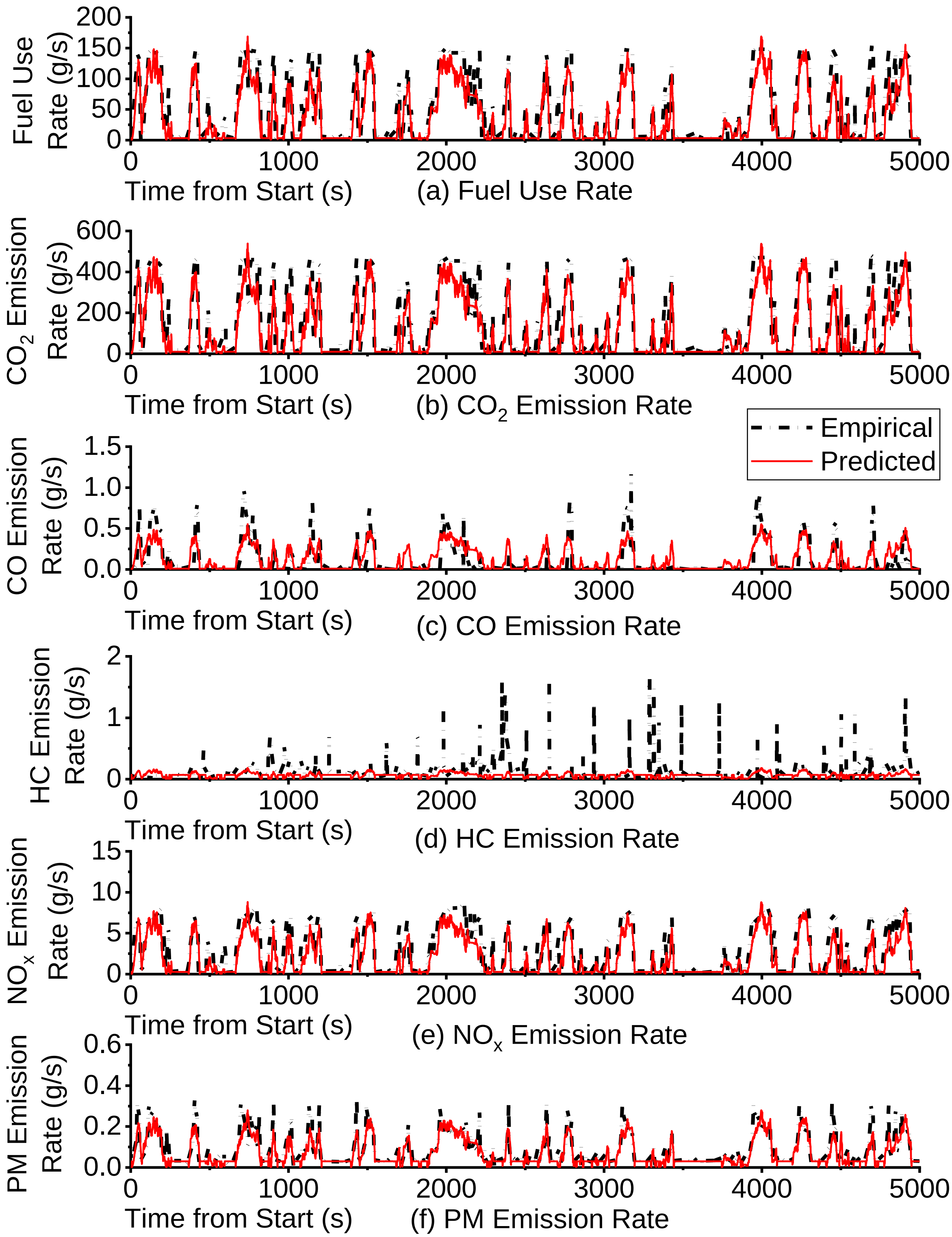


FIGURE 5-7. Comparison of Predicted Fuel Use and Emission Rates based on Locomotive Power Demand Model Calibrated Without Lagged Error Terms versus Empirical Fuel Use and Emission Rates at 1 Hz for the First 5000 seconds of a One-way Trip on Single-consist Locomotive NC 1859 operated on ULSD: (a) Fuel 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.

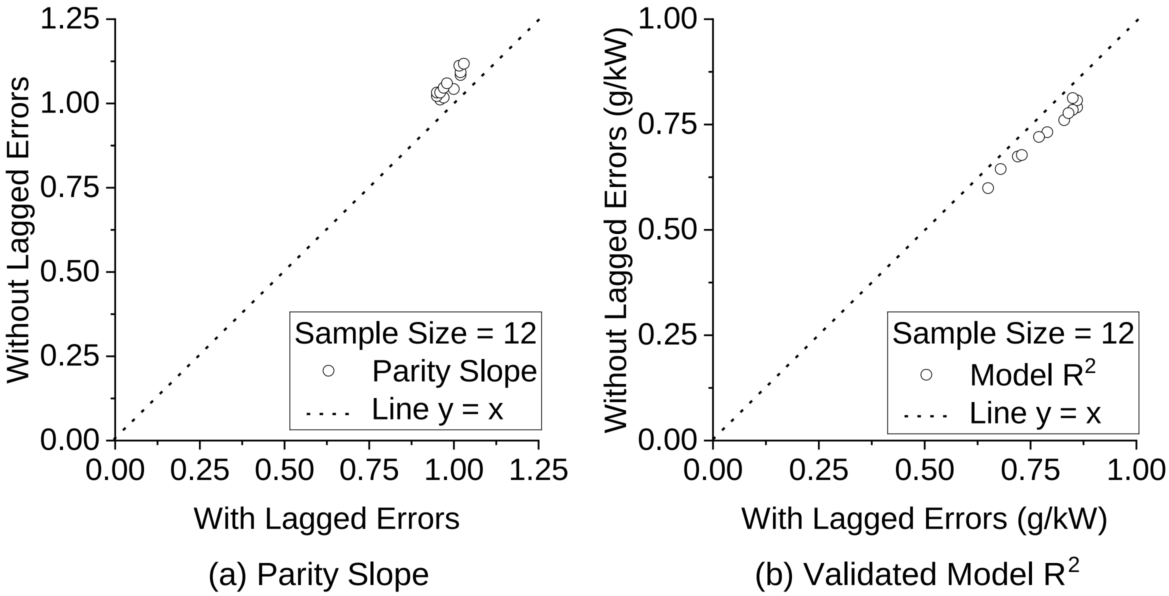


FIGURE 5-8. Comparison of Average Parity Slope and Validation Model Goodness-of-fit for Fuel Use Rate for Each Combination of Locomotive, Consist, and Fuel based on Locomotive Power Demand Model Calibrated With and Without Lagged Error Terms: (a) Parity Slope; and (b) Validated Model Goodness-of-fit.

Similar to the model calibration, model R^2 for the validation data for the models without lagged error terms was lower by an average of only 9 percent or less relative to the models with lagged error terms. Thus, the model performance was not substantially affected when the models were calibrated and validated without the lagged error terms.

5.3.6.5. Trip-Based Model Validation

The calibrated models without lagged error terms for each LOO cross-validation case were evaluated for predicted versus empirical TFUE. A plot of predicted trip fuel use and emissions versus empirical trip fuel use and emissions based on all valid data for each locomotive, consist, and fuel is presented in Figure 5-9. Each of the trips may have missing data. To have a consistent base for comparison for predicted versus estimated, the trip fuel use and emissions were predicted for valid data only.

Typically, predicted trip fuel use and trip emissions of CO_2, NO_x, and PM were within 10 percent of the empirical trip fuel use and trip emissions for each locomotive, consist and fuel. Predicted trip CO emissions were within 15 percent and HC emissions were within 20 percent of the empirical. On average over all trips for a given locomotive, consist and fuel, the average error in trip fuel use and emissions of CO_2, NO_x and PM was 5 percent or lower and 8 percent or lower for CO and HC emissions. Therefore, the model performance for predicting average trip fuel use and emissions was good.

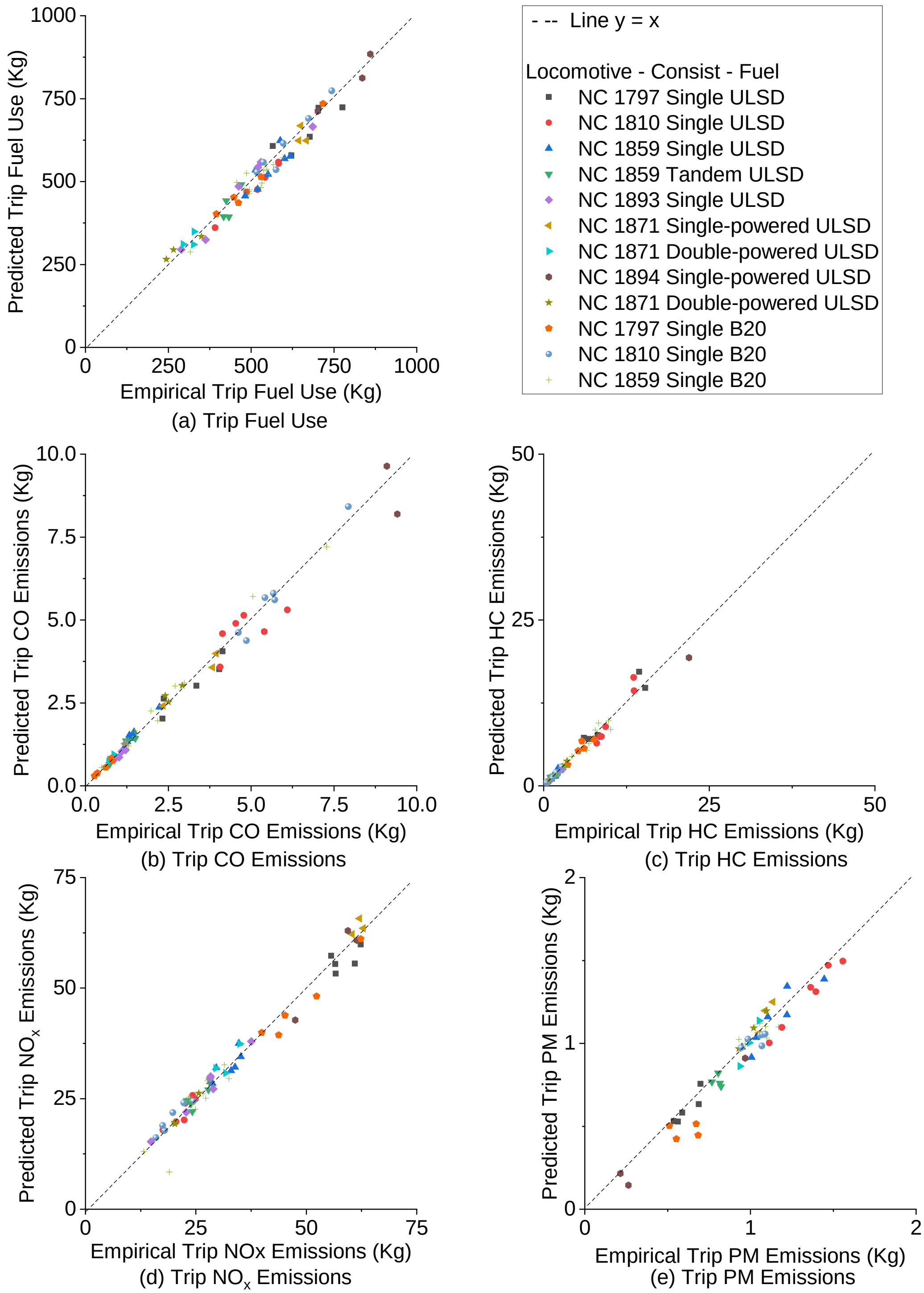


FIGURE 5-9. Comparison of Predicted Trip Fuel Use and Emissions with Estimated Trip Fuel Use and Emissions based on Valid Data for Each Locomotive, Consist and Fuel for Locomotive Power Demand Model Calibrated Without Lagged Error Terms: (a) Fuel Use; (b) CO Emissions; (c) HC Emissions; (d) NO_x Emissions; and (e) PM Emissions. Distribution of Predicted versus Estimated CO_2 emissions was similar to Fuel Use, skipped. Each point indicates one one-way trip for a given combination of locomotive, consist, and fuel.

As indicated in Table 5-7, there is large variability in the proportionality constants among the combinations of locomotives, consists, and fuels. This variability is larger than the variability in the observed CAER among the combinations of locomotives, consists, and fuels. Figure 5-10 illustrates the variability for cycle-average fuel use versus variability in proportionality constants for fuel use rate for each of the 12 locomotive, consist, and fuel combinations for which models were developed. For a given locomotive, consist, and fuel combination, CAER were estimated as an average of all 1 Hz predictions for all available one-way trips. The trends in proportionality constants are not indicative of trends in CAERs because of differences in the data that is included for each estimate. The proportionality constants are calibrated based on non-idle data only. In contrast, CAER are estimated based on all seconds of data. Therefore, the relative variability in the proportionality constant does not translate into the same relative variability in predicted cycle average rates. For example, for fuel use rate, the proportionality constants range from 0.019 g/kW to 0.041 g/kW, which is variation of a factor of 2.2 for the highest to the lowest value.

In contrast, the predicted cycle average fuel use rates for mass per unit of engine output vary from 152 g/kW-hr to 195 g/kW-hr, which is a factor of only 1.3. The relative variability in the proportionality constant does not translate into the same relative variability in predicted average mass per time-based fuel use rates. The predicted average fuel use rates vary from 33.2 g/s to 54.2 g/s, which is a factor of only 1.6. The variability in mass per time-based fuel use rates is larger than for cycle-average rates because the average engine load varies from trip to trip depending on operator choices regarding throttle notch positions and on external factors such as delays induced by other trains. However, the relative variability in the mass per time cycle average rates is still less than the relative variability in the proportionality constants. An implication is that variability in proportionality constants, as indicated by Table 5-7, should be used to infer the range of variability that will be found by applying the model to predict rates for cycles.

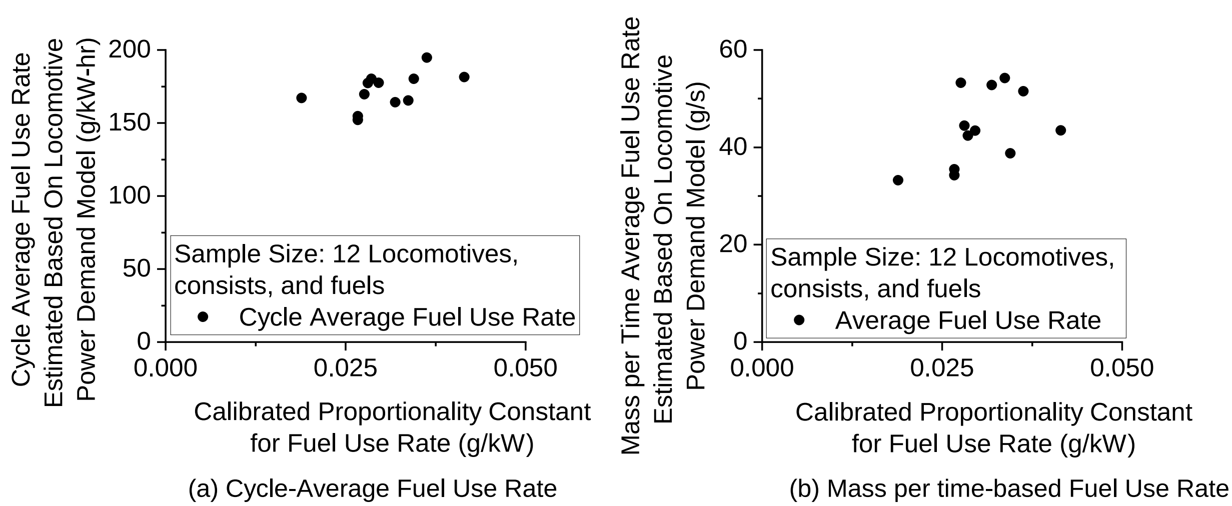


FIGURE 5-10. Comparison of Estimated Cycle Average Fuel Use Rates versus Average Model Calibrated Proportionality Constants Without Lagged Error Terms based on the Locomotive Power Demand Model Calibrated to all Available One-way Trips for a given Locomotive, Consist, and Fuel Combination: (a) Mass per Unit Engine Output-based Fuel Use Rate; and (b) Mass per Time-based Fuel Use Rate. Cycle-Average Fuel Use Rates were estimated as an average of all 1 Hz predictions for all available one-way trips.

5.3.7 Model Applications

In this section, the application of the LPD-based modeling approach to evaluate the impact of infrastructure changes and train trajectories on fuel use and emissions is demonstrated. Thus, the model is applied to two case studies. Model Case Study 1 is focused on comparison of grade. Model Case Study 2 is focused on comparison of speed trajectories.

5.3.7.1. Model Case Study 1: Grade

To evaluate the impact of infrastructure changes that affect grade, a hypothetical case of replacing a mile of track with ascent followed by descent with a mile of flat track (zero grade) is evaluated. Ascent is at 1.0 percent grade for 0.5 miles followed by a descent on -1.0 percent grade for 0.5 miles. The train is assumed to be a single consist locomotive NC 1859 operated on ULSD with 3 passenger cars and 1 baggage/café car. The train is assumed to run at a constant speed of 35 mph. This speed was selected because, based on empirical data, the train can maintain at least this speed when climbing a hill of 1.0 percent grade for 0.5 miles.

The model case study quantifies the difference in fuel use and emission rates over the 1 mile of track for the hill described above compared to a level flat track. This type of regrading might occur, for example, in a real project for which a grade crossing is separated. To focus the comparison only on the effect of grade, the train is assumed to run at a constant speed of 35 mph over the level track. The predicted fuel use and emissions for the one mile of track for the hilly and flat alternatives are given in Table 5-9. Leveling the track is estimated to result in a localized 65 percent reduction in fuel use and emissions of CO_2 and reductions of 18 percent, 58 percent, and 39 percent in CO, HC, NO_x, and PM emissions, respectively. Conversely, if a flat track is replaced by a hill, fuel use and emissions will increase.

TABLE 5-9. Predicted Fuel Use and Emissions for a Model Case Study 1 To Illustrate the Effect of Grade Based on Model Predictions

Species	Hilly Track[a]	Flat Track[b]	Percentage Reduction Compared to Hilly Track (%)
Fuel Use (g)	2408	842	65
CO_2 Emissions (g)	7599	2623	65
CO Emissions (g)	7.6	2.6	65
HC Emissions (g)	9.5	7.8	18
NO_x Emissions (g)	147	62	58
PM Emissions (g)	6.4	3.9	39

The train for each case comprised a Single-Locomotive Consist with Locomotive NC 1859 operated on Ultra-low Sulfur Diesel.

[a] *The hilly track case corresponds to a track with 0.5 miles of ascent at 1 percent grade followed by a 0.5 mile descent at -1 percent grade. The train is assumed to operate at a constant speed of 35 mph.*

[b] *The train is assumed to operate at a constant speed of 35 mph over a flat track.*

5.3.7.2. Model Case Study 2: Comparison of Trajectories

To quantify the effect of differences in trajectories on TFUE for the Piedmont route, the empirical and predicted fuel use and emissions for two trajectories are compared. The trajectories were measured for the single locomotive consist with NC 1859 operated on ULSD from Charlotte to Raleigh. The variation of speed with distance from Charlotte is given in Figure 5-11. Trip 1 had a duration of 12,643 seconds and Trip 2 had a duration of 13,137 seconds. These travel times differed by only 3.8 percent and, therefore, are comparable.

The trips had similar average speeds at 49 mph for Trip 1 and 48 mph for Trip 2. However, because of differences in the frequency and magnitude of accelerations, the average power demand for Trip 1 was 5 percent higher versus Trip 2. The percentage difference in the fuel use and emissions is affected not just be differences in trip average power demand, but also by differences in episodes of high-power demand at various locations throughout the trip. Therefore, average positive power demand was compared among trips. The average positive power demand was estimated as average of all power demand greater than zero. The average positive power demand for Trip 1 was 11 percent higher versus Trip 2. The empirical and modeled TFUEs for the two trips are given in Table 5-10. Based on the empirical data, Trip 1 had 26 percent, 13 percent, and 13 percent higher fuel use, NO_x emissions and PM emissions, respectively, versus Trip 2. Based on the LPD model, Trip 1 had 24 percent, 15 percent, and 17 percent higher fuel use, NO_x emissions and PM emissions, respectively, versus Trip 2. The modeled results were similar to the measured values. Thus, the model is useful for comparing trajectories and evaluating the impact of trajectory changes of fuel use and emissions.

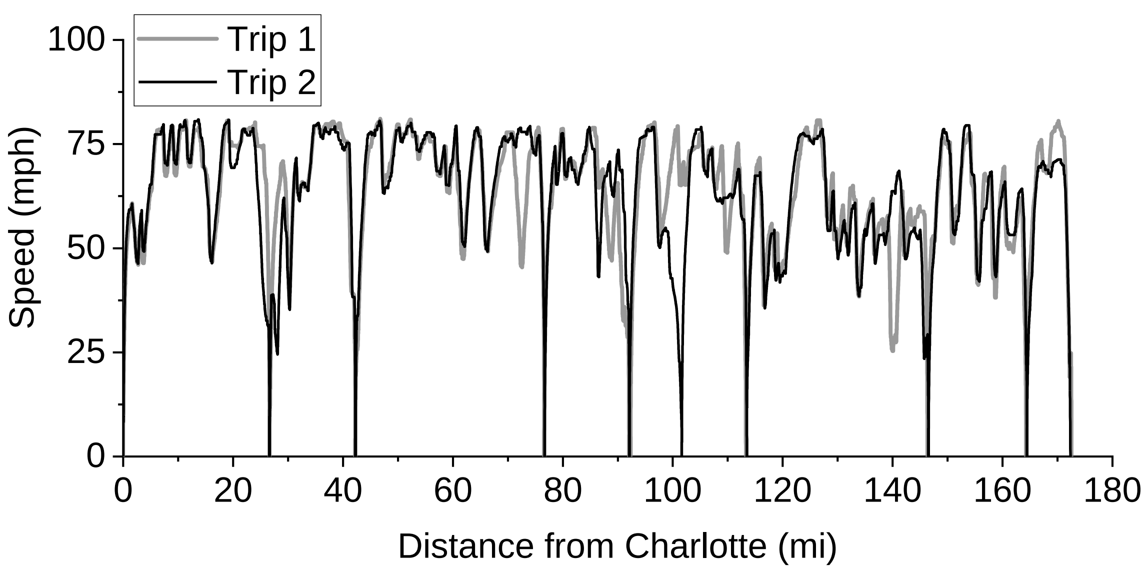


FIGURE 5-11. Variation in Speed with Distance for Two Selected One-way Trips Measured for Single Locomotive Consist of NC 1859 operated on ULSD from Charlotte to Raleigh, NC. Trip 1 had a duration of 12,643 seconds and Trip 2 had a duration of 13,137 seconds.

TABLE 5-10. Model Case Study 2: Comparison of Train Trajectories for One-Way Travel from Raleigh to Charlotte: Predictions with Locomotive Power Demand Model and Measured Values

Characteristic	Empirical			Model Case Study 2		
	Trip 1	Trip 2	Percent Difference (%)	Trip 1	Trip 2	Percent Difference (%)
Duration (h:mm)	3:30	3:38	4	3:30	3:38	4
Average Speed (mph)	49	48	-2	49	48	-2
Average Power Demand (kW/mile)	421	400	421	421	400	-5
Fuel Use (kg)	713	530	26	664	503	24
NO_x Emissions (kg)	39	34	13	42	36	15
PM Emissions (g)	1122	978	13	1243	1033	17

The train for each case comprised a Single-Locomotive Consist with Locomotive NC 1859 operated on Ultra-low Sulfur Diesel.

Chapter 6. Conclusions and Recommendations

Baseline fuel use and emission rates (FUER) were quantified for two recently acquired locomotives based on rail yard (RY) and over-the-rail (OTR) measurements. The OTR measurements were conducted for double- and single-powered push/pull consists. FUER for all NCDOT locomotives were benchmarked to the EPA reported FUER for the same model prime mover engines (PMEs) and to each other. To identify needs for emission reduction interventions, FUER were benchmarked to emission standards. Based on OTR measurements, trip fuel use and emissions (TFUE) were compared for steady-state versus transients. The double- and single-powered push/pull consists were compared to each other in terms of TFUE. A model to predict FUER at 1 Hz for given track geometry, train trajectory, train consist and fuel was demonstrated. They key findings are given in Section 6.1, conclusions are given in Section 6.2, and recommendations are given in Section 6.3.

6.1 Key Findings

NCDOT locomotives were benchmarked to one another and to emission standards based on RY and OTR measurements. Based on OTR measurements, differences in TFUEs based on steady-state versus transients were quantified. The trade-offs in TFUEs for double-versus single-powered consists were quantified based on transient data. A model to predict 1 Hz FUER based on locomotive power demand (LPD) was calibrated and validated. Application of the model to evaluate the effect of infrastructure and trajectory changes is demonstrated.

6.1.1 Locomotive Benchmarking

Based on RY and OTR measurements, the EPA line-haul duty-cycle fuel specific engine output (FSEO) for NCDOT locomotives was typically higher than the EPA benchmark FSEO. The measured OTR notch-average CO, NO_x and PM emission rates were approximately similar to those reported by the EPA for the same model PME based on engine dynamometer measurement, whereas, the notch-average HC emission rates were approximately 3 to 4 times higher. For most NCDOT locomotives and PME notch positions, the measured exhaust concentrations were below the gas analyzer detection limit. Therefore, the differences in HC emission rates compared to the EPA reported rates are not significant.

The NCDOT locomotives are configured to operate at different notch-average engine revolutions per minute (RPM), intake air temperature (IAT) and manifold absolute pressure (MAP) for a given notch-position. In addition, notch-average IAT depends on ambient temperature. The fuel injection of NCDOT locomotives is either mechanically-governed or electronically-governed. For a given notch position, F59PHI locomotives and F59PH locomotives with mechanically-governed fuel injection operated at the same engine power output as each other. The notch-average engine output for F59PH locomotives with electronically-governed fuel injection differed compared to the mechanically-governed locomotives. For a given locomotive, average engine power output for notches 7 and 8 differed for RY versus OTR measurements because each of the PMEs are configured to operate at lower engine output during static-load RY measurement versus OTR operation. During OTR measurements, each of the PMEs operated at a rated power of 3000 hp at notch 8.

Locomotives with electronically-governed fuel injection were typically more fuel-efficient versus locomotives with mechanically-governed fuel injection. Consequently, CO_2 emission rates were lower for locomotives with electronically-governed fuel injection. No particular trends in emissions rates were measured based on whether the fuel injection is electronically or mechanically. Based on OTR measurements, locomotives NC 1871 and NC 1984 typically had the highest cycle-average FSEOs based on single- and double-powered push/pull consists compared to other locomotives. Locomotives NC 1810, NC 1869, and NC 1893 have the highest FSEO based on single-locomotive consists. These numbers are not directly comparable, because the consists differ. A given locomotive is typically more efficient fuel-efficient in a double-locomotive consist.

Based on RY and OTR measurements, the EPA line-haul duty-cycle based CO emission rates were lower than the level of the Tier 0+ emission standard for each locomotive. However, the EPA line-haul duty-cycle based HC, NO_x, and PM emission rates were higher than the level of the Tier 0+ standards for most locomotives.

6.1.2 Steady-State versus Transients

On average, OTR operation is mostly comprised of transient operation. Steady-state operation only accounts for an average of 35 percent of the trip duration. The steady-state operation contributes 38 percent to 60 percent to TFUEs. Therefore, it is not possible to estimate trip total fuel use or emissions simply by summing observed second-by-second steady state operation. Steady-state notch average emission rates tend to be higher, on average, than transient emission rates. Therefore, using notch average rates based on steady-state data extrapolated to the total amount of time in each notch position for real-world trips will lead to overestimation of trip total fuel use and emissions. Accurate TFUEs can be quantified based on incorporating transients using several approaches described here. Alternate approaches include measuring 1 Hz FUER for the entire trip duration or to use an appropriate modeling approach such as LPD model.

6.1.3 Trade-offs of the Double- versus Single-Powered Consists

TFUEs for the double- and single-powered consists were estimated taking transients into account. Based on measurements of NC 1871 and NC 1984 in single and double powered consists, inferences are made regarding the TFUEs of push/pull consist trains with two locomotives. The double-powered configuration has lower fuel use and lower emissions of CO_2, CO and NO_x. These findings are consistent based on measurements of both of the locomotives. However, the findings are inconsistent for HC and PM emissions. The TFUE for a push/pull consistent for HC and PM emission rates was higher for the single-powered configuration based on NC 1984 but lower based on NC 1871.

6.1.4 Model to Predict 1 Hz Locomotive Fuel Use and Emission Rates

The backward moving average time period for which LPD was most highly correlated with 1 Hz FUER was 12 seconds. Thus, the models for all locomotives, fuels, and consists for fuel use and emission rates were calibrated based on a 12-second backward moving average of LPD.

For autocorrelated data with autocorrelated errors, such as the LPD model data, the data can be well-described by a model that accounts for autocorrelation. Such models are time series models that are calibrated based on past data. Such models are useful to predict FUER for the remainder of a trajectory for which FUER are known an initial part of the trajectory. These models cannot be applied to a completely different trajectory for which FUER are not known for any part. To predict FUER for any given trajectory, LPD models were calibrated without the lagged error terms. The estimated coefficients and diagnostic parameters in such a case would be biased. The bias in estimated coefficients and diagnostic parameters was quantified. The model performance was not substantially affected when the model was calibrated and validated without the lagged error terms. Therefore, LPD-based models without the lagged error terms are useful for predicting FUER.

For model calibration without lagged error terms, there is substantial variability in the proportionality constants among locomotives, consists, and fuels. For a given locomotive, consist, and fuel combination, the calibrated proportionality constants were typically within ± 10% of each other for a given species (i.e. fuel or a specific pollutant). Therefore, the models were robust to the choice of trips used for model calibration. A final model was calibrated for the rate of each species for each combination of locomotive, consist and fuel based on all available one-way trips. The 95% confidence interval on the proportionality constant is typically within ± 1% indicating that these parameters are precisely estimated because of the large sample sizes of 32,214 to 65,634 for these models. On average for all locomotives, consists, and fuels, the model R^2 without lagged error terms for fuel use and CO_2 emission rates was 0.74. The average R^2 for NO_x and PM emission rates was 0.72 and 0.62, respectively.

For model validation without lagged error terms, there is substantial variability in the parity slope among locomotives, consists, and fuels. on average over all trips, the parity slope of fuel use and emission rates of CO_2, $NO_{x,}$ and PM were within ±10 percent of one. However, parity slopes for all combinations and species were within ±20 percent of one. On average over all available trips, the models were accurate for each combination of locomotives, consists, and fuels, because the average parity slope was typically close to one. The 95% confidence interval on the parity slope was typically within ± 10% for each for each species, locomotive, consist, and fuel, except for HC, indicating that these parameters are precisely estimated because of the large sample sizes of 10,434 to 14,132 for these models. On average for all locomotives, consists, and fuels, the model R^2 without lagged error terms for fuel use and CO_2 emission rates was 0.73. The average R^2 for NO_x and PM emission rates was 0.69 and 0.62, respectively. However, the average R^2 for CO emission rates was 0.36. The average R^2 for HC emission rates was 0.08. The coefficients of determination for model validation are similar to those for model calibration and have the same pattern of being highest for fuel use rate and CO_2 emission rate and lowest for HC emission rate.

6.1.5 Locomotive Power Demand Model Applications

The model case study 1 quantifies the difference in fuel use and emission rates over the 1 mile of track for the hill described above compared to a level flat track. Leveling the track is estimated to result in a localized 65 percent reduction in fuel use and emissions of CO_2 and reductions of 18 percent, 58 percent, and 39 percent in CO. HC, NO_x and PM emissions, respectively.

The model case study 2 quantifies the difference in fuel use and emission rates for two train trajectories. The trips had similar average speeds at 49 mph for Trip 1 and 48 mph for Trip 2. However, because of differences in the frequency and magnitude of accelerations, the average power demand for Trip 1 was 5 percent higher versus Trip 2. The percentage difference in the fuel use and emissions is affected not just be differences in trip average power demand, but also by differences in episodes of high-power demand at various locations throughout the trip. Trip 1 had 24 percent, 15 percent, and 17 percent higher fuel use, NO_x emissions and PM emissions, respectively, versus Trip 2. The modeled results were similar to the measured values.

6.2 Conclusions

Locomotives were benchmarked to the EPA dynamometer data, to each other and to emission standards. Several approaches to estimate TFUEs based on steady-state operation versus transient operation were compared. The trade-offs in TFUEs for the double- versus single-powered consists are quantified. Applicability of the LPD model is demonstrated.

6.2.1 Locomotive Benchmarking

Fuel Use and Emission Rates (FUER) measured for the Prime Mover Engines (PMEs) of each of the NCDOT locomotives were typically consistent with EPA reported data for the same models of PMEs. The NCDOT locomotives are typically more fuel efficient than indicated by EPA's benchmark fuel specific engine output. Within the NCDOT locomotive fleet, locomotives with electronically-governed fuel injection were typically more fuel-efficient versus locomotives with mechanically-governed fuel injection. Consequently, CO_2 emission rates were lower for locomotives with electronically-governed fuel injection. However, no particular trend in emissions rates were observed based on whether fuel injection is electronically or mechanically governed.

Based on RY and OTR measurements, the EPA line-haul duty-cycle based CO emission rates were lower than the level of the Tier 0+ emission standard for each locomotive. However, the EPA line-haul duty-cycle based HC, NO_x, and PM emission rates were higher than the corresponding levels of the Tier 0+ standards for most locomotives.

6.2.2 Steady-State versus Transients

Most of the time spent in real-world over-the-rail operations involves transients. Steady state operation accounts for only approximately one-third of average operational time. Therefore, it is not possible to estimate trip total fuel use or emissions simply by summing observed second-by-second steady state operation. Steady-state notch average emission rates tend to be higher, on average, than transient emission rates. Therefore, using notch average rates based on steady-state data extrapolated to the total amount of time in each notch position for real-world trips will lead to overestimation of trip total fuel use and emissions. Accurate TFUEs can be quantified based on incorporating transients. Approaches that incorporate transients include measuring 1 Hz FUER for the entire trip duration, estimating trip total emission rates based on modal average rates that are calibrated based on transient data, or estimating average rates using an LPD-based modeling approach.

6.2.3 Trade-offs of the Double- versus Single-powered Consists

Based on measurements of two locomotives, the double-powered push/pull consist has 19% lower train trip average fuel consumption and CO_2 emissions versus a single-powered push/pull consist. Train trip average CO and NO_x emissions were 62 percent and 9 percent lower, respectively. In contrast, train trip average HC and PM emissions were 40 percent and 3 percent higher. The double-powered push/pull consist is preferred in terms of fuel savings and emissions reductions emissions of CO_2, CO, and NO_x with trade-offs of higher HC and PM emissions versus the single-powered consist. However, the differences between consists with respect to TFUE may be different for different locomotives. Thus, given the small sample size of these data, in that they are based on only two locomotives, further work is warranted to confirm or refine these findings.

6.2.4 Model to Predict 1 Hz Locomotive Fuel Use and Emission Rates

Since the model is based on physics of overcoming resistances opposing train motion, the model formulation is robust. In general, the models were more precise for fuel use and emission rates of CO_2, NO_x, and PM than for CO and HC emissions. The imprecision of CO and HC emission rates is because measured notch average concentrations for multiple notch positions for all locomotives were below the detection limit of the analyzers. Nonetheless, the calibrated proportionality constant for each locomotive, consist, fuel, and species (i.e. fuel, pollutant) was robust to the choice of trips for model calibration. Although, modeled CO and HC emission rates were imprecise, proportionality constants were estimated with high precision for these pollutants, and for other species, because of large sample sizes.

On average over all available trips, the models were accurate for each combination of locomotives, consists, and fuels. The rates estimated by the LPD models are able to appropriately respond to changes in model inputs such as speed, acceleration, grade, and curvature. The random errors at 1 Hz compensate to a large extent when averaged over a larger period of time such as trip duration. Overall, the model performed well for pollutants of greatest concern, including CO_2, NO_x and PM. The model is calibrated based on real-world data for the Piedmont rail operation, including typical train consists. Therefore, the model is representative of real-world Piedmont rail operation. Models were calibrated for 12 combinations of locomotives, consists, and fuels. Not all locomotives were measured for all consists and fuels. This suite of models can be used to compare TFUEs among combinations of locomotives, consists, and fuels based on real-world operation.

6.2.5 Locomotive Power Demand Model Applications

Application of the model to evaluate the effect of infrastructure changes was demonstrated. Replacing positive and negative grades with zero grade leads to a net reduction in fuel use and emissions. The differences in TFUEs among the two trajectories were similar for the model and empirical data. Thus, the model is useful for comparing trajectories and evaluating the impact of trajectory changes of fuel use and emissions.

6.3 Recommendations

The inter-locomotive variability in the fuel use rates indicates the potential to reduce fuel consumption for NCDOT passenger rail operations by operating more fuel-efficient locomotives more frequently than other less fuel-efficient locomotives.

Steady-state based FUER provide a consistent basis for comparing locomotives, fuels, operations and enable benchmarking to emission standards. However, transient-based FUER provide more accurate estimate of TFUEs. Thus, transient data enable more accurate comparisons among TFUEs for evaluating trade-offs among consists and other applications.

The push/pull consist with double-powered locomotive operation is promising with respect to reducing train fuel use and emissions of CO_2, CO, and NO_x. The results for HC and PM are not conclusive. Measurement of additional locomotives for both double- and single-powered push/pull consists would be needed to obtain a more definitive finding.

The LPD model was found to be accurate for estimating average TFUEs over multiple trips. At 1 Hz, predicted FUER may differ by as much as 30 percent from the empirical FUER. However, the modeled estimates of rates appropriately responded to variation in input variables including speed, acceleration, grade, and curvature. The model prediction precision is within ±7 percent on a trip average basis in most cases. The model prediction accuracy for a given combination of locomotive, consist, and fuel for TFUEs is within ±2 percent in most cases. The model can be used to demonstrate emission reduction benefits related to infrastructure improvements. Potential emission reductions can be used to seek Federal funding for transportation improvement programs. Variation in train trajectories indicates that there is potential to reduce train fuel use and emissions via improved operational practices.

Given that the real-world emission rates of HC, NO_x, and PM are higher than the levels of the corresponding Tier 0+ standards, mitigation strategies could be considered. Based on prior measurements of three NCDOT locomotives, switching from ULSD to B20 lowered cycle-average HC and PM emission rates by 54 percent and 34 percent, respectively. Assuming that these reductions could be achieved for each locomotive in the NCDOT fleet, a switch from ULSD to B20 fleet-wide might increase the number of locomotives with cycle average HC emission rates at or below the level of the Tier 0+ standard from 3 to 5. Likewise, the number of locomotives with cycle average PM emission rates at or below the level of the Tier 0+ standard would increase from 3 to 7. Prior work on one NCDOT locomotive demonstrated that a retrofitted blended exhaust after treatment system (BATS) was able to achieve a reduction of 70 percent in cycle average rates. Assuming that the same reduction could be achieved for each locomotive in the NCDOT fleet, retrofitting BATS fleet-wide might increase the number of locomotives with cycle average NO_x emission rates at or below the level of the Tier 0+ standard from 2 to all locomotives in the NCDOT fleet.

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Appendix A. Abbreviations and Acronyms

Abbreviation	Definition
AFR	Air to Fuel Ratio
AREMA	American Railway Engineering and Maintenance-of-Way Association
ARIMA	Auto Regressive Integrated Moving Average
B20	A Blend Of 20 Percent Biodiesel in Diesel
BAR	California Bureau of Automotive Repair
BATS	Blended-exhaust After-treatment System
CAER	Cycle-Average Emission Rates
CAT ACERT	Caterpillar Advanced Combustion Emissions Reduction Technology
CAT-ET	Caterpillar Electronic Technician
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CV	Coefficient of Variation (Standard deviation divided by mean)
DB	Dynamic Brake
DEMs	Digital Elevation Models
ECU	Electronic Control Unit
EF&EE	Engine Fuels and Emissions Engineering
EF&EE	Engine Fuels and Emissions Engineering
EMD	Electro Motive Diesel
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification program of the US EPA
FEM	Federal Equivalent Method
FRA	Federal Railroad Administration
FRM	Federal Reference Method
FSEO	Fuel Specific Engine Output
FUER	Fuel Use and Emission Rates
GHG	Greenhouse Gas
GPS	Global Position System
GPS/BA	GPS Receivers with Barometric Altimeters
GTM	Gross Ton-Miles
H_2O	Water Vapor
HC	Hydrocarbons
HEP Engine	Head End Power Engine
HFID	Heated Flame Ionization Detection
IAT	Intake Air Temperature
ISO	International Organization for Standardization
LEMS	Locomotive Emissions Measurement System
LIDAR	Light Detection and Ranging
LOO	Leave-One-Out
LPD	Locomotive Power Demand
MAD	Maximum Allowable Difference
MAF	Mass Air Flow

Abbreviation	Definition
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 Ultraviolet
NEI	National Emission Inventory
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
O_2	Oxygen
OTR	Over-The-Rail
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
PM_{10}	Particulate Matter less than 10 micro-meters in aerodynamic diameter
$PM_{2.5}$	Particulate Matter less than 2.5 micro-meters in aerodynamic diameter
PME	Prime Mover Engine
PN	Predecessor Notch
R^2	Coefficient of Determination
RPM	Engine Revolutions Per Minute
RY	Rail Yard
SCR	Selective Catalytic Reduction
SN	Successor Notch
SO_2	Sulfur Dioxide
SOTR	Sum of Transient Rates
SRAC	Steady-State Rates and Actual Cycle
SRCT	Steady-State Rate, Cycle and Transition Modes
SRSC	Steady-State Rates and Steady-State Cycle
TFUE	Trip Fuel Use and Emissions
THC	Total Hydrocarbons
TRAC	Transient Rates Actual Cycle
U.S. EPA	United States Environmental Protection Agency
ULSD	Ultra-low Sulfur Diesel

Letter Variables

Letter Variable	Definition
$\boldsymbol{a_t}$	train acceleration at time *t* (*m/s²*)
$\boldsymbol{B}$	flange resistance coefficient (*lbs/ton-mph*)
$\boldsymbol{bhp_j}$	brake horsepower at notch *j* (*bhp*)
$\boldsymbol{C}$	Index for train consist. *C* ϵ {single, single-powered push/pull and double-powered push/pull}
$\boldsymbol{CAER_s}$	cycle-average emission rate for pollutant species *s* (*g/bhp-hr*)
$\boldsymbol{C_{PM,t,dry}}$	measured PM concentration in the exhaust at time *t* on a dry basis (mg/m^3)
$\boldsymbol{C_{d,l}}$	drag coefficient for locomotive from Table 5-1 (lbs/ft^2-mph^2)
$\boldsymbol{C_{d,p}}$	drag coefficient for passenger car from Table 5-1 (lbs/ft^2-mph^2)
$\boldsymbol{C_d}$	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). See Table 5-1 for typical values.
$\boldsymbol{d_t}$	degree of a curve at time *t* (*degrees*)
$\boldsymbol{D}$	unit curve resistance (0.8 *lbs/ton-degree of curve*)
$\boldsymbol{E}$	unit grade resistance (20 *lbs/ton-percent grade)*
$\boldsymbol{EC}$	engine strokes per cycle (1 for two-stroke engines and 2 for four-stroke engines)
$\boldsymbol{ER}$	engine compression ratio
$\boldsymbol{ES_t}$	engine speed at time *t* (*RPM*)
$\boldsymbol{EV}$	engine displacement (*L*)
$\boldsymbol{F}$	Index for fuel. *F* ϵ {ULSD and B20}
$\boldsymbol{F_{L,C,i}}$	Actual trip total PME and HEP engine trip fuel use for locomotive *L* in consist *C* for the i^{th} one-way trip (*gal*).
$\boldsymbol{FR_{fj}}$	fuel use rate at notch *j* (*g/bhp-hr*)
$\boldsymbol{FSEO_f}$	cycle-average engine power output per unit fuel consumption for fuel *f* (*bhp-hr/gal*)
$\boldsymbol{F}$	frontal cross-sectional area of the locomotive (F_l) or passenger car (F_p) in (ft^2).
$\boldsymbol{F_l}$	frontal area of locomotive (ft^2)
$\boldsymbol{F_p}$	frontal area of passenger car (ft^2)
$\boldsymbol{f_{L,C,i,t_{L,C,i,0}}}$	Activity recorder display at the beginning of the i^{th} one-way trip for a locomotive *L* in a consist *C* (*gal*).
$\boldsymbol{f_{L,C,i,t_{L,C,i,n}}}$	Activity recorder display at the end of the i^{th} one-way trip for a locomotive *L* in a consist *C* (*gal*).
$\boldsymbol{G}$	unit acceleration resistance (200 *lbs-* s^2*/ton-m*)
$\boldsymbol{h_L}$	Index for the status of the HEP engine of locomotive *L*, 1 if the HEP engine was ON and 0 if the HEP engine was OFF.
$\boldsymbol{h_{L_1}}$	Index for the status of the HEP engine of locomotive L_1, 1 if the HEP engine was ON and 0 if the HEP engine was OFF.

Letter Variable	Definition
$\boldsymbol{h_{L_2}}$	Index for the status of the HEP engine of locomotive L_2, 1 if the HEP engine was ON and 0 if the HEP engine was OFF.
$\boldsymbol{H}$	HEP engine fuel consumption rate at 5.5 gal/hr
$\boldsymbol{I}$	factor for modernized train equipment (post 1950) to account for improved train and rail designs, equals 0.85
$\boldsymbol{i}$	index for one-way trips (1, 2, 3, ….., $N_{L,C}$)
$\boldsymbol{j}$	index for notch position {low idle, high idle, dynamic brake, 1, 2, 3, 4, 5, 6, 7 and 8}
$\boldsymbol{\bar{K}_{s,mode,L,C,i}}$	Modal average rate of species s for fuel use or emissions for locomotive *L* in consist *C* for the i^{th} one-way trip (g/s)
$\boldsymbol{k}$	Number of transition modes
$\boldsymbol{L}$	Index for locomotive. $L \in$ {NC 1797, NC 1810, NC 1859, NC 1893, NC 1871 and NC 1984}
$\boldsymbol{LP}$	number of powered locomotives (1 for single-powered, and 2 for double-powered)
$\boldsymbol{LPD_t}$	locomotive power demand at time *t* (*kW*)
$\boldsymbol{\overline{LPD}_{n,t}}$	average of the locomotive power demand at time *t* and the past (n-1) seconds
$\boldsymbol{M_{a,t}}$	intake molar air flow rate at time *t* (*gmol/s*)
$\boldsymbol{M_{e,t,dry}}$	molar exhaust flow rate at time *t* on a dry basis (*gmol/s*)
$\boldsymbol{\overline{M'}_{s,j,L,C,i}}$	Estimated notch-average steady-state fuel use rate or emission rates of species *s* for notch *j* of locomotive *L* in consist *C* for the i^{th} one-way trip (*g/s*)
$\boldsymbol{\bar{M}_{sj}}$	steady-state emission rate for pollutant species *s* at notch *j* (*g/bhp-hr*)
$\boldsymbol{m'_{s,j,L,C,i}}$	Steady-state 1 Hz fuel use rate or emission rate of species *s* at notch *j* of locomotive *L* in consist *C* for the i^{th} one-way trip (*g/s*)
$\boldsymbol{m}$	moles of carbon per gram mole of the hydrocarbon
$\boldsymbol{m_{PM,t,dry}}$	PM mass emission rate at time *t* on a dry basis (*g/s*)
$\boldsymbol{m_{f,t}}$	mass fuel use rate by the engine at time *t* (*g/s*)
$\boldsymbol{m_{s,L,C,F,t}}$	Empirical 1 Hz fuel use or emission rate of species *s* for locomotive *L* and consist *C* operated on fuel *F* at time *t* (*g/s*)
$\boldsymbol{m_{s,L,C,F,t,T\neq i}}$	Empirical 1 Hz fuel use or emission rate of species *s* for locomotive *L* and consist *C* operated on fuel *F* at time *t* for all one-way trips but the i^{th} one-way trip (*g/s*)
$\boldsymbol{m^{modeled}_{s,L,C,F,t,T=i}}$	Modeled 1 Hz fuel use or emission rate of species *s* for locomotive *L* and consist *C* operated on fuel *F* at time *t* for the i^{th} one-way trip predicted based on $PC_{s,L,C,F,T\neq i}$ calibrated to all one-way trips but the i^{th} one-way trip (*g/s*)
$\boldsymbol{m^{train}_{s,t,L_1,L_2,C,F,i}}$	Train total fuel use or emission rate of species *s* at time *t* for a consist *C* including one or two locomotives and operated on fuel *F* (*g/s*).
$\boldsymbol{m_{s,idle,L_1,C,F}}$	Idle fuel use or emission rate of species *s* for locomotive *L* and consist *C* operated on fuel *F* (*g/s*)
$\boldsymbol{m_{s,idle,L_1,C,F}}$	Idle fuel use or emission rate of species *s* for the prime mover engine of locomotive L_1 in consist *C* operated on fuel *F* (*g/s*).

Letter Variable	Definition
$\boldsymbol{m_{s,idle,L_2,C,F}}$	Idle fuel use or emission rate of species *s* for the prime mover engine of locomotive L_2 in consist *C* operated on fuel *F* (*g/s*).
$\boldsymbol{m^{HEP}_{s,t,L_1,F,i}}$	Fuel use or emission rate of species *s* for the HEP engine of the locomotive L_1 corresponding to load *l hp* operated on fuel *F* (*g/s*). (See Tables F1 through F2 for ULSD and B20, respectively, in Appendix F).
$\boldsymbol{m^{HEP}_{s,t,L_1,F,i}}$	Fuel use or emission rate of species *s* for the HEP engine of the locomotive L_2 corresponding to load *l hp* operated on fuel *F* (*g/s*). (See Tables F1 through F2 for ULSD and B20, respectively, in Appendix F).
$\boldsymbol{m_{s,t}}$	mass emission rate of pollutant species *s* at time *t* (*g/s*)
$\boldsymbol{MW_f}$	equivalent molecular weight of fuel (*g/gmolC*)
$\boldsymbol{MW_s}$	equivalent molecular weight of pollutant species *s* (*gmol/s*)
$\boldsymbol{N}$	number of locomotives per train other than the lead locomotive
$\boldsymbol{n}$	number of axles in a locomotive (n_l) or a passenger car (n_p)
$\boldsymbol{n_l}$	number of axles per locomotive
$\boldsymbol{n_p}$	number of axles per passenger car
$\boldsymbol{N_{L,C}}$	number of one-way trips for locomotive *L* in consist *C*
$\boldsymbol{P}$	number of passenger cars per train
$\boldsymbol{P_B}$	barometric pressure (*101 kPa*)
$\boldsymbol{PC_{s,L_1,C,F}}$	proportionality constant for species *s* for the prime mover engine of locomotive L_1 and consist *C* operated on fuel *F* (*g/kW*).
$\boldsymbol{PC_{s,L_1,C,F}}$	proportionality constant for species *s* for the prime mover engine of locomotive L_2 and consist *C* operated on fuel *F* (*g/kW*).
$\boldsymbol{PC_{s,L,C,F}}$	proportionality constant for species *s* for locomotive *L* and consist *C* operated on fuel *F* (*g/kW*)
$\boldsymbol{PC_{s,L,C,F,T\neq i}}$	Calibrated proportionality constant for species *s* for a given LOO cross-validation case of locomotive *L* and consist *C* operated on fuel *F* or all one-way trips but the i^{th} one-way trip (*g/kW*)
$\boldsymbol{P_{L,C,i}}$	trip PME fuel use estimated based on the locomotive activity recorder display for both engines less the estimated fuel consumption of the HEP engine (*gal*) for locomotive *L* in consist C for the i^{th} one-way trip (*gal*).
$\boldsymbol{P_{M,t}}$	engine manifold absolute pressure at time *t* (*kPa*)
$\boldsymbol{R_{T,t}}$	traction resistance at time *t* (*lbs/ton*)
$\boldsymbol{R_{a,t}}$	acceleration resistance at time *t* (*lbs/ton*)
$\boldsymbol{R_{c,t}}$	curvature resistance at time *t* (*lbs/ton*)
$\boldsymbol{R_{d,t}}$	air resistance for trains with speeds less than 60 mph at time *t* (*lbs/ton*)
$\boldsymbol{R_{f,t}}$	flange resistance at time *t* (*lbs/ton*)
$\boldsymbol{R_{g,t}}$	gross resistance at time *t* (*lbs/ton*)
$\boldsymbol{R_{j,t}}$	journal resistance at time *t* (*lbs/ton*)
$\boldsymbol{R_{s,t}}$	starting resistance at time *t* (*lbs/ton*)
$\boldsymbol{R_{w,t}}$	wind resistance for trains with directly opposing wind at time *t* (*lbs/ton*)
$\boldsymbol{R_{x,t}}$	grade resistance at time *t* (*lbs/ton*)
$\boldsymbol{R}$	universal gas constant ($8.314\ J\ mol^{-1}\ K^{-1}$)
$\boldsymbol{s}$	Index for species. $s \in$ {fuel use rate, emission rate of CO_2, CO, HC, NO_x or PM}

Letter Variable	Definition
$\boldsymbol{SOTR_{s,L,C,i}}$	Estimated trip PME fuel use or emission rates of species *s* for locomotive *L* in consist *C* for the i^{th} one-way trip based on the sum of transient rates approach (*g*)
$\boldsymbol{SOTR^{modeled}_{s,L,C,i}}$	Modeled trip fuel use or emissions of species *s* for locomotive *L* and consist *C* operated on fuel *F* for the i^{th} one-way trip *(g)*.
$\boldsymbol{SRAC_{s,L,C,i}}$	Estimated trip PME fuel use or emission rates of species *s* for locomotive *L* in consist *C* for the i^{th} one-way trip based on the steady-state rates and actual cycle approach (*g*).
$\boldsymbol{SRCT_{s,L,C,i}}$	Estimated trip PME fuel use or emission rates of species *s* for locomotive *L* in consist *C* for the i^{th} one-way trip based on the steady-state rate, cycle and transition modal approach (*g*)
$\boldsymbol{SRSC_{s,L,C,i}}$	Estimated trip PME fuel use or emissions of species *s* for locomotive *L* in consist *C* for the i^{th} one-way trip based on the steady-state rates and steady-state cycle approach (*g*).
$\boldsymbol{SOMR^{modeled}_{s,L,C,F,i}}$	modeled trip fuel use or emissions of species *s* for locomotive *L* and consist *C* operated on fuel *F* for the i^{th} one-way trip estimated as the sum of modeled 1 Hz rates *(g)*.
$\boldsymbol{T}$	standard temperature (*298 K*)
$\boldsymbol{T_{int,t}}$	intake air temperature at time *t* (*K*)
$\boldsymbol{TRAC_{s,L,C,i}}$	Estimated trip PME fuel use or emission rates of species *s* for locomotive *L* in consist *C* for the i^{th} one-way trip based on the transient rates and actual cycle approach (*g*).
$\boldsymbol{T''_{mode,L,C,i}}$	Time spent in a transition mode of locomotive L for consist C for the i^{th} one-way trip (*s*)
$\boldsymbol{T'_{j,L,C,i}}$	Time spent in steady-state at notch *j* of locomotive L in consist *C* for the i^{th} one-way trip (*s*)
$\boldsymbol{T^{D}_{j,L,C,i}}$	Time spent in notch *j* of locomotive *L* in consist *C* for the i^{th} one-way trip, based on the actual duty cycle (*s*)
$\boldsymbol{t_{L,C,i,0}}$	start of the i^{th} one-way trip for locomotive *L* in consist C (*s*)
$\boldsymbol{t_{L,C,i,n}}$	end of the i^{th} one-way trip for locomotive *L* in consist C (*s*)
$\boldsymbol{v_t}$	Train speed at time *t* (*mph*)
$\boldsymbol{v_{t-1}}$	Train speed at time *t-1* (*mph*)
$\boldsymbol{v_{w,t}}$	wind speed opposite to train motion at time *t* (*mph*)
$\boldsymbol{w_l}$	weight per unit axle of locomotive (*tons*)
$\boldsymbol{w_p}$	weight per unit axle of passenger car (*tons*)
W	total train weight (*tons*)
w	weight of locomotive per axle (w_l) or passenger car per axle (w_p) (*tons/axle)*
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
$\boldsymbol{x_t}$	rail grade at time *t* (*%*)
$\boldsymbol{y_{s,t,dry}}$	mole fraction of pollutant species *s* at time *t* for a PME on a dry basis (*gmol/gmol of dry exhaust*)
z	Index for moving average period. Ranges from 0 to (*n-1*)

Greek Variables

Greek Variable	Definition
$\boldsymbol{\lambda_{C_1}}$	number of powered prime mover engines in the train consist. 0 for single-powered and single consists, and 1 for double-powered and tandem consists.
$\boldsymbol{\lambda_{C_2}}$	Index for power provided by each locomotive. 1 for single-powered and single consists, and 0.5 for double-powered and tandem consists.
$\boldsymbol{\mu_f}$	density of fuel *f* (*g/gal*); 3184 g/gal for ULSD and 3229 g/gal for B20
$\boldsymbol{\epsilon_t}$	Error term at time *t*
$\boldsymbol{\eta_{ev,t}}$	engine volumetric efficiency of the engine at time *t*
$\boldsymbol{\eta}$	locomotive efficiency factor, 0.82 for diesel-electric locomotives

Appendix B. NCDOT Locomotive Fleet

The North Carolina Department of Transportation (NCDOT) has a fleet of two F59PHIs and six F59PHs series locomotives configured for passenger service. Two of the F59PHs are recently acquired and rebuilt by NCDOT. The recently acquired locomotives are NC 1871 “Town of Cary” and NC 1984 “City of Kannapolis.” The other 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”. 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 specifications of the PMEs of the locomotives in NCDOT fleet are given in Table B-1. The specifications of the HEP engine of the locomotives in NCDOT fleet are given in Table B-2.

TABLE B-1. Prime Mover Engine Specifications

Locomotive Model	F59PHI	F59PH		GP40
Fuel Injection	Electronically governed	Mechanically governed	Electronically governed	Mechanically governed
Locomotives	NC 1755, NC 1797	NC 1810, NC 1859, NC 1869, NC 1893	NC 1871, NC 1984	NC 1792
Prime Mover Diesel Engine	EMD	EMD	EMD	EMD
Model	12N-710G3B-EC	12N-710G3	12N-710G3	16-645E3
Aspiration	Turbocharged	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)	169.1 L (10,320 in^3)
Number of Cylinders	12	12	12	16
Cylinder Arrangement	45° "V"	45° "V"	45° "V"	45° "V"
Compression Ratio	16:1	16:1	16:1	14.5:1
Displacement per Cylinder	11,635 cm^3 (710 in^3)	11,635 cm^3 (710 in^3)	11,635 cm^3 (710 in^3)	10,570 cm^3 (645 in^3)
Cylinder Bore	230.19 mm (9.06 in)	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)	254.0 mm (10.0 in)
Operating Principle	2 Stroke Cycle	2 Stroke Cycle	2 Stroke Cycle	2 Stroke Cycle
Rotation (Facing Flywheel End)	Counterclockwise	Counterclockwise	Counterclockwise	Counterclockwise
Full Speed	904 RPM	904 RPM	904 RPM	904 RPM
High Idle Speed	343 RPM	371 RPM	268 RPM	235 RPM
Low Idle Speed	200 RPM	238 RPM	219 RPM	310 RPM
Rated speed of traction motors	110 mph	83 mph	83 mph	103 mph
Weight	13,700 kg (30,200 lbs)	13,700 kg (30,200 lbs)	13,700 kg (30,200 lbs)	14,700 kg (32,500 lbs)
Rated power	3,000 hp (2,240 kW)	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+	U.S. EPA Tier 0+

TABLE B-2. Head End Power Engine Specifications

HEP Engine Model	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	1132 mm (44.6 in)	1132 mm (44.6 in)
Height	1356 mm (53.4 in)	1356 mm (53.4 in)
Weight - Net Dry (Basic Operating Engine Without Optional Attachments)	1717 kg (3785 lb)	1666 kg (3673 lb)

Appendix C. Locomotive Emission Standards

This appendix consists of a description of the emission standards applicable to locomotives. The locomotive standards apply to locomotives originally built in or after 1973 that operate extensively within the U.S., except for: (1) historic steam-powered locomotives; (2) electric locomotives; and (3) some existing locomotives owned by small businesses. Furthermore, engines used in locomotive-type vehicles with less than 750 kW total power, engines used only for hotel power, and engines that are used in self-propelled passenger-carrying railcars, are excluded from the regulations. The engines are subject to the nonroad engine requirements. The prime mover engine (PME) provides traction to the wheels whereas the head end power (HEP) engine provides hotel services. PMEs are regulated under locomotive emission standards (40 CFR 1033, 2008, 1998; EPA, 1998). The HEP engine is considered a non-road engine (40 CFR 9, 69, 80, 86, 89, 94, 1039, 1048, 1051, 1065, 1068, 2004). Thus, different standards apply for the PME and the HEP engine. The standards applicable to the PME and the HEP engine are described below.

C.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 throttle notch position and the associated notch-average emission factors obtained from Federal Reference Method measurements made using engine dynamometers (40 CFR 1033, 2008, 1998; EPA, 1998). 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 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. There has been some change in duty cycle composition over the past 20 years, especially with the addition of dynamic braking (40 CFR 1033, 2008, 1998; EPA, 1998).

Locomotives are regulated under 40 CFR part 1033. The first standards came into effect in 1998 and specified three standards for locomotives based on the year of manufacture/remanufactured (40 CFR 1033, 1998). The Tier 0 standard applies to locomotives and locomotive engines originally manufactured from 1973 through 2001, and any time they are remanufactured. Tier 1 apply to locomotives and locomotive engines originally manufactured from 2002 through 2004 and at each subsequent remanufacture. Tier 2 locomotives and locomotive engines are required to meet the applicable standards at the time of original manufacture and at each subsequent remanufacture. The 2008 regulation strengthened the existing Tier 0 to Tier 2 standards applicable to locomotives when they are remanufactured, and introduced new Tier 3 and Tier 4 emission standards (40 CFR 1033, 2008). The more stringent Tier 0 to Tier 2 standards are known as Tier 0+ to Tier 2+ standards. The revised Tier 0+, Tier 1+ and Tier 2+ standards are applicable to remanufactured locomotives that were originally subject to Tier 0, Tier 1 and Tier 2, respectively, when they were manufactured. The most stringent of these standards, Tier 4, is predicated on the use of post combustion controls for particulate matter (PM) and NO_x, including diesel particulate filters (DPF) and selective catalytic reduction (SCR), respectively. Emission standards for the EPA line-haul cycle are given in Table C-1.

TABLE C-1. U.S. EPA Line-Haul Locomotive Emission Standards

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

[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+ standard.*

[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.*

[e] *Source: 40 CFR 1033, 2008, 1998; EPA, 1998*

C.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.

Nonroad diesel engines are regulated under 40 CFR part 1039 and stationary compression-ignition engines that are certified to the standards in 40 CFR part 1039, as specified in 40 CFR part 60, subpart IIII. For earlier model years, manufacturers may use the test procedures in this part or those specified in 40 CFR part 89. Emission standards applicable to nonroad engines for sizes relevant to the HEP engines of the NCDOT fleet are given in Table C-2.

C.3 Comparison of PME and HEP Engine Standards

In this section, PME and HEP engine standards applicable to NCDOT locomotives are compared to each other. The PMEs of NCDOT locomotives have a rated power of 2240 kW and are all certified to the Tier 0+ PME standard. As discussed in Section 2.6.2, the PMEs typically operate at the rated power typically for 25 percent to 50 percent of the trip duration.

TABLE C-2. Nonroad Compression-Ignition Engine Exhaust Emission Standards

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

[a] *No Tier 3 standard for engine size between 560 kW and 900 kW.*
Source: (40 CFR 9, 69, 80, 86, 89, 94, 1039, 1048, 1051, 1065, 1068, 2004)

The HEP engines of two recently acquired locomotives NC 1871 and NC 1984 have a rated power of 447 kW and are certified to the Tier 3 nonroad standard. The HEP engines of other locomotives have a rated power of 671 kW and are certified to the Tier 2 nonroad standard. The HEP engines typically operate at approximately constant load depending on the number of passenger cars. For 2-4 passenger cars, these HEP engines operate between 25 to 50 kW (Frey and Hu, 2015).

CO emission limits for the Tier 0+ PMEs are 5 g/bhp-hr versus 3.5 g/bhp-hr for each of the HEP engines models, even though one is Tier 2 and the other is Tier 3. Thus, the PMEs have less stringent CO emission limits than the HEP engines.

The PMEs have a separate emission limits for HC and NO_x emissions whereas, the HEP engines have a common standard. Therefore, for consistent comparison, HC and NO_x emission rates for PMEs are summed. The combined HC + NO_x emission limits are 9 g/bhp-hr, 6.4 g/bhp-hr, and 4.0 g/bhp-hr for PMEs, Tier 2 HEP engines and Tier 3 HEP engines, respectively. Thus, the PMEs have less stringent HC + NO_x emission limits than the HEP engines.

PM emission limits are 0.22 g/bhp-hr for PMEs and 0.20 g/bhp-hr for each of the HEP engines models, even though one is Tier 2 and the other is Tier 3.

The PMEs have less stringent emission limits of CO and HC + NO_x compared to HEP engines. Although the PME and HEP engines have PM emission limits of similar magnitude, the PME will have much higher mass per time emissions of all pollutants because it runs at much higher load than the HEP engines.

References

40 CFR 9, 69, 80, 86, 89, 94, 1039, 1048, 1051, 1065, 1068, 2004. Control of Emissions of Air Pollution from Nonroad Diesel Engines and Fuel; Final Rule. Fed. Regist. 69, 38958–39273.

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Frey, H.C., Hu, J., 2015. Measurement of Locomotive Head End Power Engine Fuel and Emissions (Technical Report No. 0704–0188). Prepared by North Carolina State University for North Carolina Department of Transportation, Raleigh, NC.

Appendix D. Baseline Rail Yard Fuel Use and Emission Rates

The results of rail yard measurements (RY) on the prime mover engines (PMEs) of locomotives NC 1871 and NC 1984 are given here. Simultaneous exhaust gas measurements were conducted using Axion portable emissions measurement system (PEMS) and SEMTECH-DS PEMS. Additionally, particulate matter (PM) measurements were conducted using the Axion PEMS. Engine activity variables were measured using an engine sensor array connected to the Axion PEMS. This section provides a summary of notch-average measured concentrations and engine activity variables for each replicate. Fuel use and emission rates (FUER) are also shown based on Axion PEMS and SEMTECH-DS PEMS measurements. Cycle-average emission rates (CAER) were estimated for the EPA line-haul duty cycle. Finally, notch-average NO_x/NO and THC/HC ratio were estimated based on SEMTECH-DS measurements and used to bias correct NO and HC measurements made using Axion PEMS.

D.1 Locomotive NC 1871: December 21 2017

Engine activity variables including engine revolutions per minute (RPM), intake air temperature (IAT) and manifold absolute pressure (MAP) were measured with the Axion PEMS. The notch-average RPM, IAT, and MAP for the three replicates are summarized in Table D-1(a), Table D-1(b) and Table D-1(c), respectively. Notch-average measured exhaust concentrations of CO_2, CO, HC, NO and PM measured using Axion PEMS are summarized in Table D-2.

Engine RPM varied from 268 rpm at idle and notch 1 to 903 rpm at notch 8. This PME had two idle positions, but is configured to operate at only one idle position during RY measurement. The notch-average RPM had an inter-replicate coefficient of variation (CV) of 0.01 or lower for each notch position. Thus, the RPM measurements were highly repeatable.

Notch-average IAT varied from 345 K at notch 1 to 355 K at notch 7 and notch 8. In general, IAT increased with the increasing notch position. However, IAT differed by approximately one Kelvin degree between adjacent notch positions. Inter-replicate CV for each notch position was 0.02 or lower. Therefore, IAT measurements were highly repeatable.

Notch-average MAP varied from 103 kPa at idle to 205 kPa at notch 8. MAP increased with engine RPM. Inter-replicate CV for MAP was 0.01 or lower for each notch position. Therefore, MAP measurements were highly repeatable.

Notch-average measured exhaust concentrations of CO_2, CO, HC, NO and PM measured using Axion PEMS are summarized in Table D-2. Notch-average CO_2 concentrations varied from 0.65 vol % at idle to 5.15 vol % at notch 8. Notch-average CO_2 concentrations increased with increasing notch position except for notch 7 and notch 8, which had CO_2 concentrations within 0.06 vol % each other. Notch-average CO_2 concentrations were highly repeatable with an inter-replicate CV of 0.03 or lower for each notch position.

TABLE D-1. Notch-Average Engine Activity Variables for the Prime Mover Engine of Locomotive NC 1871 measured using an Engine Sensor Array on December 21, 2017: (a) Engine RPM; (b) Intake Air Temperature; and (c) Manifold Absolute Pressure.

(a) Engine RPM (RPM)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	268	268	268	268	2.04	0.007
1	268	268	268	268	0.004	0.00001
2	388	389	389	388	0.267	0.0006
3	509	511	512	510.	1.60	0.003
4	702	702	702	702	0.223	0.0003
5	728	710.	709	716	10.6	0.014
6	791	794	792	792	1.24	0.001
7	830.	829	826	828	1.88	0.002
8	903	904	903	903	2.6	0.012

(b) Intake Air Temperature (K)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	346	347	348	347	0.68	0.002
1	345	345	346	345	0.72	0.002
2	347	347	348	347	0.46	0.001
3	350	350	350	350	0.23	0.001
4	352	353	353	353	0.15	0.000
5	353	352	353	353	0.20	0.001
6	354	354	354	354	0.47	0.001
7	354	355	355	355	0.35	0.001
8	355	355	354	355	0.25	0.001

(c) Manifold Absolute Pressure (kPa)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	104	103	104	104	0.210	0.002
1	103	103	103	103	0.0001	0.000001
2	105	105	106	105	0.068	0.0006
3	116	117	117	116	0.256	0.002
4	152	152	152	152	0.049	0.0003
5	158	155	155	156	1.86	0.012
6	178	178	178	178	0.124	0.0006
7	190	190	189	190	0.390	0.002
8	208	205	203	205	2.33	0.011

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

TABLE D-2. Notch-Average Prime Mover Engine Exhaust Concentrations of locomotive NC 1871 measured on December 21, 2017 using Axion Portable Emissions Measurement System: (a) CO_2; (b) CO; (c) HC; (d) NO; and (e) PM.

(a) CO_2 concentration (vol %)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	0.66	0.65	0.63	0.75	0.017	0.065
1	1.17	1.16	1.15	1.16	0.005	0.004
2	2.36	2.30	2.33	2.33	0.029	0.012
3	3.32	3.28	3.31	3.30	0.017	0.005
4	3.54	3.51	3.65	3.57	0.072	0.020
5	4.43	4.26	4.23	4.30	0.108	0.025
6	4.76	5.02	5.01	4.93	0.149	0.030
7	5.11	5.20	5.13	5.15	0.045	0.008
8	5.15	5.19	4.92	5.09	0.144	0.028

(b) CO concentration (vol %)[b]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	*0.000*	*0.000*	*0.000*	0.000	0.000	0.000
1	*0.000*	*0.000*	*0.000*	0.000	0.000	0.000
2	*0.000*	*0.000*	*0.000*	0.000	0.000	0.000
3	*0.000*	*0.000*	*0.000*	0.000	0.000	0.000
4	*0.000*	*0.000*	*0.000*	0.000	0.000	0.000
5	*0.000*	*0.000*	*0.000*	0.000	0.000	0.000
6	*0.000*	*0.000*	*0.000*	0.000	0.000	0.000
7	*0.004*	*0.004*	*0.005*	0.005	0.0006	0.122
8	*0.001*	*0.004*	*0.006*	0.004	0.002	0.699

(c) HC concentration (ppm)[c]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	*8*	*5*	*6*	6	1.27	0.192
1	*9*	*9*	17	12	4.25	0.352
2	*7*	17	*6*	10	5.99	0.578
3	*4*	*10*	*11*	8	3.77	0.442
4	*1*	*1*	*2*	1	0.678	0.368
5	*4*	*8*	*12*	8	4.30	0.498
6	*5*	*1*	*4*	3	2.22	0.569
7	*6*	*8*	*4*	6	2.23	0.344
8	*2*	*0*	*0*	1	1.22	1.34

Table D-2 Continued on next page.

Table D-2 Continued from previous page.

(d) NO concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	162	158	158	159	37.8	0.010
1	324	317	317	319	3.93	0.0123
2	598	603	630	610	17.1	0.0280
3	1020	1030	1040	1030	10.4	0.0101
4	982	1000	1030	1000	22.6	0.0226
5	1330	1270	1300	1300	28.2	0.0217
6	1300	1370	1380	1350	43.9	0.0325
7	1250	1270	1270	1260	15.0	0.0119
8	1210	1220	1200	1210	14.1	0.0117

(e) PM Concentration (mg/m^3)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	4.55	4.64	4.71	4.63	0.0761	0.016
1	4.78	4.74	4.70	4.74	0.0428	0.009
2	4.48	4.45	4.42	4.45	0.0298	0.006
3	4.66	4.58	4.57	4.60	0.0502	0.010
4	4.97	4.81	4.88	4.89	0.0820	0.016
5	4.98	4.83	4.89	4.90	0.0775	0.015
6	6.43	6.33	6.39	6.39	0.0489	0.007
7	7.94	8.07	8.26	8.09	0.160	0.019
8	8.18	8.29	8.44	8.30	0.129	0.015

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*
[b] *The values in italics are below the detection limit of the Axion PEMS (0.008 vol % for CO).*
[c] *The values in italics are below the detection limit of the Axion PEMS (13 ppm for HC).*

Notch-average CO and HC concentrations were below the detection limit of the Axion PEMS for all notch positions and all replicates. Notch-average NO concentrations varied between 159 ppm at idle and 1350 ppm at notch 6. Notch-average NO concentrations typically increased with increasing notch position from idle through notch 6 and decreased to 1210 ppm at notch 8. Notch-average NO concentrations were highly repeatable with an inter-replicate CV of 0.03 or lower.

Notch-average PM concentrations varied between 4.5 mg/m^3 and 8.3 mg/m^3. Notch-average PM was within 0.4 mg/m^3 of each other for idle and notches 1 through 5. For notches 5 to 8, notch-average PM concentrations increased with increasing notch position to 8.3 mg/m^3. Notch-average PM concentrations were highly repeatable with an inter-replicate CV of 0.02 or lower.

Notch-average exhaust gas concentrations of THC, HC, NO and NO_2 measured using SEMTECH-DS PEMS are summarized in Table D-3. No trend in notch-average THC concentrations was observed. Notch-average THC concentrations were repeatable for each notch position with an inter-replicate CV of 0.06 or lower. Notch-average HC concentrations typically increased with increasing notch position. Notch-average HC concentrations were repeatable as the inter-replicate CV was 0.2 or lower for each notch position.

TABLE D-3. Notch-Average Prime Mover Engine Exhaust Concentrations of Locomotive NC 1871 measured using SEMTECH-DS Portable Emissions Measurement System on December 21, 2017: (a) THC; (b) HC; (c) NO; and (d) NO_2.

(a) THC concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	21.5	21.1	22.4	21.6	0.6	0.03
1	18.5	17.8	18.0	18.1	0.3	0.01
2	22.0	21.9	21.2	21.7	0.4	0.02
3	23.9	23.3	21.7	23.0	1.1	0.04
4	20.5	19.7	18.8	19.7	0.8	0.04
5	20.5	19.3	18.5	19.5	1.0	0.05
6	21.9	21.3	20.1	21.1	0.9	0.04
7	22.9	22.4	21.6	22.3	0.7	0.03
8	26.3	24.7	22.9	24.6	1.6	0.06

(b) HC concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	5.1	3.3	3.6	4.0	0.9	0.2
1	5.2	4.7	4.2	4.7	0.4	0.09
2	7.9	7.5	7.8	7.7	0.2	0.02
3	9.7	9.3	9.0	9.3	0.3	0.03
4	9.9	9.0	8.7	9.2	0.6	0.06
5	10.0	9.8	9.0	9.6	0.5	0.05
6	10.4	9.5	9.1	9.7	0.6	0.07
7	9.9	9.3	8.3	9.2	0.8	0.09
8	9.7	7.5	6.7	8.0	1.6	0.2

(c) NO concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	195	198	192	196	3.0	0.2
1	381	373	373	376	4.8	0.01
2	693	703	699	698	5.3	0.007
3	1050	1040	1050	1050	4.2	0.004
4	997	997	999	998	1.3	0.001
5	1320	1260	1260	1280	33.1	0.02
6	1310	1320	1320	1310	5.7	0.004
7	1240	1230	1240	1230	3.6	0.002
8	1210	1140	1170	1180	35.0	0.02

Table D-3 Continued on next page.

Table D-3 Continued from previous page.

(d) NO_2 concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	7	6	6	6	2.6	0.05
1	17	14	15	16	1.5	0.09
2	31	28	29	29	1.1	0.03
3	53	49	50	51	2.0	0.03
4	51	48	50	50	1.3	0.02
5	72	65	66	68	3.7	0.05
6	69	67	69	68	0.9	0.01
7	66	64	66	65	1.3	0.02
8	68	68	69	68	0.5	0.008

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

Notch-average NO concentrations were repeatable with an inter-replicate CV of 0.2 or lower for each notch position. Notch-average NO_2 concentrations were repeatable with an inter-replicate CV of 0.09 or lower for each notch position.

The SEMTECH-DS measurements were used to obtain notch-average ratios of NO_x/NO and THC/HC. These ratios were multiplied with the Axion PEMS measured NO and HC concentrations to estimate bias corrected NO_x and THC concentrations. These ratios are summarized in Table D-4. The NO_x/NO ratio varied from 1.03 at idle to 1.06 at notch 8. This ratio was 1.05 for notch 3 through notch 8 and around 1.05 on average for all notch positions. The notch-average NO_x/NO ratios were highly repeatable with inter-replicate CV of 0.003 or lower for each notch position. These ratios are comparable to the expected NO_x/NO ratio of 1.053 based on typical diesel exhaust composition of 95 percent NO and 5 percent NO_2 (Flagan and Seinfeld, 2012).

Notch-average THC/HC ratios varied from 2.0 at notch 6 to 5.6 at idle. The ratio was highest at idle and decreased through notch 5. The highest notch-average THC/HC ratio was 3.4 at notch 8. Notch-average THC/HC ratios were highly repeatable with inter-replicate CV of 0.12 or lower for each notch position. The overall response to NDIR to a mixture of hydrocarbons in engine exhaust is approximately 23% to 68% of the actual total HC (Stephens *et al.*, 1996). Therefore, THC/HC ratio in typical diesel exhaust is expected to range between 1.5 and 4.3. Thus, the observed THC/HC ratios are consistent with expectations based on prior studies.

Notch-average fuel use and emission rates were estimated for locomotive NC 1871 based on Axion PEMS measurements of engine activity and exhaust gas and PM. Axion PEMS measured NO and HC concentrations were bias corrected for NO_x and THC using the NO_x/NO and THC/HC ratios estimated in the previous section. For PM, a correction factor of 5 was used based on literature review. The mass per time based fuel use rate and emission rates of CO_2, CO, THC, NO_x and PM are shown in Table D-5.

TABLE D-4. Notch-Average Prime Mover Engine Exhaust Concentration based NO_x/NO and THC/HC ratios for locomotive NC 1871 measured using SEMTECH-DS Portable Emissions Measurement System on December 21, 2017: (a) NO_x/NO ratio; and (b) THC/HC Ratio

(a) NO_x/NO ratio

Throttle Notch Position	NO_x/NO Ratio					
	21-Dec	21-Dec	21-Dec	3 Rep	3 Rep	3 Rep
	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	1.04	1.03	1.03	1.03	0.003	0.003
1	1.04	1.04	1.04	1.04	0.004	0.003
2	1.04	1.04	1.04	1.04	0.002	0.002
3	1.05	1.05	1.05	1.05	0.002	0.002
4	1.05	1.05	1.05	1.05	0.002	0.001
5	1.05	1.05	1.05	1.05	0.002	0.001
6	1.05	1.05	1.05	1.05	0.001	0.001
7	1.05	1.05	1.05	1.05	0.001	0.001
8	1.06	1.06	1.06	1.06	0.002	0.002

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

(b) THC/HC ratio

Throttle Notch Position	THC/HC Ratio					
	21-Dec	21-Dec	21-Dec	3 Rep	3 Rep	3 Rep
	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	4.2	6.4	6.2	5.6	1.21	0.22
1	3.6	3.8	4.3	3.9	0.37	0.10
2	2.8	2.9	2.7	2.8	0.10	0.04
3	2.5	2.5	2.4	2.5	0.05	0.02
4	2.1	2.2	2.2	2.1	0.06	0.03
5	2.1	2.0	2.1	2.0	0.05	0.02
6	2.1	2.2	2.2	2.2	0.07	0.03
7	2.3	2.4	2.6	2.4	0.15	0.06
8	2.7	3.3	3.4	3.1	0.38	0.12

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

TABLE D-5. Notch-Average Fuel Use and Emission Rates based on Axion Portable Emissions Measurement System measured Concentrations for the Prime Mover Engine of Locomotive NC 1871 measured on December 21, 2017: (a) Fuel use rate; (b) CO_2 emission rate; (c) CO emission rate; (d) THC emission rate; (e) NO_x emission rate; and (f) PM emission rate.

(a) Mass per time based fuel use rate (g/s)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	2.9	2.9	2.9	2.9	0.02	0.001
1	5.2	5.2	5.2	5.2	0.03	0.006
2	14.0	13.7	13.9	13.9	0.1	0.009
3	25.7	25.6	25.8	25.7	0.1	0.004
4	42.1	41.7	43.1	42.3	0.6	0.01
5	55.7	51.7	51.5	53.0	2.3	0.04
6	69.4	72.5	72.1	71.3	1.6	0.02
7	80.2	81.1	79.8	80.4	0.6	0.008
8	90.2	88.2	83.2	87.2	3.5	0.04

(b) Mass per time based CO_2 emission rate (g/s)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	9.1	9.2	9.0	9.2	0.2	0.1
1	16.4	16.3	16.2	16.3	0.1	0.007
2	43.7	42.8	43.3	43.3	0.4	0.01
3	80.3	79.9	80.6	80.3	0.3	0.004
4	132	130.	135	132	2.1	0.01
5	174	162	161	166	7.4	0.04
6	217	227	225	223	5.2	0.02
7	251	253	249	251	2.1	0.008
8	282	276	260.	273	11.3	0.04

(c) Mass per time based CO emission rate (g/s)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	*0.000*	*0.002*	*0.008*	*0.000*	*0.004*	*1.01*
1	*0.000*	*0.000*	*0.001*	*0.000*	*0.0006*	*1.10*
2	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
3	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
4	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
5	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
6	*0.001*	*0.007*	*0.001*	*0.003*	*0.003*	*0.9*
7	0.154	0.135	0.172	0.153	0.018	0.1
8	0.0283	0.141	0.189	0.119	0.082	0.6

Table C-5 Continued on next page.

Table C-5 Continued from previous page.

(d) Mass per time based THC emission rate (g/s)[b]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	0.0563	0.0397	0.0425	0.0462	0.00889	0.193
1	0.0670	0.0655	0.117	0.0830	0.0291	0.350
2	0.0650	0.157	0.0604	0.0941	0.0545	0.579
3	0.0495	0.123	0.131	0.101	0.0451	0.445
4	0.0285	0.0244	0.0471	0.0333	0.0121	0.364
5	0.0833	0.161	0.241	0.162	0.0787	0.487
6	0.132	0.0336	0.0940	0.0865	0.0496	0.573
7	0.155	0.207	0.101	0.155	0.0533	0.345
8	0.0617	0.0114	#NUM!	0.0244	0.0328	1.35

(e) Mass per time based NO_x emission rate (g/s)[c]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	0.351	0.246	0.250	0.282	0.0594	0.210
1	0.503	0.492	0.489	0.495	0.00709	0.0143
2	1.22	1.23	1.29	1.25	0.0370	0.0297
3	2.72	2.76	2.80	2.76	0.0395	0.0143
4	4.02	4.09	4.17	4.09	0.0766	0.0187
5	5.75	5.32	5.46	5.51	0.220	0.0398
6	6.53	6.83	6.83	6.73	0.173	0.0256
7	6.72	6.84	6.77	6.78	0.0605	0.00892
8	7.31	7.15	6.95	7.14	0.182	0.0255

(f) Mass per time based PM emission rate (g/s)[d]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	0.02	0.02	0.02	0.02	0.00	0.02
1	0.02	0.02	0.02	0.02	0.00	0.01
2	0.02	0.02	0.02	0.02	0.00	0.00
3	0.03	0.03	0.03	0.03	0.00	0.01
4	0.05	0.05	0.05	0.05	0.00	0.02
5	0.06	0.05	0.05	0.05	0.00	0.04
6	0.08	0.08	0.08	0.08	0.00	0.01
7	0.11	0.11	0.11	0.11	0.00	0.02
8	0.13	0.13	0.13	0.13	0.00	0.01

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

[b] *HC concentration measured with Axion PEMS were multiplied with a correction factor shown in Table D-4(b) to obtain THC concentration.*

[c] *NO concentration measured with Axion PEMS were multiplied with a correction factor shown in Table D-4(a) to obtain NO_x concentration.*

[d] *PM emission rates estimated with Axion measurements have been multiplied by a factor of 5 to account for total PM.*

D.2 Locomotive NC 1871: June 11 2019

Engine activity variables including RPM, IAT, and MAP measured with the Axion PEMS. Notch-average RPM, IAT, and MAP for the three replicates are summarized in Table D-6(a), Table D-6(b) and Table D-6(c), respectively. Notch-average engine RPM varied from 268 rpm at idle and notch 1 to 902 rpm at notch 8. Notch-average RPM had an inter-replicate coefficient of variation (CV) of 0.002 or lower for each notch position. Thus, the RPM measurements were highly repeatable.

Notch-average IAT varied from 313 K at notch 1 to 318 K at notches 4, 6, 7 and 8. In general, IAT increased with the increasing notch position. However, IAT differed by typically less than one kelvin between adjacent notch positions. Inter-replicate CV for each notch position for IAT was 0.01 or lower. Therefore, IAT measurements were highly repeatable. Notch-average MAP varied from 98 kPa at idle to 201 kPa at notch 8. MAP increased with engine RPM. Inter-replicate CV for each notch position for MAP was 0.006 or lower. Therefore, MAP measurements were highly repeatable.

Notch-average measured exhaust concentrations of CO_2, CO, HC, NO and PM measured using Axion PEMS are summarized in Table D-7. Notch-average CO_2 concentrations varied from 0.71 vol % at idle to 6.09 vol % at notch 7. The notch-average CO_2 concentration at notch 8 was 6.03 vol %. Notch-average CO_2 concentrations increased with increasing notch position for idle through notch 7. Notch-average CO_2 concentrations were highly repeatable with inter-replicate CV of 0.06 or lower for each notch position.

Notch-average CO concentrations were below the detection limit of the Axion PEMS for idle through notch 5. Inter-replicate CVs for notch-average CO concentrations were 0.10 or lower. Notch-average HC concentrations were above the PEMS HC detection limit for notches 1 through 3 and lower for others. Inter-replicate CV was 0.2 or lower for notches with HC concentrations above the detection limit and 0.5 or lower for 6 out of the 9 notch positions.

Notch-average NO concentrations varied between 192 ppm at idle and 1460 ppm at notch 5. Notch-average NO concentrations typically increased with notch position from idle through notch 5 and decreased to 1206 ppm at notch 8. Notch-average NO concentrations were highly repeatable with inter-replicate CV of 0.05 or lower for each notch position.

Notch-average PM concentrations varied from 4.4 mg/m^3 and 15.4 mg/m^3. Notch-average PM concentrations were within 0.4 mg/m^3 of each other for idle and notches 1 through 4. Thereafter, notch-average PM concentrations increased with increasing notch position to 15.4 mg/m^3 at notch 7 and was 14.4 mg/m^3 at notch 8. Notch-average PM concentrations were highly repeatable with inter-replicate CV of 0.02 or lower for each notch position.

TABLE D-6. Notch-Average Engine Activity Variables for the Prime Mover Engine of Locomotive NC 1871 measured on June 11, 2019 using an Engine Sensor Array: (a) Engine RPM; (b) Intake Air Temperature; and (c) Manifold Absolute Pressure.

(a) Engine RPM (rpm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	269	269	268	269	0.51	0.0019
1	268	268	268	268	0.02	0.0001
2	389	389	389	389	0.01	0.0000
3	509	509	509	509	0.04	0.0001
4	702	702	702	702	0.01	0.0000
5	728	728	728	728	0.11	0.0002
6	819	819	819	819	0.08	0.0001
7	859	859	859	859	0.02	0.0000
8	900	903	903	902	1.72	0.0019

(b) Intake Air Temperature (K)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	311	314	316	314	2.52	0.008
1	312	313	314	313	1.00	0.003
2	313	314	316	314	1.53	0.005
3	314	317	318	316	2.08	0.007
4	315	318	320	318	2.52	0.008
5	315	317	319	317	2.00	0.006
6	316	318	319	318	1.53	0.005
7	314	319	321	318	3.61	0.011
8	316	318	319	318	1.53	0.005

(c) Manifold Absolute Pressure (kPa)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	98	98	98	98	0.18	0.002
1	98	97	97	97	0.20	0.002
2	106	106	106	106	0.22	0.002
3	118	118	118	118	0.23	0.002
4	149	148	148	149	0.47	0.003
5	155	155	154	155	0.54	0.004
6	178	178	177	178	0.57	0.003
7	194	194	192	193	1.18	0.006
8	202	201	201	201	0.87	0.004

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

TABLE D-7. Notch-Average Prime Mover Engine Exhaust Concentrations of Locomotive NC 1871 measured using Axion Portable Emissions Measurement System on June 11, 2019: (a) CO_2; (b) CO; (c) HC; (d) NO; and (e) PM.

(a) CO_2 concentration (vol %)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	0.72	0.75	0.67	0.71	0.04	0.06
1	1.24	1.20	1.18	1.21	0.03	0.03
2	2.40	2.41	2.42	2.41	0.01	0.00
3	3.54	3.52	3.54	3.53	0.01	0.00
4	3.91	3.91	3.94	3.92	0.02	0.00
5	4.97	4.95	5.03	4.98	0.04	0.01
6	5.90	6.13	5.85	5.96	0.15	0.02
7	6.05	6.14	6.09	6.09	0.04	0.01
8	5.99	6.11	5.99	6.03	0.07	0.01

(b) CO concentration (vol %)[b]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	*0.001*	*0.001*	*0.001*	*0.001*	*0.000*	*0.17*
1	*0.000*	*0.002*	*0.000*	*0.001*	*0.001*	*1.71*
2	*0.000*	*0.001*	*0.000*	*0.000*	*0.001*	*1.60*
3	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.00*
4	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.00*
5	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.00*
6	0.014	0.021	0.017	0.017	0.004	0.21
7	0.036	0.038	0.036	0.037	0.001	0.02
8	0.031	0.031	0.026	0.029	0.003	0.10

(c) HC concentration (ppm)[c]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	*13*	*4*	19	*12*	7	0.63
1	14	*13*	17	15	2	0.15
2	16	*11*	15	14	3	0.20
3	15	*11*	14	14	2	0.16
4	*2*	*7*	*7*	*5*	*3*	*0.56*
5	*1*	*8*	*5*	*5*	*4*	*0.82*
6	*4*	*2*	*5*	*3*	*2*	*0.51*
7	*6*	*5*	*7*	*6*	*1*	*0.13*
8	*1*	*0*	*1*	*1*	*0*	*0.77*

Table D-7 Continued on next page.

Table D-7 Continued from previous page.

(d) NO concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	187	203	187	192	9	0.05
1	340	329	327	332	7	0.02
2	692	690	710	697	11	0.02
3	1149	1147	1162	1153	8	0.01
4	1152	1125	1160	1146	19	0.02
5	1466	1440	1474	1460	18	0.01
6	1380	1421	1408	1403	21	0.02
7	1217	1250	1216	1228	19	0.02
8	1174	1241	1203	1206	34	0.03

(e) PM Concentration (mg/m^3)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	5.4	5.0	4.0	4.8	0.7	0.14
1	5.0	4.4	4.6	4.7	0.3	0.06
2	5.1	4.8	4.8	4.9	0.2	0.03
3	4.6	4.5	4.5	4.6	0.1	0.02
4	4.7	4.4	4.0	4.4	0.3	0.07
5	5.6	5.2	5.1	5.3	0.2	0.05
6	11.4	12.2	11.3	11.6	0.5	0.04
7	17.0	15.2	14.1	15.4	1.5	0.10
8	16.6	13.9	12.7	14.4	2.0	0.14

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*
[b] *The values in italics are below the detection limit of the Axion PEMS (0.008 vol % for CO).*
[c] *The values in italics are below the detection limit of the Axion PEMS (13 ppm for HC).*

Notch-average exhaust gas concentrations of THC, HC, NO and NO_2 measured using SEMTECH-DS PEMS are summarized in Table D-8. No trend in notch-average THC concentrations was observed. Notch-average THC and HC concentrations have low inter-replicate repeatability, but the concentrations are also very low. Inter-replicate CVs for notch-average THC concentrations ranged from 0.06 to 0.25 and were at or below 0.12 for 6 of the 9 notch positions. Inter-replicate CVs for notch-average HC concentrations ranged from 0.06 to 0.43 and were at or below 0.18 for 6 of the 9 notch positions. Notch-average NO concentrations were repeatable with CVs of 0.09 or lower. Notch-average NO_2 concentrations were repeatable with CVs of 0.13 or lower.

TABLE D-8. Notch-Average Prime Mover Engine Exhaust Concentrations of Locomotive NC 1871 measured on June 11, 2019 using SEMTECH-DS Portable Emissions Measurement System: (a) THC; (b) HC; (c) NO; and (d) NO_2.

(a) THC concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	21	19	18	19	2	0.08
1	25	20	24	23	3	0.11
2	27	33	20	27	7	0.25
3	24	26	27	26	1	0.06
4	33	29	30	31	2	0.07
5	24	26	16	22	5	0.25
6	33	29	26	29	4	0.12
7	27	32	39	33	6	0.18
8	30	35	38	34	4	0.12

(b) HC concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	9	10	11	10	1	0.06
1	16	14	16	15	1	0.07
2	22	20	15	19	3	0.18
3	20	18	14	17	3	0.17
4	16	24	26	22	5	0.22
5	18	22	9	16	7	0.43
6	25	13	22	20	6	0.32
7	17	15	18	17	1	0.07
8	15	18	21	18	3	0.17

(c) NO concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	204	201	189	198	8.3	0.04
1	383	363	373	373	9.8	0.03
2	732	705	781	739	38.5	0.05
3	1012	1095	1104	1070	50.5	0.05
4	1036	1044	949	1010	52.6	0.05
5	1392	1164	1258	1271	114.4	0.09
6	1395	1406	1386	1396	9.8	0.01
7	1264	1288	1206	1253	42.2	0.03
8	1276	1105	1171	1184	86.2	0.07

Table D-8 Continued on next page.

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(d) NO_2 concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	7	5	5	6	0.7	0.13
1	19	21	21	21	1.2	0.06
2	31	37	29	32	4.3	0.13
3	62	48	57	56	7.1	0.13
4	60	47	51	52	6.4	0.12
5	76	63	75	71	6.9	0.10
6	63	70	67	67	3.3	0.05
7	64	70	70	68	3.4	0.05
8	61	77	69	69	7.7	0.11

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

The SEMTECH-DS measurements were used to obtain notch-average ratios of NO_x/NO and THC/HC concentrations that were used to bias correct Axion measurements. These ratios are summarized in Table D-9. The notch-average NO_x/NO ratio varied from 1.03 at high idle to 1.07 at notch 8. These ratios were highly repeatable for a given notch position with inter-replicate CV of 0.01 or lower. The THC/HC ratio varied from 1.2 at notches 2 and 3 to 2.2 at high idle and notches 6 and 7. Inter-replicate CV was 0.5 for high idle and notch 7, below 0.20 for 5 of the 9 notch positions and below 0.30 for 7 of the 9 notch positions. On average, the THC/HC ratio was approximately 1.5, except for notches 6, 7 and 8, for which the average is approximately 2.0.

Notch-average fuel use and emission rates were estimated for locomotive NC 1871 based on Axion PEMS measurements of engine activity and exhaust gas and PM. Axion measured NO and HC were bias corrected for NO_x and THC using the NO_x/NO and THC/HC ratios estimated in the previous sections. For PM, a correction factor of 5 was used based on literature review. Mass per time based and engine output based emission rates were estimated. Engine-output based emission rates were weighted to EPA Line-haul cycle to estimate cycle-average emission rates. The mass per time based fuel use rate and emission rates of CO_2, CO, THC, NO_x and PM are shown in Table D-10.

TABLE D-9. Notch-Average Prime Mover Engine Exhaust Concentrations based NO_x/NO and THC/HC ratios for locomotive NC 1871 measured using SEMTECH-DS Portable Emissions Measurement System on June 11, 2019: (a) NO_x/NO ratio; and (b) THC/HC Ratio

(a) NO_x/NO ratio

Throttle Notch Position	NO_x/NO Ratio					
	11-Jun	11-Jun	11-Jun	3 Rep	3 Rep	3 Rep
	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	1.03	1.03	1.03	1.03	0.003	0.003
1	1.05	1.06	1.06	1.06	0.005	0.004
2	1.04	1.05	1.04	1.04	0.008	0.008
3	1.06	1.04	1.05	1.05	0.009	0.008
4	1.06	1.05	1.05	1.05	0.006	0.006
5	1.05	1.05	1.06	1.06	0.003	0.003
6	1.05	1.05	1.05	1.05	0.002	0.002
7	1.05	1.05	1.06	1.05	0.004	0.003
8	1.05	1.07	1.06	1.06	0.011	0.010

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

(b) THC/HC ratio

Throttle Notch Position	THC/HC Ratio					
	11-Jun	11-Jun	11-Jun	3 Rep	3 Rep	3 Rep
	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	1.5	1.4	1.5	1.5	0.07	0.05
1	1.2	1.7	1.3	1.4	0.23	0.16
2	1.2	1.5	1.9	1.6	0.35	0.23
3	2.0	1.2	1.2	1.5	0.47	0.32
4	1.4	1.2	1.9	1.5	0.36	0.25
5	1.3	2.2	1.2	1.6	0.57	0.36
6	1.6	2.1	2.2	2.0	0.35	0.18
7	2.0	2.0	1.8	2.0	0.10	0.05
8	2.2	2.0	1.7	2.0	0.27	0.14

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

TABLE D-10. Notch-average Fuel Use and Emission Rates based on Axion Portable Emission Measurement System measured Concentrations for the Prime Mover Engine of Locomotive NC 1871 measured on June 11, 2019: (a) Fuel use rate; (b) CO_2 emission rate; (c) CO emission rate; (d) THC emission rate; (e) NO_x emission rate; and (f) PM emission rate.

(a) Mass per time based fuel use rate (g/s)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	3.5	3.6	3.2	3.4	0.2	0.06
1	6.0	5.7	5.6	5.8	0.2	0.03
2	16.0	16.0	16.0	16.0	0.0	0.00
3	31.0	30.5	30.6	30.7	0.3	0.01
4	51.0	50.4	50.5	50.6	0.3	0.01
5	68.5	67.9	67.9	68.1	0.3	0.00
6	98.1	100	96.6	98.4	1.9	0.02
7	112	110	109	110	1.1	0.01
8	116	117	115	116	1.1	0.01

(b) Mass per time based CO_2 emission rate (g/s)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	11	11	10	11	0.7	0.06
1	19	18	17	18	0.6	0.03
2	50	50	50	50	0.0	0.00
3	97	95	96	96	0.8	0.01
4	160	158	158	158	1.0	0.01
5	214	212	212	213	1.1	0.01
6	306	313	301	307	5.8	0.02
7	347	343	340	343	3.5	0.01
8	362	364	358	361	3.2	0.01

(c) Mass per time based CO emission rate (g/s)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	*0.008*	*0.010*	*0.011*	*0.010*	*0.002*	*0.16*
1	*0.000*	*0.020*	*0.000*	*0.007*	*0.011*	*1.71*
2	*0.000*	*0.016*	*0.001*	*0.005*	*0.009*	*1.60*
3	*0.000*	*0.003*	*0.001*	*0.001*	*0.002*	*1.18*
4	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*1.46*
5	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*1.73*
6	0.4	0.7	0.6	0.6	0.1	0.20
7	1.3	1.3	1.3	1.3	0.3	0.02
8	1.2	1.2	1.0	1.1	0.1	0.10

Table D-10 Continued on next page.

Table D-10 Continued from previous page.

(d) Mass per time based THC emission rate (g/s)[b]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	*0.094*	*0.029*	0.136	*0.086*	*0.054*	*0.62*
1	0.104	*0.095*	0.126	0.108	0.016	0.14
2	0.164	*0.111*	0.154	0.143	0.028	0.20
3	0.203	*0.146*	0.191	0.180	0.030	0.17
4	*0.036*	*0.137*	*0.136*	*0.103*	*0.058*	*0.56*
5	*0.012*	*0.169*	*0.108*	*0.096*	*0.079*	*0.82*
6	*0.089*	*0.039*	*0.126*	*0.085*	*0.044*	*0.51*
7	*0.161*	*0.136*	*0.178*	*0.159*	*0.021*	*0.13*
8	*0.019*	*0.002*	*0.025*	*0.016*	*0.012*	*0.77*

(e) Mass per time based NO_x emission rate (g/s)[c]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	0.31	0.33	0.31	0.25	0.005	0.02
1	0.56	0.54	0.53	0.54	0.01	0.02
2	1.58	1.57	1.61	1.59	0.02	0.01
3	3.46	3.42	3.45	3.44	0.02	0.01
4	5.17	4.99	5.12	5.09	0.09	0.02
5	6.96	6.79	6.86	6.87	0.08	0.01
6	7.88	7.99	7.99	7.95	0.07	0.01
7	7.68	7.68	7.47	7.61	0.12	0.02
8	7.82	8.15	7.91	7.96	0.17	0.02

(f) Mass per time based PM emission rate (g/s)[d]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Idle	0.02	0.02	0.02	0.02	0.00	0.15
1	0.02	0.02	0.02	0.02	0.00	0.06
2	0.03	0.03	0.03	0.03	0.00	0.04
3	0.04	0.03	0.03	0.03	0.00	0.02
4	0.05	0.05	0.05	0.05	0.00	0.08
5	0.07	0.06	0.06	0.06	0.00	0.06
6	0.17	0.18	0.16	0.17	0.01	0.04
7	0.24	0.23	0.22	0.23	0.03	0.11
8	0.28	0.24	0.22	0.25	0.04	0.15

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

[b] *HC concentration measured with Axion PEMS were multiplied with a correction factor shown in Table D-9(b) to obtain THC concentration.*

[c] *NO concentration measured with Axion PEMS were multiplied with a correction factor shown in Table D-9(a) to obtain NO_x concentration.*

[d] *PM emission rates estimated with Axion measurements have been multiplied by a factor of 5 to account for total PM.*

D.3 Locomotive NC 1984: January 25, 2018

Notch-average engine activity variables including RPM, IAT, and MAP measured with the Axion PEMS. The notch-average RPM, IAT, and MAP for the three replicates are summarized in Table D-11(a), Table D-11(b) and Table D-11(c), respectively. Notch-average engine RPM varied from 219 rpm at low idle and notch 1 to 903 rpm at notch 8. The notch-average RPM had inter-replicate CV of 0.008 or lower for each notch position. Thus, the RPM measurements were highly repeatable.

Notch-average IAT varied from 348 K at notches 1, 2 and 3 to 358 K at notches 7 and 8. In general, notch-average IAT increased with the increasing notch position. However, notch-average IAT differed by less than two kelvin for adjacent notch positions. Inter-replicate CV for IAT was 0.003 or lower for each notch poison. Therefore, IAT measurements were highly repeatable.

Notch-average MAP varied from 98 kPa at idle to 213 kPa at notch 8. Notch-average MAP increased with increase in engine RPM. Inter-replicate CV for MAP was 0.016 or lower for each notch position. Therefore, MAP measurements were highly repeatable.

Notch-average measured exhaust concentrations of CO_2, CO, HC, NO and PM measured using Axion PEMS are summarized in Table D-12. Notch-average CO_2 concentrations varied from 0.70 vol % at idle to 5.46 vol % at notch 8. The notch-average CO_2 concentration at notch 8 was 6.03 vol %. Notch-average CO_2 concentrations increased with notch position for idle through notch 8. Notch-average CO_2 concentrations were highly repeatable with inter-replicate CV of 0.04 or lower for each notch position.

Notch-average CO concentrations were below the detection limit of the Axion PEMS for all notch positions. Notch-average HC concentrations were below the PEMS detection limit for all notch positions. Inter-replicate CV was 0.8 or lower for each notch position. However, although these results were imprecise, the measured concentrations were consistently low.

Notch-average NO concentrations varied between 170 ppm at high idle and 1534 ppm at notch 6. Notch-average NO concentrations typically increased with notch position from high idle through notch 5 and decreased to 1463 ppm at notch 8. Notch-average NO concentrations were highly repeatable with inter-replicate CV of 0.06 or lower for each notch position.

Notch-average PM concentrations varied from 5.6 mg/m^3 and 9.3 mg/m^3. Notch-average PM concentrations were highly repeatable with inter-replicate CV of 0.12 or lower for each notch position, and 0.06 or lower for nine of the ten notch positions.

Notch-average exhaust gas concentrations of THC, HC, NO and NO_2 measured using SEMTECH-DS PEMS are summarized in Table D-13. No trend in notch-average THC concentrations was observed. Notch-average THC and HC concentrations have low inter-replicate repeatability, but the concentrations were also low. Inter-replicate CVs for notch-average THC concentrations ranged from 0.06 to 0.25 and were at or below 0.12 for 6 of the 9 notch positions. Inter-replicate CVs for notch-average HC concentrations ranged from 0.06 to 0.43 and were at or below 0.18 for 6 of the 9 notch positions.

TABLE D-11. Notch-Average Engine Activity Variables for the Prime Mover Engine of Locomotive NC 1984 measured on January 25, 2018 using an Engine Sensor Array: (a) Engine RPM; (b) Intake Air Temperature; and (c) Manifold Absolute Pressure.

(a) Engine RPM (rpm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	219	219	219	219	0.08	0.0003
High Idle	268	268	268	268	0.08	0.0003
1	268	268	268	268	0.006	0.00002
2	386	389	389	388	1.44	0.003
3	509	506	509	508	1.48	0.002
4	702	700.	702	701	1.14	0.001
5	728	727	727	727	0.36	0.0004
6	814	818	819	817	2.56	0.003
7	858	857	858	858	0.78	0.0009
8	901	901	889	897	7.19	0.008

(b) Intake Air Temperature (K)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	347	349	347	348	1.13	0.003
High Idle	348	349	348	348	0.82	0.002
1	348	348	349	348	0.62	0.002
2	349	350	350	350	0.78	0.002
3	351	352	353	352	1.10	0.003
4	353	354	354	354	0.55	0.002
5	354	354	355	354	0.51	0.001
6	356	357	357	357	0.44	0.001
7	357	358	358	358	0.60	0.002
8	358	358	358	358	0.25	0.001

(c) Manifold Absolute Pressure (kPa)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	98.1	98.1	98.2	98.1	0.05	0.0005
High Idle	101	101	101	101	0.05	0.0005
1	101	101	101	101	0.07	0.0007
2	110	110	110	110	0.07	0.0007
3	123	123	123	123	0.304	0.002
4	156	156	156	156	0.31	0.002
5	163	163	162	163	0.27	0.001
6	186	187	187	186	0.35	0.001
7	207	204	204	205	1.73	0.008
8	217	213	210	213	3.62	0.017

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

TABLE D-12. Notch-Average Prime Mover Engine Exhaust Concentrations of locomotive NC 1984 measured using Axion PEMS on January 25, 2018: (a) CO_2; (b) CO; (c) HC; (d) NO; and (e) PM.

(a) CO_2 concentration (vol %)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	0.70	0.71	0.68	0.70	0.01	0.02
High Idle	0.71	0.70	0.72	0.71	0.01	0.02
1	1.30	1.24	1.20	1.25	0.05	0.04
2	2.34	2.33	2.36	2.34	0.02	0.01
3	3.35	3.35	3.37	3.36	0.01	0.00
4	3.63	3.60	3.66	3.63	0.03	0.01
5	4.43	4.49	4.47	4.46	0.03	0.01
6	5.17	5.26	5.28	5.24	0.05	0.01
7	5.38	5.27	5.33	5.33	0.05	0.01
8	5.52	5.53	5.33	5.46	0.11	0.02

(b) CO concentration (vol %)[b]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*1.571*
High Idle	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*1.450*
1	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
2	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*1.304*
3	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*1.732*
4	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
5	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*1.732*
6	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
7	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*1.732*
8	*0.000*	*0.001*	*0.003*	*0.001*	*0.001*	*0.753*

(c) HC concentration (ppm)[c]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	*2*	*8*	*4*	*5*	*3.12*	*0.64*
High Idle	*2*	*3*	*6*	*4*	*1.76*	*0.47*
1	*3*	*4*	*7*	*4*	*1.83*	*0.41*
2	*7*	*8*	*9*	*8*	*1.26*	*0.16*
3	*8*	*8*	*6*	*7*	*0.82*	*0.11*
4	*3*	*4*	*4*	*4*	*0.68*	*0.19*
5	*4*	*2*	*6*	*4*	*1.79*	*0.46*
6	*3*	*4*	*3*	*3*	*0.79*	*0.24*
7	*2*	*9*	*3*	*5*	*3.54*	*0.75*
8	*1*	*2*	*3*	*2*	*0.94*	*0.50*

Table D-12 Continued on next page.

Table D-12 Continued from previous page.

(d) NO concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	182	190	171	181	9.60	0.05
High Idle	168	175	168	170	4.02	0.02
1	360	365	334	353	16.27	0.05
2	633	674	653	653	20.72	0.03
3	1046	1139	1083	1090	46.84	0.04
4	1025	1082	1065	1057	29.00	0.03
5	1305	1459	1385	1383	76.70	0.06
6	1424	1595	1582	1534	94.97	0.06
7	1387	1485	1515	1463	66.92	0.05
8	1398	1502	1490	1463	56.85	0.04

(e) PM Concentration (mg/m^3)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	6.5	7.0	6.8	6.8	0.25	0.04
High Idle	7.3	7.3	6.6	7.0	0.36	0.05
1	6.5	6.8	6.4	6.6	0.19	0.03
2	5.9	5.7	6.0	5.8	0.15	0.03
3	5.5	5.6	5.7	5.6	0.09	0.02
4	6.0	6.2	6.1	6.1	0.09	0.02
5	6.3	6.3	6.1	6.2	0.14	0.02
6	7.9	8.0	7.7	7.8	0.13	0.02
7	9.1	8.6	8.7	8.8	0.27	0.03
8	10.6	8.6	8.7	9.3	1.13	0.12

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

[b] *The values in italics are below the detection limit of the Axion PEMS (0.008 vol % for CO).*

[c] *The values in italics are below the detection limit of the Axion PEMS (13 ppm for HC).*

Notch-average NO concentration varied from 188 ppm at high idle to 1406 ppm at notch 6. Notch-average NO measurements were repeatable with a highest CV of 0.09. Notch-average NO_2 concentrations varied from 5 ppm at high idle to 77 ppm at notch 8.

The SEMTECH-DS measurements were used to obtain notch-average ratios of NO_x/NO and THC/HC. These ratios were multiplied with the Axion PEMS measured NO and HC concentrations, respectively to estimate NO_x and THC concentrations. These ratios are summarized in Table D-14.

TABLE D-13. Notch-Average Prime Mover Engine Exhaust Concentrations of locomotive NC 1984 measured on January 25, 2018 using SEMTECH-DS PEMS: (a) THC; (b) HC; (c) NO; and (d) NO_2.

(a) THC concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low idle	32.0	17.9	16.4	22.1	8.6	0.39
High idle	20.6	19.0	17.0	18.9	1.8	0.10
1	21.3	20.5	18.4	20.1	1.5	0.07
2	21.8	25.7	22.0	23.2	2.2	0.09
3	19.7	27.7	23.6	23.7	4.0	0.17
4	15.2	25.4	20.8	20.5	5.1	0.25
5	15.8	23.3	20.0	19.7	3.8	0.19
6	18.6	29.6	25.7	24.6	5.6	0.23
7	23.2	35.4	31.1	29.9	6.2	0.21
8	30.8	37.2	32.0	33.4	3.4	0.10

(b) HC concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low idle	8.8	9.2	9.5	9.2	0.3	0.04
High idle	9.9	9.8	10.3	10.0	0.3	0.03
1	11.7	11.7	11.8	11.7	0.0	0.00
2	13.8	13.9	14.1	13.9	0.2	0.01
3	15.2	15.0	15.6	15.2	0.3	0.02
4	15.0	14.9	15.8	15.2	0.5	0.03
5	15.7	16.1	16.0	15.9	0.2	0.01
6	16.9	16.2	16.3	16.5	0.4	0.02
7	16.2	15.5	15.2	15.6	0.5	0.03
8	16.3	14.8	14.0	15.0	1.2	0.08

(c) NO concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low idle	220	221	214	218	3.6	0.02
High idle	212	212	211	211	0.7	0.00
1	426	403	392	407	17.5	0.04
2	723	743	738	735	10.4	0.01
3	1076	1083	1087	1082	5.4	0.00
4	1027	1030	1036	1031	4.4	0.00
5	1337	1341	1343	1340	2.9	0.00
6	1427	1453	1460	1447	17.4	0.01
7	1401	1361	1369	1377	20.9	0.02
8	1410	1374	1323	1369	43.7	0.03

Table D-13 Continued on next page.

Table D-13 Continued from previous page.

(d) NO_2 concentration (ppm)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low idle	24	20	20	21	2.4	0.12
High idle	21	19	20	20	1.0	0.05
1	31	28	29	29	1.7	0.06
2	41	39	41	40	0.9	0.02
3	60	56	59	58	2.1	0.04
4	57	55	57	57	1.0	0.02
5	74	72	75	74	1.4	0.02
6	73	74	77	75	2.2	0.03
7	71	71	75	72	1.9	0.03
8	71	78	78	76	4.1	0.05

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

TABLE D-14. Notch-Average Prime Mover Engine Exhaust Concentration based NO_x/NO and THC/HC ratios for locomotive NC 1984 measured using SEMTECH-DS PEMS January 25, 2018 :(a) NO_x/NO ratio; and (b) THC/HC Ratio

(a) NO_x/NO ratio

Throttle Notch Position	NO_x/NO Ratio					
	21-Dec	21-Dec	21-Dec	3 Rep	3 Rep	3 Rep
	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low idle	1.11	1.09	1.09	1.10	0.010	0.009
High idle	1.10	1.09	1.09	1.10	0.005	0.004
1	1.07	1.07	1.07	1.07	0.002	0.002
2	1.06	1.05	1.06	1.05	0.002	0.002
3	1.06	1.05	1.05	1.05	0.002	0.002
4	1.06	1.05	1.06	1.05	0.001	0.001
5	1.06	1.05	1.06	1.05	0.001	0.001
6	1.05	1.05	1.05	1.05	0.001	0.001
7	1.05	1.05	1.05	1.05	0.002	0.002
8	1.05	1.06	1.06	1.06	0.005	0.004

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

Table D-14 Continued on next page.

Table D-14 Continued from previous page.

(b) THC/HC ratio

Throttle Notch Position	THC/HC Ratio					
	21-Dec	21-Dec	21-Dec	3 Rep	3 Rep	3 Rep
	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low idle	3.6	2.0	1.7	2.4	1.04	0.43
High idle	2.1	1.9	1.6	1.9	0.22	0.12
1	1.8	1.8	1.6	1.7	0.13	0.08
2	1.6	1.8	1.6	1.7	0.16	0.09
3	1.3	1.8	1.5	1.6	0.27	0.18
4	1.0	1.7	1.3	1.3	0.35	0.26
5	1.0	1.5	1.3	1.2	0.22	0.18
6	1.1	1.8	1.6	1.5	0.37	0.25
7	1.4	2.3	2.1	1.9	0.44	0.23
8	1.9	2.5	2.3	2.2	0.32	0.14

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

The notch-average NO_x/NO ratio varied from 1.03 at high idle to 1.07 at notch 8. These ratios were highly repeatable for a given notch position with inter-replicate CV of 0.01 or lower. The THC/HC ratio varied from 1.2 at notches 2 and 3 to 2.2 at high idle and notches 6 and 7. Inter-replicate CV was 0.5 for high idle and notch 7, below 0.20 for 5 of the 9 notch positions and below 0.30 for 7 of the 9 notch positions. On average, the THC/HC ratio was approximately 1.5, except for notches 6, 7 and 8, for which the average is approximately 2.0.

Notch-average fuel use and emission rates were estimated for locomotive NC 1871 based on Axion PEMS measurements of engine activity and exhaust gas and PM. Axion measured NO and HC were bias corrected for NO_x and THC using the NO_x/NO and THC/HC ratios estimated in the previous sections. For PM, a correction factor of 5 was used based on literature review. Mass per time based and engine output based emission rates were estimated. Engine-output based emission rates were weighted to EPA Line-haul cycle to estimate cycle-average emission rates. The mass per time based fuel use rate and emission rates of CO_2, CO, THC, NO_x and PM are shown in Table D-15.

D.4 EPA Reported Fuel Use and Emission Rates

This section has details of rated power, notch-average brake horsepower, mass per time-based fuel use rate and engine output-based emission rates of CO, HC, NO_x and PM for EMD 16-645 and EMD 12-710 PMEs given in Tables D-16 and D-17, respectively.

TABLE D-15. Notch-Average mass per time based Fuel Use and Emission Rates based on Axion PEMS measured concentrations for the Prime Mover Engine of locomotive NC 1984 measured on January 25, 2018: (a) fuel use rate; (b) CO_2 emission rate; (c) CO emission rate; (d) THC emission rate; (e) NO_x emission rate; and (f) PM emission rate.

(a) Mass per time based fuel use rate (g/s)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	2.59	2.61	2.53	2.58	0.03	0.01
High Idle	3.09	3.02	3.17	3.10	0.07	0.02
1	5.70	5.42	5.23	5.45	0.2	0.04
2	14.2	14.2	14.3	14.2	0.1	0.007
3	26.9	26.7	26.9	26.8	0.08	0.003
4	43.5	43.0	43.8	43.4	0.4	0.009
5	56.2	56.5	56.4	56.4	0.1	0.003
6	77.6	79.4	79.6	78.9	1.1	0.01
7	90.3	87.7	88.4	88.8	1.3	0.01
8	98.9	97.0	92.2	96.0	3.4	0.03

(b) Mass per time based CO_2 emission rate (g/s)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	8.09	8.12	7.91	8.04	0.1	0.01
High Idle	9.66	9.44	9.90	9.67	0.2	0.02
1	17.8	16.9	16.3	17.0	0.7	0.04
2	44.2	44.3	44.8	44.5	0.3	0.007
3	84.0	83.6	84.1	83.9	0.2	0.003
4	136	134	137	136	1.2	0.009
5	176	177	176	176	0.5	0.003
6	243	248	249	247	3.4	0.01
7	282	274	277	278	4.2	0.01
8	309	303	288	300	10.9	0.03

(c) Mass per time based CO emission rate (g/s)

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	*0.002*	*0.0001*	*0*	*0.0007*	*0.001*	*1.57*
High Idle	*0.002*	*0*	*0.0003*	*0.001*	*0.001*	*1.45*
1	*0.0004*	*0.001*	*0*	*0.0007*	*0.0009*	*1.30*
2	*0*	*0.0007*	*0*	*0.0002*	*0.0004*	*1.73*
3	*0*	*0.00005*	*0*	*0.00001*	*0.00002*	*0*
4	*0*	*0.001*	*0*	*0.0004*	*0.0007*	*1.73*
5	*0*	*0*	*0*	*0*	*0*	*0*
6	*0*	*0*	*0.0007*	*0.0002*	*0.0004*	*1.73*
7	*0.01*	*0.04*	*0.08*	*0.04*	*0.03*	*0.75*
8	*0.003*	*0.003*	*0.05*	*0.02*	*0.03*	*1.47*

Table C-15 Continued on next page.

Table D-15 Continued from previous page.

(d) Mass per time based THC emission rate (g/s)[b]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	0.01	0.04	0.02	0.02	0.01	0.6
High Idle	0.01	0.02	0.03	0.02	0.01	0.4
1	0.02	0.02	0.04	0.02	0.01	0.4
2	0.06	0.07	0.08	0.07	0.01	0.1
3	0.09	0.09	0.07	0.08	0.01	0.1
4	0.05	0.07	0.07	0.06	0.01	0.1
5	0.08	0.03	0.1	0.07	0.03	0.4
6	0.06	0.09	0.07	0.07	0.01	0.2
7	0.05	0.2	0.08	0.12	0.08	0.7
8	0.03	0.04	0.07	0.05	0.02	0.4

(e) Mass per time based NO_x emission rate (g/s)[c]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	0.23	0.23	0.21	0.23	0.01	0.04
High Idle	0.25	0.26	0.25	0.25	0.005	0.02
1	0.54	0.54	0.50	0.53	0.02	0.04
2	1.32	1.41	1.36	1.36	0.04	0.03
3	2.89	3.13	2.98	3.00	0.1	0.04
4	4.24	4.45	4.39	4.36	0.1	0.02
5	5.70	6.33	6.01	6.01	0.3	0.05
6	7.36	8.30	8.22	7.96	0.5	0.06
7	8.01	8.50	8.65	8.39	0.3	0.03
8	8.63	9.08	8.86	8.86	0.2	0.02

(f) Mass per time based PM emission rate (g/s)[d]

Throttle Notch Position	RY Rep1	RY Rep2	RY Rep3	Avg	Std Dev	CV[a]
Low Idle	0.02	0.022	0.022	0.022	0.0007	0.03
High Idle	0.028	0.027	0.025	0.027	0.001	0.04
1	0.025	0.026	0.024	0.025	0.0007	0.02
2	0.031	0.030	0.032	0.031	0.0007	0.02
3	0.039	0.039	0.040	0.039	0.0005	0.01
4	0.064	0.065	0.064	0.064	0.0009	0.01
5	0.071	0.070	0.067	0.069	0.001	0.02
6	0.104	0.107	0.103	0.105	0.001	0.01
7	0.136	0.127	0.128	0.130	0.004	0.03
8	0.169	0.134	0.133	0.145	0.020	0.1

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of three replicates*

[b] *HC concentration measured with Axion PEMS were multiplied with a correction factor shown in Table D-14(b) to obtain THC concentration.*

[c] *NO concentration measured with Axion PEMS were multiplied with a correction factor shown in Table D-14(a) to obtain NO_x concentration.*

[d] *PM emission rates estimated with Axion measurements have been multiplied by a factor of 5 to account for total PM.*

TABLE D-16. EPA Reported Notch-average and Cycle-average Brake Horsepower, Fuel Use Rate and Emission Rates for EMD 16-645E3 Prime Mover Engines with a Rated Power of 3000 hp Operated on ULSD.

Throttle Notch Position	Brake Horsepower (bhp)	Fuel Rate (lb/hr)	Fuel Rate (g/s)	CO Emission Rate (g/bhp-hr)	HC Emission Rate (g/bhp-hr)	NO_x Emission Rate (g/bhp-hr)	PM Emission Rate (g/bhp-hr)
Idle	17	40	5.0	9.58	4.26	96.18	2.82
Dynamic Brake	69	114	14.4	33.18	10.88	69.91	1.16
1	105	64	8.1	2.54	1.48	26.74	0.34
2	395	167	21.0	0.74	.51	15.29	0.34
3	686	275	34.6	.48	.36	14.84	.33
4	1034	404	50.9	.42	.31	14.9	.25
5	1461	556	70.1	.52	.29	14.3	.23
6	1971	740	93.2	.97	.31	12.97	.28
7	2661	994	125	1.89	.33	11.72	.24
8	3159	1177	148	1.87	.37	11.69	.26
EPA Line-haul Cycle-average	-	-	-	1.85	0.48	13.64	.29

TABLE D-17. EPA Reported Notch-average and Cycle-average Brake Horsepower, Fuel Use Rate and Emission Rates for EMD 12-710G3A Prime Mover Engines with a Rated Power of 3000 hp Operated on ULSD.

Throttle Notch Position	Brake Horsepower (bhp)	Fuel Rate (lb/hr)	Fuel Rate (g/s)	CO Emission Rate (g/bhp-hr)	HC Emission Rate (g/bhp-hr)	NO_x Emission Rate (g/bhp-hr)	PM Emission Rate (g/bhp-hr)
Idle	8	19	2.4	6.75	6.86	111.13	3.88
Dynamic Brake	84	142	17.9	1.48	1.09	21.98	0.78
1	209	91	11.5	0.54	0.40	15.97	0.17
2	372	141	17.8	0.34	0.22	15.05	0.31
3	717	258	32.5	0.25	0.17	13.88	0.30
4	1053	372	46.9	0.29	0.13	12.01	0.23
5	1402	491	61.9	0.61	0.12	10.93	0.21
6	1696	587	74.0	0.83	0.11	10.71	0.25
7	2534	848	107	1.71	0.09	9.36	0.21
8	3196	1077	136	1.23	0.11	9.51	0.23
EPA Line-haul Cycle-average	-	-	-	1.09	0.15	10.75	0.25

References

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Appendix E. Baseline Over-the-Rail Fuel Use and Emission Rates

The results of over-the-rail (OTR) measurements on the prime mover engines (PMEs) of locomotives NC 1871 and NC 1984 are given here. Exhaust gas and particulate matter (PM) concentration measurements were conducted using an Axion portable emissions measurement system (PEMS). Engine activity variables were measured using an engine sensor array connected to the Axion PEMS. Each locomotive was measured for double- and single-powered consists. The first and second OTR measurements on locomotive NC 1871 were conducted between August 21, 2018 and August 23, 2018, and between January 30, 2019 and February 16, 2019, respectively. The first and second OTR measurements on locomotive NC 1984 were conducted between June 12, 2018 and June 14, 2018, and between June 18, 2019 and June 20, 2019, respectively. The purpose of the first measurements on each locomotive was to quantify baseline steady-state FUER for the now typical Piedmont double-powered push/pull consist. However, the train may also be operated as single-powered push/pull. Locomotive FUER may differ for double- and single-powered push/pull consists. To quantify the differences in FUER for double- versus single-powered consists, a second set of OTR measurements for each locomotive were made that included three one-way trips each in double- and single-powered push/pull consists. Only the indicated locomotives were measured during each one-way trip. Depending on the direction of travel, the measured locomotives were either pulling or pushing the train. The locomotive at the other end of the train was not measured.

Results of the OTR measurements of locomotives NC 1871 and NC 1984 include duty cycles and steady-state notch-average engine activity variables, exhaust gas concentrations and FUER. Section E.1 and E.2 have results of the OTR measurements of NC 1871 conducted during August 2018 and January - February 2019, respectively. Section E.3 and E.4 have results of OTR measurements of NC 1984 conducted during June 2018 and June 2019, respectively.

E.1 Locomotive NC 1871: August 2018

OTR measurements of the PME of NC 1871 were conducted between August 21, 2018 and August 23, 2018. Three one-way trips each were conducted for trains 75 and 76 following the measurement schedule given in Table 2-4. The train consist included two locomotives, three passenger cars and one baggage/café car. Locomotive NC 1984 was used as a second locomotive on August 21, 2018 and locomotive NC 1797 was used as a second locomotive on August 22-23, 2018. One one-way trip on train 76 on August 21 was based on a single-powered push/pull consist with locomotive NC 1871 providing full power. The remaining five one-way trips were based on double-powered push/pull.

Steady-State Notch-Average Engine Activity Variables

The steady-state notch-average RPM, IAT, and MAP are summarized in Table E-1. The amount of steady-state data measured in each notch position depends on the number of times an operator transitions to a given notch position and the average time the operator stays in that notch position per transition. When the throttle is switched to a different position, the engine activity variables and FUER change over a period of 5 seconds to 30 seconds during a transition from steady-state operation in the preceding to the successive notch setting. The transition time depends on the

TABLE E-1. Steady-state Notch-average Engine Activity Variables for Locomotive NC 1871 for Over-the-Rail Measurements of Double- and single-powered Push/Pull Train Consists Conducted between August 21 and August 23, 2018: (a) Engine RPM; (b) Intake Air Temperature; and (c) Manifold Absolute Pressure.

(a) Engine RPM (RPM)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	219[b]	219	219[b]	219[b]	219	219	0.000	219
High Idle	268	268	268	268	268	268	0.000	268
Dynamic Brake	432	389	414	419	438	418	0.046	523
1	268	268	268	268	268	268	0.000	268
2	389	389	389	389	389	389	0.000	388
3	508	509	509	509	509	509	0.001	509
4	701	702	702	703	702	702	0.001	701
5	728	727	726	722	726	726	0.003	727
6	817	819	819	818	820	819	0.001	819
7	860	856	847	855	855[b]	855	0.006	858
8	900	900	900	901	901	900	0.001	901

(b) Intake Air Temperature (K)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	354[c]	333	324[c]	324[c]	327	332	0.01	354
High Idle	354	330	327	325	326	333	0.04	356
Dynamic Brake	355	330	328	327	326	333	0.04	358
1	354	330	328	325	326	333	0.04	358
2	355	331	327	326	327	333	0.04	356
3	356	331	328	324	326	333	0.04	356
4	360	330	327	325	324	333	0.05	361
5	357	330	327	327	325	333	0.04	362
6	357	330	326	324	325	333	0.04	363
7	356	329	324	322	325[c]	331	0.04	365
8	360	330	326	324	324	333	0.05	364

Table E-1. Continued on next page.

Table E-1. Continued from previous page.

(c) Manifold Absolute Pressure (kPa)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	93[b]	92	93[b]	93[b]	93	93	0.01	93
High Idle	96	95	95	96	96	96	0.01	96
Dynamic Brake	109	103	107	108	111	108	0.03	120
1	97	95	95	96	96	96	0.01	96
2	105	103	103	104	104	104	0.01	104
3	116	114	114	117	115	115	0.01	116
4	145	143	143	145	146	144	0.01	144
5	150	148	148	151	151	150	0.01	151
6	171	170	171	168	174	171	0.01	173
7	182	177	178	192	182[b]	182	0.04	200
8	205	203	200	208	203	204	0.01	223

[a] *CV = coefficient of variation (standard deviation divided by mean)*

[b] *No steady-state data for the given notch position. Value shown is the average from the remaining over-the-rail trips belonging to the same group.*

difference between the two notches. For example, a switch to notch 8 from notch 1 will have a larger transition time than a switch to notch 8 from notch 7. In some cases, changes in notch positions occurred more frequently than the transition time required to achieve steady-state. Thus, in such cases, it was not possible for the engine operation to reach steady-state and no steady-state data were measured. Consequently, a larger percentage of time in one notch position versus another does not necessarily mean a higher percentage of steady-state operation. For example, no steady-state FUER data were measured in notch 7 for train 76 on August 23, although this trip had the second highest percentage of time in notch 7 compared to other trips. Steady-state data at notch 7 was measured for the remaining one-way trips.

For notch positions for which steady-state data were not measured, notch-average RPM, MAP and exhaust concentrations were replaced by the average of other trips measured at that notch on the same locomotive and same consist. Notch-average IAT depends on notch position and ambient temperature. Therefore, IAT for a given notch position of a locomotive may vary by as much as 40 K based on the season in which the locomotive was measured. However, notch-average IAT typically differs by less than 15 K between idle and notch 8 on a given day of the measurement. This difference has less than one percent effect on FUER. Therefore, for notch positions with no steady-state data, IAT were replaced by the average of notch-average IATs of the remaining notch positions.

The notch-average RPM for a given notch position was within 2 RPM for double- versus single-powered consists for each notch position, except for dynamic brake. Therefore, notch-average RPM for a given notch position were approximately similar for the two consists. Notch-average RPM varied from 219 RPM at low idle to 901 RPM at notch 8. Notch-average RPM increased monotonically from low idle to notch 8, except for dynamic brake. Dynamic brake can be initiated from any throttle notch position (Hay, 1982). Thus, the engine RPM at dynamic brake can vary substantially. Notch-average RPM for the double-powered consist had inter-trip CV of 0.01 or lower for each notch position, except for dynamic brake, for which the CV was 0.05. Thus, the RPM measurements were highly repeatable. Only one one-way trip was conducted for the single-powered consist. Therefore, the repeatability of the latter was not quantified.

Notch-average IAT for the double-powered consist varied from 330 K at low idle to 333 K for other notch positions. Notch-average IAT for the double-powered consist had inter-trip CV of 0.05 or lower for each notch position. Thus, the IAT measurements were highly repeatable. Notch-average IAT for the single-powered consist varied from 354 K at low idle to 365 K at notch 7.

The notch-average MAP for a given notch position was within 2 kPa for double- versus single-powered consists for each notch position, except for dynamic brake, notch 7 and notch 8. Therefore, notch-average MAP for a given notch position were approximately similar for the two consists, except for dynamic brake, notch 7 and notch 8. For the double-powered consist, notch-average MAP varied from 93 kPa at low idle to 204 kPa at notch 8. Notch-average MAP for the double-powered consist had inter-trip CV of 0.03 or lower for each notch position. Thus, the MAP measurements were highly repeatable. For the single-powered consist, notch-average MAP varied from 93 kPa at low idle to 223 kPa at notch 8. For both consists, notch-average MAP increased monotonically from low idle to notch 8, except for dynamic brake. The single-powered consist had 19 kPa to 20 kPa higher MAP at notches 7 and 8 versus the double-powered consist. Higher MAP results in a greater air flow and exhaust flow rate.

Steady-State Exhaust Gas and PM Concentrations

Steady-state notch-average measured exhaust concentrations of CO_2, CO, HC, NO and PM measured using an Axion PEMS are summarized in Table E-2. Steady-state notch-average CO_2 concentrations for the double-powered consist varied from 0.68 vol % at low idle to 5.29 vol % at notch 8. Notch-average CO_2 concentrations increased monotonically from low idle through notch 8. Notch-average CO_2 concentrations for a given notch position had inter-trip CV of 0.2 or lower for each notch position. Inter-trip CVs for notch positions at which operators typically spent more than 70 percentage of time including low idle, high idle, dynamic brake and notch 8 were 0.07 or lower. Thus, these measurements were highly repeatable.

Steady-state notch-average CO concentrations for the double-powered consist varied from 0.000 vol % at low idle to 0.035 vol % at notch 8. The notch-average CO concentrations were below the detection limit of the Axion PEMS for low idle through notch 6. For notches 7 and 8, CO concentrations were above the detection limit and inter-trip CV was lower compared to other notch positions.

Steady-state notch-average HC concentrations for the double-powered consist varied from 10 ppm at notch 8 to 28 ppm at dynamic brake. The notch-average HC concentration was below the detection limit of the PEMS at notch 8. Inter-trip CV for a given notch position was 0.6 or lower for each notch position. However, notch-average HC concentrations were low, the highest being 2.5 times the detection limit.

TABLE E-2. Steady-state Notch-average Concentrations for Locomotive NC 1871 for Over-the-Rail Measurements of Push/Pull Train Consists Conducted between August 21 and August 23, 2018: (a) CO_2; (b) CO; (c) HC; (d) NO; and (e) PM.

(a) CO_2 concentration (vol %)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	0.68[b]	0.61	0.68[b]	0.68[b]	0.75	0.68	0.15	0.77
High Idle	0.70	0.71	0.74	0.73	0.73	0.72	0.02	0.64
Dynamic Brake	0.89	0.83	0.86	0.86	0.94	0.88	0.05	0.99
1	0.76	1.05	1.24	0.96	0.95	0.99	0.18	0.80
2	1.99	2.49	2.29	2.39	1.58	2.15	0.17	1.81
3	2.84	3.48	3.34	3.53	3.19	3.28	0.08	3.38
4	4.04	4.04	3.69	3.02	3.47	3.65	0.12	3.70
5	4.59	4.51	3.78	3.90	4.16	4.19	0.09	4.41
6	5.32	5.63	5.52	2.98	5.90	5.07	0.23	4.64
7	4.12	4.35	5.28	6.75	5.13[b]	5.13	0.23	6.22
8	5.39	5.32	4.86	5.68	5.20	5.29	0.06	5.75

(b) CO concentration (vol %)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	*0.000*[b]	*0.000*	*0.000*[b]	*0.000*[b]	-[d]	*0.000*	-	*0.001*
High Idle	*0.001*	*0.000*	*0.001*	*0.001*	*0.001*	*0.001*	*0.559*	*0.001*
Dynamic Brake	*0.001*	*0.000*	*0.000*	*0.000*	*0.001*	*0.000*	*1.369*	*0.002*
1	*0.001*	*0.000*	*0.000*	*0.001*	*0.001*	*0.001*	*0.913*	*0.001*
2	*0.002*	*0.001*	*0.000*	*0.001*	*0.001*	*0.001*	*0.707*	*0.001*
3	*0.001*	*0.000*	*0.000*	*0.001*	-[d]	*0.001*	*1.155*	*0.001*
4	0.016	*0.001*	*0.003*	-[d]	*0.001*	*0.005*	*1.377*	*0.004*
5	*0.000*	*0.002*	*0.002*	*0.003*	*0.002*	*0.002*	*0.609*	0.009
6	-[d]	*0.006*	*0.007*	-[d]	*0.004*	*0.006*	*0.270*	0.009
7	-[d]	-[d]	0.011	0.031	*0.000*[b]	0.021	0.673	0.030
8	0.041	0.041	0.028	0.039	0.025	0.035	0.221	0.047

**The values in italics are below the detection limit of the instrument (0.008 vol % for CO).*

Table E-2 Continued on next page.

Table E-2 Continued from previous page.

(c) HC concentration (ppm)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	26[b]	27	26[b]	26[b]	25	26	0.1	47
High Idle	23	15	19	33	24	23	0.3	41
Dynamic Brake	15	*12*	32	51	29	28	0.6	36
1	24	*13*	15	37	25	23	0.4	70
2	*9*	*12*	27	20	31	20	0.5	42
3	39	14	17	23	33	25	0.4	87
4	15	17	*11*	23	19	17	0.3	72
5	31	*10*	30	17	*11*	20	0.5	57
6	31	*13*	*13*	17	*10*	17	0.5	52
7	38	48	-[d]	15	26[b]	34	0.5	15
8	*11*	*9*	*5*	16	*9*	*10*	0.4	25

**The values in italics are below the detection limit of the instrument (13 ppm for HC).*

(d) NO concentration (ppm)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	227[b]	215	227[b]	227[b]	239	227	0.1	194
High Idle	174	192	207	212	220	201	0.1	184
Dynamic Brake	166	191	198	214	225	199	0.1	179
1	188	319	356	290	301	291	0.2	220
2	455	678	610	700	403	569	0.2	453
3	716	1043	982	1142	1033	983	0.2	945
4	990	1086	957	764	932	946	0.1	918
5	1148	1213	950	1049	1257	1123	0.1	1169
6	1233	1424	1367	664	1688	1275	0.3	1075
7	925	1180	1277	1507	1222[b]	1222	0.2	1297
8	943	1020	968	1196	1163	1058	0.1	1101

Table E-2 Continued on next page.

Table E-2 Continued from previous page.

(e) PM Concentration (mg/m^3)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	4.9[b]	3.7	4.0[b]	4.0[b]	4.3	4.0	0.12	3.0
High Idle	4.7	4.7	4.2	4.5	4.2	4.5	0.05	3.5
Dynamic Brake	4.3	4.1	4.0	4.0	4.1	4.1	0.03	3.6
1	4.8	5.3	5.0	4.7	4.7	4.9	0.06	4.8
2	5.4	5.8	5.9	5.2	4.6	5.4	0.09	4.9
3	6.1	5.5	5.5	6.4	5.2	5.7	0.09	6.1
4	6.9	5.0	5.0	5.7	5.3	5.6	0.14	6.3
5	6.5	5.2	4.9	6.2	5.3	5.6	0.12	6.7
6	7.3	8.6	7.2	6.7	7.4	7.4	0.09	8.1
7	6.5	4.7	3.6	17.8	8.2[b]	8.2	0.80	18.0
8	14.9	17.5	12.2	13.4	11.0	13.8	0.18	15.2

[a] *CV = coefficient of variation (standard deviation divided by mean)*
[b] *No steady-state data for the given notch position. Value shown is the average from the remaining over-the-rail trips belonging to the same group.*
[c] *HC, NO and PM concentrations reported are without bias corrections, as measured by Axion PEMS*
[d] *Measurements less than zero*
[e] *The values in italics are below the detection limit of the Axion PEMS: 0.008 vol % for CO and 13 ppm for HC.*

Steady-state notch-average NO concentrations for the double-powered consist varied from 199 ppm at dynamic brake to 1275 ppm at notch 6. Notch-average NO concentrations increased monotonically with notch position for high idle through notch 6 and the average concentration was 1058 ppm at notch 8. Notch-average NO concentrations for a given notch position had inter-trip CV of 0.3 or lower for each notch position. inter-trip CV for low idle, high idle, dynamic brake and notch 8 was 0.1 or lower. Thus, these measurements were repeatable, with the latter being highly repeatable.

Steady-state notch-average PM concentrations for the double-powered consist varied from 4.0 mg/m^3 at low idle to 13.8 mg/m^3 at notch 8. Notch-average PM concentrations were within 10 percent of each other for low idle, high idle and dynamic brake. Notch-average PM concentrations for notches 1 through 5 were within 7 percent of each other, but higher than for low idle, high idle and dynamic brake. Notch-average PM concentrations increased monotonically from 5.6 mg/m^3 at notch 5 to 13.6 mg/m^3 at notch 8. Notch-average PM concentrations for a given notch position had inter-trip CV of 0.7 or lower for each notch position. inter-trip CV for low idle, high idle, dynamic brake and notch 8 was 0.2 or lower. Thus, these latter measurements were repeatable.

The CVs for inter-trip variability in the OTR measurements are typically higher than CVs for inter-replicate variability in RY measurements because of more inherent variability in real-world operation.

The steady-state notch-average CO_2 concentrations for the single-powered consist varied from 0.77 vol % at low idle to 6.22 vol % at notch 7. Only 10 seconds of steady-state data were measured at notch 7 and the high concentrations were based on a small sample size compared to at least 30 seconds for other notch positions and greater than 1000 seconds each for high idle and notch 8. Notch-average CO_2 concentrations for a given notch position for the double- versus single-powered consist were not statistically significantly different for each other, except for notch 7 and notch 8. The notch-average CO_2 concentration at notch 8 was 10 percent higher for the double- versus single-powered consist. The differences in the steady-state notch-average Co and HC concentrations for the double- versus single-powered consist is associated with random errors from CO and HC concentrations that were typically below the detection limit of the PEMS.

The steady-state notch-average NO concentrations were 3 to 30 percent higher for idle through notch 7 and 4 to 6 percent lower at notches 7 and 8 for the double- versus single-powered consist. The steady-state notch-average PM concentrations were 2 to 30 percent higher for idle through notch 2 and 6 to 30 percent lower at notches 3 through 7 for the double- versus single-powered consist. At notch 8, the notch-average PM concentrations for the double-powered consist were 9 percent lower versus single-powered consist. Five percent or higher differences in the notch-average NO and PM concentrations were typically due to artifacts of random variations in small sample sizes measured for notch 1 through 7 compared to the much larger sample size at idle and notch 8, and due to only one one-way trip for the single-powered consist. Differences in NO and PM concentrations lead to differences in NO_x and PM emission rates for the double- versus single-powered consist.

Steady-State Fuel Use and Emission Rates

Steady-state notch-average engine output, fuel use rate and emission rates of CO_2, CO, HC, NO_x and PM are summarized in Table E-3. No differences in the steady-state notch-average engine output were observed for the double- versus single-powered consists. The net engine power output increased monotonically from notch 1 through notch 8. For the OTR measurements, net engine power output at notches 7 and 8 were 400 hp and 650 hp higher, respectively, versus RY measurements. At idle, the net engine power output displayed by the locomotive activity recorder was zero. However, engine power output was assumed to be 9 hp based on prior dynamometer measurements of the same locomotive type (Graver and Frey, 2013).

The steady-state notch-average fuel use rates for the double-powered consist varied from 2.6 g/s at low idle to 97.8 g/s at notch 8. Notch-average fuel use rate increased monotonically from low idle through notch 8. Notch-average fuel use rate for a given notch position had inter-trip CV of 0.2 or lower for each notch position. The inter-trip CV for low idle, high idle, dynamic brake and notch 8 was 0.07 or lower. Thus, fuel use rate measurements for the latter were highly repeatable. Steady-state notch-average CO_2 emission rates had similar trends as fuel use rate.

The steady-state notch-average CO and HC emission rates for the double-powered consist were typically based on low CO and HC concentrations; typically the highest concentration was only 2-3 times higher than the detection limit. Therefore, the CO and HC emission rates were low. Notch-average CO and HC emission rates increased monotonically with notch position.

TABLE E-3. Steady-state Notch-average Net Engine Output, Fuel Use and Emission Rates for Locomotive NC 1871 for Over-the-Rail Measurements of Push/Pull Train Consists Conducted between August 21 and August 23, 2018: (a) fuel use rate; (b) CO_2 emission rate; (c) CO emission rate; (d) THC emission rate; (e) NO_x emission rate; and (f) PM emission rate.

(a) Mass per time-based fuel use rate (g/s)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	2.6[b]	2.3	2.6[b]	2.6[b]	2.8	2.6	0.1	2.7
High Idle	2.9	3.1	3.3	3.4	3.3	3.2	0.1	2.7
Dynamic Brake	5.8	5.1	5.8	6.0	6.8	5.9	0.1	7.9
1	3.2	4.6	5.5	4.4	4.3	4.4	0.2	3.4
2	11.0	15.0	14.0	15.0	10.0	13.0	0.2	10.0
3	22.0	28.0	27.0	29.0	26.0	26.4	0.1	26.0
4	45.0	49.0	45.0	38.0	43.0	44.0	0.1	41.0
5	54.0	57.0	49.0	50.0	54.0	52.8	0.1	52.0
6	76.0	86.0	86.0	46.0	92.0	77.2	0.2	65.0
7	64.0	73.0	86.0	119	85.5[b]	85.5	0.3	99.0
8	92.0	99.0	91.0	109	98.0	97.8	0.1	104

(b) Mass per time-based CO_2 emission rate (g/s)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	8[b]	7	8[b]	8[b]	9	8	0.2	8
High Idle	9	10	10	10	10	10	0.0	8
Dynamic Brake	18	16	18	18	21	18	0.1	24
1	10	14	17	14	13	14	0.2	10
2	36	47	44	47	30	41	0.2	32
3	67	88	84	92	82	83	0.1	80
4	140	152	141	118	134	137	0.1	128
5	169	178	151	156	170	165	0.1	162
6	236	268	267	143	288	240	0.2	203
7	199	227	269	369	266[b]	266	0.3	309
8	286	307	281	337	305	303	0.1	321

Table E-3 Continued on next page.

Table E-3 Continued from previous page.

(c) Mass per time-based CO emission rate (g/s)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	*0.0*[b]	*0.0*	*0.0*[b]	*0.0*[b]	-[d]	*0.0*	-	*0.0*
High Idle	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	-	*0.0*
Dynamic Brake	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	-	*0.0*
1	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	-	*0.0*
2	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	-	*0.0*
3	*0.0*	*0.0*	*0.0*	*0.0*	-[d]	*0.0*	-	*0.0*
4	0.4	*0.0*	*0.1*	-[d]	*0.0*	*0.1*	1.5	*0.1*
5	*0.0*	*0.0*	*0.1*	*0.1*	*0.1*	*0.1*	0.9	0.2
6	-[d]	*0.2*	*0.2*	-[d]	*0.1*	*0.2*	0.3	0.3
7	-[d]	-[d]	0.3	1.1	0.7[b]	0.7	0.8	0.9
8	1.4	1.5	1.0	1.5	0.9	1.3	0.2	1.7

Values in italics correspond to estimates based on concentrations below-detection limit

(d) Mass per time-based THC emission rate (g/s)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	0.2[b]	0.2	0.2[b]	0.2[b]	0.1	0.2	0.5	0.2
High Idle	0.1	0.1	0.1	0.2	0.2	0.1	0.4	0.3
Dynamic Brake	0.1	*0.1*	0.3	0.5	0.3	0.3	0.6	0.4
1	0.2	*0.1*	0.1	0.3	0.2	0.2	0.5	0.4
2	*0.1*	*0.1*	0.3	0.2	0.3	0.2	0.5	0.4
3	0.5	0.2	0.2	0.3	0.4	0.3	0.4	1.0
4	0.2	0.3	*0.2*	0.4	0.4	0.3	0.3	1.2
5	0.6	*0.2*	0.6	0.3	*0.2*	0.4	0.5	1.0
6	0.7	*0.3*	*0.3*	0.4	*0.2*	0.4	0.5	1.1
7	0.9	1.2	-[d]	0.4	0.8[b]	0.8	0.5	0.4
8	*0.3*	*0.2*	*0.1*	0.5	*0.2*	*0.3*	0.6	0.7

Table E-3 Continued on next page.

Table E-3 Continued from previous page.

(e) Mass per time-based NO_x emission rate (g/s)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	0.3[b]	0.3	0.3[b]		0.3[b]	0.3	0.3	0.0
High Idle	0.2	0.3	0.3		0.3	0.3	0.3	0.2
Dynamic Brake	0.4	0.4	0.5		0.5	0.6	0.5	0.2
1	0.3	0.5	0.5		0.5	0.5	0.5	0.2
2	0.9	1.4	1.3		1.5	0.8	1.2	0.3
3	1.9	2.9	2.7		3.3	2.9	2.7	0.2
4	3.8	4.5	4.0		3.3	4.0	3.9	0.1
5	4.7	5.3	4.2		4.6	5.6	4.9	0.1
6	6.0	7.5	7.3		3.5	9.1	6.7	0.3
7	4.9	6.8	7.2		9.1	7.0[b]	7.0	0.2
8	5.5	6.5	6.2		7.8	7.5	6.7	0.1

(f) Mass per time-based PM emission rate (g/s)

Consist	Double-powered							Single-powered
Throttle Notch Position	Trip 1 Train 75	Trip 3 Train 75	Trip 4 Train 76	Trip 5 Train 75	Trip 6 Train 76	5 Trips Avg	5 Trips CV[a]	Trip 2 Train 76
Low Idle	0.15[b]	0.16	0.15[b]	0.15[b]	0.14	0.15	0.06	0.25
High Idle	0.15	0.10	0.13	0.23	0.16	0.16	0.31	0.26
Dynamic Brake	0.15	0.11	0.32	0.53	0.32	0.29	0.58	0.43
1	0.15	0.09	0.10	0.25	0.17	0.15	0.42	0.44
2	0.07	0.11	0.25	0.19	0.29	0.18	0.50	0.37
3	0.45	0.17	0.21	0.29	0.42	0.31	0.40	1.01
4	0.25	0.31	0.20	0.44	0.36	0.31	0.30	1.21
5	0.56	0.18	0.59	0.33	0.22	0.38	0.50	1.03
6	0.67	0.30	0.31	0.39	0.23	0.38	0.45	1.10
7	0.90	1.21	0.85	0.39	0.83[b]	0.83	0.50	0.35
8	0.27	0.25	0.14	0.45	0.25	0.27	0.42	0.69

[a] *CV = coefficient of variation (standard deviation divided by mean)*

[b] *No steady-state data for the given notch position*

[c] *HC emission rates estimated with Axion PEMS-measured HC concentrations have been multiplied with a correction factor shown in Table 7 to obtain THC emission rates. NO emission rates estimated with Axion PEMS-measured NO concentrations have been multiplied with a correction factor shown in Table 7 to obtain NO_x emission rates. PM emission rates estimated with Axion PEMS-measured PM concentrations have been multiplied with a correction factor of 5 to obtain PM emission rates.*

[d] *Measurements less than zero*

The steady-state notch-average NO_x emission rates for the double-powered consist varied from 0.3 g/s at low idle to 7.0 g/s at notch 7. Notch-average NO_x emission rates increased monotonically from low idle through notch 7 and the rate was 6.7 g/s at notch 8. Notch-average NO_x emission rates for a given notch position had inter-trip CV of 0.3 or lower for each notch position. The inter-trip CV for low idle, high idle, dynamic brake and notch 8 was 0.1 or lower. Thus, NO_x emission rate measurements were repeatable for these latter notch positions.

The steady-state notch-average PM emission rates for the double-powered consist varied from 0.15 g/s at low idle, high idle and notch 1 to 0.84 g/s at notch 7. Notch-average PM emission rates typically increased from low idle through notch 7, except for dynamic brake. However, some of the adjacent notch positions had notch-average rates similar to each other. Notch-average PM emission rates for a given notch position had inter-trip CV of 0.6 or lower for each notch position.

Only one measurement was conducted for the single-powered consist. Steady-state notch-average fuel use rates, and emission rates of CO_2, CO, HC, NO_x and PM for each notch position for the single-powered consist were typically 5 percent to 20 percent higher than for the double-powered consist. This indicates potential differences in notch-average engine activity variables, exhaust concentrations and FUER for double- versus single-powered consists. However, for a more robust comparison, additional OTR measurements were conducted on the PME of locomotive NC 1871 as described in the next section.

E.2 Locomotive NC 1871: January-February 2019

OTR measurements on the PME of locomotive NC 1871 were conducted again to include more measurements for the single-powered consist compared to measurements in the previous section. Eight OTR measurements were conducted including four measurements each on double-powered and single-powered consists. The engine sensor array failed during one OTR measurement for each consist. Therefore, results were obtained for only three one-way trips for each consist. Results of the valid measurements on January 30 2019, February 13 and 16, 2019 are given here. Train 75 was operated as single-powered and train 76 was operated as double-powered. Notch-average engine activity variables, measured exhaust concentrations and FUER were estimated for the steady-state.

Steady-State Engine Activity Variables

The steady-state notch-average RPM, IAT, and MAP are summarized in Table E-4**.** Notch-average RPM for a given notch position was within 3 RPM for double- versus single-powered consists for each notch position, except for dynamic brake. Therefore, notch-average RPM for a given notch position was approximately similar for the two consists. Notch-average RPM varied from 219 RPM at low idle to 902 RPM at notch 8. Notch-average RPM increased monotonically from low idle to notch 8, except for dynamic brake. Engine RPM at dynamic brake varied substantially. Notch-average RPM for double- and single-powered consists had inter-trip CV of 0.009 or lower for each notch position. Thus, the RPM measurements were highly repeatable.

TABLE E-4. Steady-State Notch-average Engine Activity Variables for Locomotive NC 1871 for Over-the-Rail Measurements of Double- and single-powered Push/Pull Train Consists Conducted between January 30 and February 16, 2019: (a) Engine RPM; (b) Intake Air Temperature; and (c) Manifold Absolute Pressure.

(a) Engine Revolutions Per Minute (RPM)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[b]	219	219	-	-[b]	-[b]	219	219	-
High Idle	268	268	268	268	0.00	268	268	268	268	0.00
Dyn Brk	428	-[b]	-[b]	428	-	-[b]	412	421	417	0.02
1	268	268	268	268	0.00	268	268	268	268	0.00
2	389	389	389	389	0.00	389	389	389	389	0.00
3	509	509	508	509	0.00	509	509	508	509	0.00
4	703	693	702	700	0.01	702	703	702	702	0.00
5	718	-[b]	727	723	0.01	725	723	727	725	0.00
6	819	-[b]	819	819	0.00	816	821	819	819	0.00
7	857	858	858	858	0.00	-[b]	-[b]	858	858	-
8	902	902	902	902	0.00	901	901	901	901	0.00

(b) Intake Air Temperature (K)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[b]	315	315	-	-[b]	-[b]	311	311	-
High Idle	353	355	319	342	0.29	349	349	313	337	0.06
Dyn Brk	352	-[b]	-[b]	352	-	-[b]	349	312	331	0.08
1	352	355	318	342	0.30	350	348	313	337	0.06
2	352	354	319	342	0.29	350	349	310	336	0.07
3	352	353	322	342	0.25	350	351	316	339	0.06
4	352	366	321	346	0.31	353	352	316	340	0.06
5	356	-[b]	320	338	0.40	353	353	316	341	0.06
6	361	-[b]	319	340	0.45	354	352	313	340	0.07
7	358	361	319	346	0.32	-[b]	-[b]	314	314	-
8	359	360	320	346	0.32	354	354	314	341	0.07

Table E-4 Continued on next page.

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(c) Manifold Absolute Pressure (kPa)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[b]	95	95	-	-[b]	-[b]	95	95	-
High Idle	97	97	97	97	0.00	97	97	98	97	0.00
Dyn Brk	113	-[b]	-[b]	113	0.00	-[b]	111	113	112	0.01
1	98	97	98	98	0.00	97	97	97	97	0.00
2	106	106	106	106	0.00	106	105	106	106	0.00
3	119	118	118	118	0.00	118	118	118	118	0.00
4	152	164	150	155	0.05	150	149	151	150	0.01
5	157	-[b]	158	158	0.00	156	154	157	156	0.01
6	184	-[b]	180	182	0.01	180	179	180	180	0.00
7	215	208	214	212	0.02	-[b]	-[b]	202	202	-
8	246	231	235	237	0.03	213	209	215	212	0.01

[a] *CV = coefficient of variation (standard deviation divided by mean)*
[b] *No steady-state data for the given notch position.*

The notch-average IAT for the double-powered consist varied from 331 K at low idle to 341 K at notch 8. Notch-average IAT for the double-powered consist had inter-trip CV of 0.07 or lower for each notch position. Thus, the IAT measurements were highly repeatable for the double-powered consist. Notch-average IAT for the single-powered consist varied from 342 K at low idle to 352 K at dynamic brake. Notch-average IAT for the double-powered consist had inter-trip CV of 0.09 or lower for each notch position. Thus, the IAT measurements were highly repeatable for the single-powered consist.

The notch-average MAP for a given notch position was within 5 kPa for double- versus single-powered consists for each notch position, except for notches 7 and 8. Therefore, notch-average MAP for a given notch position was approximately similar for the two consists, except for notches 7 and 8. For the double-powered consist, notch-average MAP varied from 95 kPa at low idle to 212 kPa at notch 8. For the single-powered consist, notch-average MAP varied from 95 kPa at low idle to 237 kPa at notch 8. Notch-average MAP for double- and single-powered consists had inter-trip CV of 0.03 or lower for each notch position. Thus, the MAP measurements were highly repeatable. For both consists, notch-average MAP increased monotonically from low idle to notch 8, except for dynamic brake. The single-powered consist had 10 kPa to 25 kPa higher MAP at notches 7 and 8 versus the double-powered consist. Higher MAP results in a higher mass air flow rate and AFR.

Steady-State Exhaust Gas and PM Concentrations

Steady-state notch-average exhaust concentrations of CO_2, CO, HC, NO and PM measured using an Axion PEMS for the double- and single-powered consists are summarized in Table E-5.

Steady-state notch-average CO_2 concentrations for the double-powered consist varied from 0.50 vol % at low idle to 6.28 vol % at notch 7. Notch-average CO_2 concentrations increased monotonically with notch position for low idle through notch 7 and decreased to 5.01 vol % at notch 8. The inter-trip CV for a given notch position was 0.2 or lower for each notch position and 0.1 or lower for notches 8, 6, 5, 1 and high idle. For these notch positions, the measurements were highly repeatable. Notch-average CO_2 concentrations varied from 0.54 vol % at low idle to 5.98 vol % at notch 7 for the single-powered consist and typically increased with notch position. For low idle and notches 1, 3, 4, 5, 7 and 8, the differences in notch-average CO_2 concentrations for double- versus single-powered consists were not statistically significant.

Steady-state notch-average CO concentrations for the double-powered consist varied from 0.000 vol % at low idle to 0.016 vol % at notch 8. Notch-average CO concentrations were below the detection limit of the Axion PEMS for low idle through notch 6. For notches 7 and 8, CO concentrations were above the detection limit. The inter-trip CV for a given notch position was 1.4 or lower. Steady-state notch-average HC concentrations for the double-powered consist varied from 2 ppm at low idle to 11 ppm at notch 2. Notch-average HC concentrations were below the detection limit of the PEMS for each notch position. Inter-trip CV for a given notch position was 0.9 or lower for each notch position.

Steady-state notch-average NO concentrations for the double-powered consist varied from 170 ppm at low idle to 1570 ppm at notch 7. Notch-average NO concentrations increased monotonically with notch position for low idle through notch 7 and was 1293 ppm at notch 8. Notch-average NO concentrations for a given notch position had inter-trip CV of 0.3 or lower for each notch position. The inter-trip CVs for high idle, notch 2, notch 5 and notch 8 were 0.1 or lower. Thus, these measurements were highly repeatable. Except for notch 5 and 6, no statistically significant differences between notch-average NO concentrations for double- versus single-powered consist were measured.

The steady-state notch-average PM concentrations for the double-powered consist varied from 3.8 mg/m^3 at low idle to 11.1 mg/m^3 at notch 7. Notch-average PM concentrations were within 10 percent of each other for low idle, high idle, dynamic brake and notch 1. Notch-average PM concentrations for notches 3 through 5 were within 5 percent of each other. Notch-average PM concentrations for a given notch position had inter-trip CV of 0.2 or lower for each notch position. The inter-trip CVs for each notch position except for notch 2 were 0.08 or lower. Thus, these latter measurements were highly repeatable. No valid PM concentration measurements were available for the trips on the 13th of February because the PM sensor had failed.

TABLE E-5. Steady-state Notch-average Concentrations for Locomotive NC 1871 for Over-the-Rail Measurements of Push/Pull Train Consists Conducted between January 30 and February 16, 2019: (a) CO_2; (b) CO; (c) HC; (d) NO; and (e) PM.

(a) CO_2 concentration (vol %)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[b]	0.54	0.54	-	-[b]	-[b]	0.50	0.50	-
High Idle	0.62	0.61	0.54	0.59	0.07	0.69	0.67	0.65	0.67	0.03
Dyn Brk	0.83	-[b]	-[b]	0.83	-	-[b]	0.87	0.64	0.76	0.21
1	0.65	0.73	0.68	0.68	0.06	0.74	0.88	0.74	0.78	0.10
2	2.30	1.97	1.61	1.96	0.17	2.47	2.23	1.99	2.23	0.11
3	3.34	3.04	2.49	2.96	0.15	3.38	3.04	2.44	2.95	0.16
4	3.72	5.50	3.39	4.20	0.27	3.92	3.19	3.65	3.59	0.10
5	4.19	-[b]	3.90	4.04	0.05	4.45	4.19	4.06	4.24	0.05
6	5.14	-[b]	5.01	5.07	0.02	4.39	4.89	4.69	4.65	0.05
7	5.98	5.32	5.40	5.57	0.06	-[b]	-[b]	6.28	6.28	-
8	5.23	5.22	5.10	5.18	0.01	5.22	5.42	4.40	5.01	0.11

(b) CO concentration (vol %)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[b]	-[d]	-	-	-[b]	-[b]	*0.000*	*0.000*	-
High Idle	*0.001*	*0.001*	*0.000*	*0.001*	*0.51*	*0.003*	*0.001*	*0.000*	*0.001*	*1.01*
Dyn Brk	*0.002*	-[b]	-[b]	*0.002*	-	-[b]	*0.002*	*0.000*	*0.001*	*1.24*
1	*0.001*	*0.001*	*0.000*	*0.001*	*0.52*	*0.003*	*0.001*	*0.000*	*0.001*	*0.95*
2	*0.000*	*0.001*	*0.001*	*0.001*	*0.48*	*0.002*	*0.000*	*0.001*	*0.001*	*0.82*
3	*0.001*	*0.001*	*0.003*	*0.001*	*0.98*	*0.001*	*0.000*	*0.000*	*0.001*	*1.04*
4	*0.000*	0.019	*0.003*	*0.007*	*1.37*	*0.000*	*0.000*	*0.001*	*0.001*	*1.09*
5	*0.001*	-[b]	*0.007*	*0.004*	*0.99*	*0.000*	*0.000*	*0.003*	*0.001*	*1.32*
6	*0.002*	-[b]	*0.004*	*0.003*	*0.51*	*0.002*	-[d]	*0.001*	*0.001*	*0.37*
7	*0.003*	*0.006*	0.020	0.010	0.89	-[b]	-[b]	0.024	0.024	-
8	0.011	0.017	0.019	0.016	0.28	0.013	0.015	0.009	0.012	0.25

**The values in italics are below the detection limit of the instrument (0.008 vol % for CO).*

Table E-5 Continued on next page.

Table E-5 Continued from previous page.

(c) HC concentration (ppm)[c]

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[b]	*8*	*8*	-	-[b]	-[b]	*2*	*2*	-
High Idle	18	*12*	*7*	*13*	*0.45*	*13*	*8*	*4*	*8*	*0.58*
Dyn Brk	*10*	-[b]	-[b]	*10*	-	-[b]	*9*	*4*	*6*	*0.52*
1	17	*10*	*6*	*11*	*0.49*	*12*	*9*	*4*	*9*	*0.50*
2	19	17	*7*	14	0.43	17	*11*	*5*	*11*	*0.55*
3	21	*11*	*5*	*13*	*0.66*	18	*8*	*2*	*9*	*0.89*
4	20	*8*	*4*	*11*	*0.75*	*12*	*6*	*3*	*7*	*0.71*
5	*12*	-[b]	*3*	*7*	*0.90*	*12*	*6*	*4*	*7*	*0.55*
6	*13*	-[b]	*5*	*9*	*0.61*	*9*	*6*	*3*	*6*	*0.49*
7	17	*8*	*4*	*10*	*0.67*	-[b]	-[b]	*4*	*4*	-
8	*8*	*7*	*3*	*6*	*0.48*	*7*	*5*	*2*	*5*	*0.49*

**The values in italics are below the detection limit of the instrument (13 ppm for HC).*

(d) NO concentration (ppm)[c]

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[b]	195	195	-	-[b]	-[b]	170	170	-
High Idle	191	196	183	190	0.03	212	205	223	213	0.04
Dyn Brk	215	-[b]	-[b]	215	-	-[b]	255	177	216	0.26
1	180	211	244	212	0.15	239	279	260	259	0.08
2	674	619	528	607	0.12	752	701	610	688	0.10
3	1130	1009	874	1004	0.13	1167	1067	880	1038	0.14
4	1169	1516	1166	1284	0.16	1367	987	1304	1219	0.17
5	1363	-[b]	1329	1346	0.02	1543	1402	1439	1461	0.05
6	1594	-[b]	1590	1592	0.00	1268	1589	1464	1441	0.11
7	1577	1572	1497	1549	0.03	-[b]	-[b]	1570	1570	-
8	1332	1357	1352	1347	0.01	1300	1370	1210	1293	0.06

Table E-5 Continued on next page.

Table E-5 Continued from previous page.

(e) PM Concentration (mg/m^3)[c]

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[e]	4.02	4.02	-	-[b]	-[e]	3.81	3.81	-
High Idle	3.17	-[e]	3.89	3.53	0.14	4.30	-[e]	4.16	4.23	0.02
Dyn Brk	3.40	-[e]	-[b]	3.40	-	-[b]	-[e]	4.36	4.36	0.00
1	3.11	-[e]	4.36	3.74	0.24	4.40	-[e]	4.22	4.31	0.03
2	4.65	-[e]	5.63	5.14	0.14	4.94	-[e]	6.84	5.89	0.23
3	5.25	-[e]	5.45	5.35	0.03	5.17	-[e]	4.83	5.00	0.05
4	4.96	-[e]	6.50	5.73	0.19	4.86	-[e]	5.06	4.96	0.03
5	5.14	-[e]	6.84	5.99	0.20	4.66	-[e]	5.18	4.92	0.08
6	5.62	-[e]	8.89	7.26	0.32	5.86	-[e]	6.17	6.02	0.04
7	9.22	-[e]	12.42	10.82	0.21	-[b]	-[e]	11.15	11.15	-
8	8.32	-[e]	11.27	9.80	0.21	8.23	-[e]	7.95	8.09	0.02

[a] *CV = coefficient of variation (standard deviation divided by mean)*
[b] *No steady-state data for the given notch position.*
[c] *HC, NO and PM concentrations reported are without bias corrections, as measured by Axion PEMS*
[d] *Measurements less than zero*
[e] *Invalid measurements: PM sensor failed. Concentrations were extremely low compared to other measurements*

Steady-State Fuel Use and Emission Rates

The steady-state notch-average engine output, fuel use rate and emission rates of CO_2, CO, HC, NO_x and PM measured using an Axion PEMS are summarized in Table E-6. The net engine power output increased monotonically from notch 1 through notch 8.

The steady-state notch-average fuel use rate varied from 2 g/s at low idle to 117 g/s at notch 7. Notch-average fuel use rates increased monotonically from low idle through notch 7. The average fuel use rate was 94.3 g/s at notch 8. The inter-trip CV of notch-average fuel use rates for a given notch position were 0.16 or lower for each notch position. Thus, these measurements were repeatable. Notch-average CO_2 emission rates varied from 6 g/s at low idle to 364 g/s at notch 7. Notch-average CO_2 emission rates had similar trends as fuel use rate.

The notch-average CO and HC emission rates were 0.1 g/s or lower for low idle through notch 6. The inter-trip CV of CO and HC emission rates for a given notch position were 1.5 or lower for each notch position. The notch-average CO and HC emission rates were low.

TABLE E-6. Steady-state Notch-average Fuel Use and Emission Rates for Locomotive NC 1871 for Over-the-Rail Measurements of Push/Pull Train Consists Conducted between January 30 and February 16, 2019: (a) fuel use rate; (b) CO_2 emission rate; (c) CO emission rate; (d) THC emission rate; (e) NO_x emission rate; and (f) PM emission rate.

(a) Mass per time-based fuel use rate (g/s)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[b]	2	2	-	-[b]	-[b]	2	2	-
High Idle	3	3	3	3	0.02	3	3	3	3	0.04
Dyn Brk	6	-[b]	-[b]	6	-	-[b]	6	5	5	0.12
1	3	3	3	3	0.08	3	4	4	3	0.08
2	14	12	11	12	0.12	15	13	13	14	0.06
3	26	24	22	24	0.10	27	24	22	24	0.10
4	44	63	45	51	0.21	46	37	49	44	0.14
5	52	-[b]	54	53	0.04	55	51	58	55	0.06
6	76	-[b]	85	81	0.08	65	73	79	72	0.10
7	104	89	108	101	0.10	-[b]	-[b]	117	117	-
8	104	99	113	105	0.07	94	96	93	94	0.02

(b) Mass per time-based CO_2 emission rate (g/s)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[b]	6	6	-	-[b]	-[b]	6	6	-
High Idle	8	8	8	8	0.02	9	9	10	9	0.05
Dyn Brk	17	-[b]	-[b]	17	-	-[b]	18	15	16	0.12
1	9	10	10	9	0.08	10	12	11	11	0.08
2	42	36	33	37	0.12	45	41	42	43	0.06
3	82	74	67	75	0.10	83	74	67	75	0.10
4	138	196	140	158	0.21	145	117	153	138	0.14
5	161	-[b]	170	165	0.04	172	160	180	171	0.06
6	238	-[b]	265	252	0.08	203	228	246	226	0.10
7	326	279	337	314	0.10	-[b]	-[b]	364	364	-
8	323	309	351	327	0.07	293	300	289	294	0.02

Table E-6 Continued on next page.

Table E-6 Continued from previous page.

(c) Mass per time-based CO emission rate (g/s)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[b]	-[d]	-	-	-[b]	-[b]	*0.00*	*0.00*	-
High Idle	*0.01*	*0.01*	*0.00*	*0.01*	*0.47*	*0.03*	*0.01*	*0.00*	*0.01*	*0.99*
Dyn Brk	*0.02*	-[b]	-[b]	*0.02*	-	-[b]	*0.02*	*0.00*	*0.01*	*1.21*
1	*0.01*	*0.01*	*0.00*	*0.01*	*0.48*	*0.02*	*0.01*	*0.00*	*0.01*	*0.94*
2	*0.01*	*0.01*	*0.02*	*0.01*	*0.50*	*0.02*	*0.00*	*0.02*	*0.01*	*0.81*
3	*0.01*	*0.01*	*0.05*	*0.02*	*1.03*	*0.02*	*0.00*	*0.00*	*0.01*	*1.02*
4	*0.00*	*0.43*	*0.08*	*0.17*	*1.32*	*0.01*	*0.00*	*0.03*	*0.01*	*1.14*
5	*0.03*	-[b]	*0.19*	*0.11*	*1.04*	*0.01*	*0.00*	*0.09*	*0.03*	*1.36*
6	*0.06*	-[b]	*0.14*	*0.10*	*0.59*	*0.04*	-[d]	*0.03*	*0.04*	*0.29*
7	*0.12*	*0.22*	0.80	0.38	0.98	-[b]	-[b]	0.89	0.89	0.00
8	0.42	0.65	0.83	0.63	0.33	0.47	0.53	0.38	0.46	0.16

Values in italics correspond to estimates based on concentrations below-detection limit

(d) Mass per time-based THC emission rate (g/s)[c]

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[b]	*0.0*	*0.0*	-	-[b]	-[b]	*0.0*	*0.0*	-
High Idle	0.1	*0.1*	*0.0*	*0.1*	*0.4*	*0.1*	*0.1*	*0.0*	*0.1*	*0.6*
Dyn Brk	*0.1*	-[b]	-[b]	*0.1*	-	-[b]	*0.1*	*0.0*	*0.1*	*0.4*
1	0.1	*0.1*	*0.0*	*0.1*	*0.5*	*0.1*	*0.1*	*0.0*	*0.1*	*0.5*
2	0.2	0.1	*0.1*	0.1	0.4	0.2	*0.1*	*0.0*	*0.1*	*0.5*
3	0.3	*0.1*	*0.1*	*0.2*	*0.6*	0.2	*0.1*	*0.0*	*0.1*	*0.9*
4	0.4	*0.1*	*0.1*	*0.2*	*0.7*	*0.2*	*0.1*	*0.1*	*0.1*	*0.7*
5	*0.2*	-[b]	*0.1*	*0.1*	*0.8*	*0.2*	*0.1*	*0.1*	*0.1*	*0.5*
6	*0.3*	-[b]	*0.1*	*0.2*	*0.5*	*0.2*	*0.1*	*0.1*	*0.1*	*0.4*
7	0.4	*0.2*	*0.1*	*0.3*	*0.6*	-[b]	-[b]	*0.1*	*0.1*	-
8	*0.2*	*0.2*	*0.1*	*0.2*	*0.4*	*0.2*	*0.1*	*0.1*	*0.1*	*0.4*

Values in italics correspond to estimates based on concentrations below-detection limit

Table E-6 Continued on next page.

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(e) Mass per time-based NO_x emission rate (g/s)[c]

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[b]	0.2	0.2	-	-[b]	-[b]	0.2	0.2	-
High Idle	0.3	0.3	0.3	0.3	0.03	0.3	0.3	0.4	0.3	0.11
Dyn Brk	0.5	-[b]	-[b]	0.5	-	-[b]	0.6	0.5	0.5	0.16
1	0.3	0.3	0.4	0.3	0.22	0.3	0.4	0.4	0.4	0.10
2	1.4	1.3	1.2	1.3	0.07	1.5	1.4	1.4	1.4	0.04
3	3.1	2.7	2.6	2.8	0.08	3.1	2.9	2.7	2.9	0.08
4	4.8	5.9	5.3	5.3	0.11	5.6	4.0	6.0	5.2	0.21
5	5.8	-[b]	6.4	6.1	0.07	6.6	5.9	7.0	6.5	0.09
6	8.1	-[b]	9.3	8.7	0.09	6.5	8.2	8.5	7.7	0.14
7	9.5	9.1	10.3	9.6	0.07	-[b]	-[b]	10.0	10.0	-
8	9.1	8.8	10.2	9.4	0.08	8.0	8.4	8.8	8.4	0.04

(f) Mass per time-based PM emission rate (g/s)[c]

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	30-Jan	13-Feb	16-Feb	3 Trips		30-Jan	13-Feb	16-Feb	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	-[b]	-[e]	0.01	0.01	-	-[b]	-[e]	0.01	0.01	-
High Idle	0.01	-[e]	0.02	0.01	0.22	0.02	-[e]	0.02	0.02	0.06
Dyn Brk	0.02	-[e]	-[b]	0.02	-	-[b]	-[e]	0.03	0.03	-
1	0.01	-[e]	0.02	0.01	0.31	0.02	-[e]	0.02	0.02	0.05
2	0.02	-[e]	0.03	0.03	0.22	0.03	-[e]	0.04	0.03	0.31
3	0.04	-[e]	0.04	0.04	0.09	0.04	-[e]	0.04	0.04	0.04
4	0.05	-[e]	0.08	0.06	0.26	0.05	-[e]	0.06	0.06	0.12
5	0.06	-[e]	0.08	0.07	0.29	0.05	-[e]	0.06	0.06	0.17
6	0.07	-[e]	0.13	0.10	0.41	0.08	-[e]	0.09	0.08	0.12
7	0.14	-[e]	0.22	0.18	0.30	-[b]	-[e]	0.18	0.18	-
8	0.15	-[e]	0.22	0.18	0.29	0.13	-[e]	0.15	0.14	0.09

[a] *CV = coefficient of variation (standard deviation divided by mean)*

[b] *No steady-state data for the given notch position.*

[c] *HC emission rates estimated with Axion PEMS-measured HC concentrations have been multiplied with a correction factor shown in Table 8 to obtain THC emission rates. NO emission rates estimated with Axion PEMS-measured NO concentrations have been multiplied with a correction factor shown in Table 8 to obtain NO_x emission rates. PM emission rates estimated with Axion PEMS-measured PM concentrations have been multiplied with a correction factor of 5 to obtain PM emission rates.*

[d] *Measurements less than zero*

[e] *Invalid measurements: PM sensor failed. Concentrations were extremely low compared to other measurements*

E.3 Locomotive NC 1984: June 2018

OTR measurements of the PME of NC 1984 were conducted between June 12, 2018 and June 14, 2018. Three one-way trips each were conducted for trains 75 and 76 following the measurement schedule given in Table 2-4. The train consist included two locomotives, three passenger cars and one baggage/café car. Each of the trip was measured as a double-powered push/pull consist.

Steady-State Engine Activity Variables

The steady-state notch-average RPM, IAT, and MAP are summarized in Table E-7. Notch-average RPM varied from 219 RPM at low idle to 900 RPM at notch 8. Notch-average RPM increased monotonically from low idle to notch 8, except for dynamic brake. Engine RPM at dynamic brake varied substantially. Notch-average RPM for a given notch position had inter-trip CV of 0.03 or lower for each notch position. Thus, the RPM measurements were highly repeatable.

The notch-average IAT varied from 314 K at low idle to 318 K at notch 5. Notch-average IAT for a given notch position had inter-trip CV of 0.01 or lower for each notch position. Thus, the IAT measurements were highly repeatable.

The notch-average MAP varied from 95 kPa at low idle to 200 kPa at notch 8. Notch-average MAP for a given notch position had inter-trip CV of 0.03 or lower for each notch position. Thus, the MAP measurements were highly repeatable.

TABLE E-7. Steady-state Notch-average Engine Activity Variables for Locomotive NC 1984 for Over-the-Rail Measurements of Double-powered Push/Pull Train Consist Conducted between June 12, 2018 and June 14, 2018: (a) Engine Revolutions per Minute; (b) Intake Air Temperature; and (c) Manifold Absolute Pressure.

(a) Engine Revolutions per Minute (RPM)

Throttle Notch Position	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips	
	Train 77	Train 78	Train 75	Train 75	Train 75	Train 75	Avg	CV[a]
Low Idle	220	219	219	219	219	219	219	0.00
High Idle	268	268	269	268	267	268	268	0.00
Dynamic Brake	452	445	472	456	455	421	450	0.04
1	268	268	268	268	268	268	268	0.00
2	389	389	388	389	389	389	389	0.00
3	509	509	509	509	509	509	509	0.00
4	703	703	-[b]	702	703	702	703	0.00
5	726	724	-[b]	715	703	728	719	0.01
6	818	818	-[b]	819	826	819	820	0.00
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	901	900	900	900	900	900	900	0.00

Table E-7 Continued on next page.

Table E-7 Continued from previous page.

(b) Intake Air Temperature (K)

Throttle Notch Position	Trip 1 Train 77	Trip 2 Train 78	Trip 3 Train 75	Trip 4 Train 75	Trip 5 Train 75	Trip 6 Train 75	6 Trips Avg	6 Trips CV[a]
Low Idle	312	311	313	312	318	320	314	0.01
High Idle	312	312	315	312	320	320	315	0.01
Dynamic Brake	312	312	315	313	320	320	315	0.01
1	311	312	316	315	320	319	316	0.01
2	313	312	316	315	320	320	316	0.01
3	311	312	316	318	319	321	316	0.01
4	312	313	-[b]	315	319	321	316	0.01
5	312	312	-[b]	321	321	321	318	0.02
6	313	313	-[b]	315	321	321	317	0.01
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	313	313	315	314	319	321	316	0.01

(c) Manifold Absolute Pressure (kPa)

Throttle Notch Position	Trip 1 Train 77	Trip 2 Train 78	Trip 3 Train 75	Trip 4 Train 75	Trip 5 Train 75	Trip 6 Train 75	6 Trips Avg	6 Trips CV[a]
Low Idle	92	93	96	93	94	92	93	0.02
High Idle	101	103	101	100	101	101	101	0.01
Dynamic Brake	114	112	118	115	112	108	113	0.03
1	98	97	98	97	96	96	97	0.01
2	106	105	106	105	104	103	105	0.01
3	118	117	118	116	115	114	117	0.01
4	148	147	-[b]	146	144	143	146	0.01
5	154	153	-[b]	144	140	149	148	0.04
6	177	174	-[b]	173	168	169	172	0.02
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	208	200	196	202	197	196	200	0.02

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of six trips*
[b] *No steady-state data available for select notch position*

Steady-State Exhaust Gas and PM Concentrations

The steady-state notch-average measured exhaust concentrations of CO_2, CO, HC, NO and PM measured using an Axion PEMS are summarized in Table E-8. Steady-state notch-average CO_2 concentrations varied from 0.74 vol % at low idle to 4.87 vol % at notch 6. Notch-average CO_2 concentrations increased monotonically from low idle through notch 6 and the average concentration was 4.80 vol % at notch 8.

TABLE E-8. Steady-state Notch-average Concentrations for Locomotive NC 1984 for Over-the-Rail Measurements of Double-powered Push/Pull Train Consist Conducted between June 12, 2018 and June 14, 2018: (a) CO_2; (b) CO; (c) HC; (d) NO; and (e) PM.

(a) CO_2 concentration (vol%)

Throttle Notch Position	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips	
	Train 77	Train 78	Train 75	Train 75	Train 75	Train 75	Avg	CV[a]
Low Idle	0.77	0.79	0.60	0.78	0.68	0.80	0.74	0.1
High Idle	0.82	0.86	0.86	0.84	0.92	0.92	0.87	0.0
Dynamic Brake	0.89	0.77	1.24	0.97	0.96	0.91	0.96	0.2
1	0.93	0.96	0.96	1.03	0.92	1.13	0.99	0.1
2	2.56	2.55	2.34	2.53	1.96	2.47	2.40	0.1
3	3.44	3.54	3.65	3.52	2.75	3.39	3.38	0.1
4	4.10	3.91	-[b]	4.04	4.31	4.11	4.10	0.0
5	4.04	4.47	-[b]	4.77	4.23	4.70	4.44	0.1
6	5.30	4.94	-[b]	5.04	4.19	4.87	4.87	0.1
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	5.13	4.82	4.20	4.72	4.79	5.11	4.79	0.1

(b) CO concentration (vol%)

Throttle Notch Position	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips	
	Train 77	Train 78	Train 75	Train 75	Train 75	Train 75	Avg	CV[a]
Low Idle	*0.005*	*0.003*	*0.000*	*0.004*	*0.001*	*0.000*	*0.002*	0.97
High Idle	*0.001*	*0.001*	*0.005*	*0.001*	*0.004*	*0.003*	*0.002*	0.74
Dynamic Brake	*0.001*	*0.001*	*0.005*	*0.002*	*0.000*	*0.002*	*0.002*	0.89
1	*0.001*	*0.000*	*0.000*	*0.001*	*0.004*	*0.002*	*0.002*	0.87
2	*0.000*	*0.000*	*0.003*	*0.000*	*0.001*	*0.001*	*0.001*	1.12
3	*0.000*	*0.000*	*0.001*	*0.000*	*0.000*	*0.000*	*0.000*	0.90
4	*0.000*	*0.000*	-[b]	*0.001*	*0.000*	*0.001*	*0.001*	0.80
5	*0.002*	*0.001*	-[b]	*0.006*	*0.004*	0.008	*0.004*	0.69
6	*0.003*	*0.001*	-[b]	*0.005*	*0.000*	0.009	*0.004*	1.01
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	0.018	0.019	0.014	0.017	0.029	0.019	0.019	0.26

**The values in italics are below the detection limit of the instrument (0.008 vol % for CO).*

Table E-8 Continued on next page.

Table E-8 Continued from previous page.

(c) HC concentration (ppm)

Throttle Notch Position	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips	
	Train 77	Train 78	Train 75	Train 75	Train 75	Train 75	Avg	CV[a]
Low Idle	17	23	41	20	39	33	29	0.4
High Idle	*12*	19	18	15	30	40	22	0.5
Dynamic Brake	*11*	*8*	22	14	65	52	29	0.8
1	*9*	17	58	16	24	22	24	0.7
2	*6*	14	31	17	*1*	32	17	0.8
3	*8*	13	36	38	40	40	29	0.5
4	*8*	24	-[b]	18	*9*	38	16	0.8
5	*2*	*5*	-[b]	20	*0*	40	*11*	1.4
6	*8*	*4*	-[b]	*12*	25	36	14	1.0
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	*4*	*8*	21	*11*	17	22	14	0.5

**The values in italics are below the detection limit of the instrument (13 ppm for HC).*

(d) NO concentration (ppm)

Throttle Notch Position	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips	
	Train 77	Train 78	Train 75	Train 75	Train 75	Train 75	Avg	CV[a]
Low Idle	177	185	178	181	188	191	183	0.03
High Idle	203	215	202	209	211	220	210	0.03
Dynamic Brake	167	152	177	165	200	183	174	0.10
1	274	290	274	276	267	278	277	0.03
2	682	693	677	687	519	684	657	0.10
3	994	1103	1151	1123	858	1094	1054	0.10
4	1128	1123	-[b]	1148	1262	1192	1171	0.05
5	1076	1297	-[b]	1251	1105	1398	1225	0.11
6	1394	1314	-[b]	1320	1319	1253	1320	0.04
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	1068	983	876	975	960	1109	995	0.08

Table E-8 Continued on next page.

Table E-8 Continued from previous page.

(e) PM Concentration (mg/m^3)

Throttle Notch Position	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips	
	Train 77	Train 78	Train 75	Train 75	Train 75	Train 75	Avg	CV[a]
Low Idle	5.55	5.83	4.99	5.69	7.57	6.48	6.02	0.15
High Idle	6.67	6.85	7.12	6.76	7.76	6.74	6.98	0.06
Dynamic Brake	6.49	6.45	6.23	6.39	6.78	6.59	6.49	0.03
1	7.18	7.11	6.92	7.30	6.51	7.41	7.07	0.05
2	7.24	7.23	7.12	7.47	7.20	7.93	7.36	0.04
3	6.56	6.79	6.66	6.74	6.94	6.82	6.75	0.02
4	6.36	6.58	-[b]	6.55	6.84	6.70	6.60	0.03
5	6.69	6.38	-[b]	6.58	6.09	7.08	6.57	0.06
6	8.27	7.75	-[b]	8.42	7.43	9.22	8.22	0.08
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	12.62	12.42	14.53	13.19	15.90	13.44	13.68	0.10

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of six trips*
[b] *No steady-state data available for select notch position*
[c] *PM concentrations reported are without bias corrections, as measured by Axion PEMS*

Notch-average CO_2 concentrations for a given notch position had inter-trip CV of 0.16 or lower for each notch position. The inter-trip CV for low idle, high idle, dynamic brake and notch 8 was 0.11 or lower. Thus, these measurements were repeatable.

The steady-state notch-average CO concentrations were below the detection limit of the Axion PEMS for low idle through notch 7. Steady-state notch-average HC concentrations varied from 13 ppm at notch 5 to 29 ppm at low idle, dynamic brake and notch 3. Notch-average HC concentration was below the detection limit of the PEMS only at notch 5. However, notch-average HC concentrations were low, the highest was 2.1 times the detection limit.

The steady-state notch-average NO concentrations for the double-powered consist varied from 174 ppm at dynamic brake to 1320 ppm at notch 6. Notch-average NO concentrations increased monotonically with notch position for high idle through notch 6 and the average concentration was 995 ppm at notch 8. Notch-average NO concentrations for a given notch position had inter-trip CV of 0.1 or lower for each notch position. Thus, these measurements were highly repeatable.

The notch-average PM concentrations varied from 6.0 mg/m^3 at low idle to 13.7 mg/m^3 at notch 8. Notch-average PM concentrations for a given notch position had inter-trip CV of 0.15 or lower for each notch position. Thus, these measurements were repeatable.

Steady-State Fuel Use and Emission Rates

The steady-state notch-average engine output, fuel use rate and emission rates of CO_2, CO, HC, NO and PM measured using an Axion PEMS are summarized in Table E-9. The net engine power output increased monotonically from notch 1 through notch 8. The notch-average fuel use rates varied from 2.7 g/s at low idle to 92.1 g/s at notch 8. Notch-average fuel use rates increased monotonically from low idle through notch 8. The inter-trip CV of notch-average fuel use rates for a given notch position were 0.20 or lower for each notch position and 0.1 or lower for each notch position except for dynamic brake. Thus, these measurements were repeatable. Notch-average CO_2 emission rates varied from 9 g/s at low idle to 286 g/s at notch 8. The notch-average CO_2 emission rates had similar trends as the fuel use rate.

The notch-average CO emission rates varied from 0.01 g/s at low idle to 0.75 g/s at notch 8. Notch-average HC emission rates varied between 0.2 g/s and 0.4 g/s. CO and HC emission rates were low.

The notch-average NO_x emission rates varied from 0.3 g/s at low idle to 7.4 g/s at notch 6. Notch-average NO_x emission rates increased monotonically from low idle through notch 6 and was 7.4 g/s at notch 6. The inter-trip CV of notch-average NO_x emission rates for a given notch position were 0.6 or lower for each notch position for each notch position and 0.1 or lower for 6 of the 10 measured notch positions. Thus, NO_x emission rate measurements were highly repeatable for 6 of the 10 measured notch positions.

The steady-state notch-average PM emission rates varied from 0.02 g/s at low idle to 0.23 g/s at notch 8. Notch-average PM emission rates increased monotonically from low idle through notch 8. The inter-trip CV of notch-average PM emission rates for a given notch position were 0.83 or lower for each notch position.

E.4 Locomotive NC 1984: June 2019

The OTR measurements of the PME of NC 1984 were conducted from June 18 to June 20, 2019. Six one-way trips were conducted for the trains 75 and 76 following the measurement schedule given in Table 2-4. During the trips on June 18, the net engine output from the locomotive activity recorder display were logged manually by writing down the readings for each notch position periodically.

Steady-State Engine Activity Variables

The steady-state notch-average RPM, IAT, and MAP are summarized in Table E-10. Notch-average RPM for a given notch position was within 3 RPM for double- versus single-powered consists for each notch position, except for dynamic brake. Therefore, notch-average RPM for a given notch position were approximately similar to each other for the two consists. Notch-average RPM varied from 219 RPM at low idle to 902 RPM at notch 8. Notch-average RPM increased monotonically from low idle to notch 8, except for dynamic brake. Engine RPM at dynamic brake varied substantially. Notch-average RPM for a given notch position for the double- and single-powered consist each had inter-trip CV of 0.03 or lower for each notch position. Thus, the RPM measurements were highly repeatable.

TABLE E-9. Steady-state Notch-average Fuel Use and Emission Rates for Locomotive NC 1984 for Over-the-Rail Measurements of Double-powered Push/Pull Train Consist Conducted between June 12, 2018 and June 14, 2018: (a) fuel use rate; (b) CO_2 emission rate; (c) CO emission rate; (d) THC emission rate; (e) NO_x emission rate; and (f) PM emission rate.

(a) Mass per time-based fuel use rate (g/s)

Throttle Notch Position	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips	
	Train 77	Train 78	Train 75	Train 75	Train 75	Train 75	Avg	CV[a]
Low Idle	2.5	2.7	2.5	2.6	2.7	3.1	2.7	0.09
High Idle	4.4	4.9	4.7	4.7	4.8	4.2	4.6	0.06
Dynamic Brake	7.0	6.0	10.3	7.7	7.4	6.4	7.5	0.20
1	4.5	4.6	4.6	4.9	4.2	5.2	4.7	0.07
2	16.8	16.7	17.2	16.6	16.3	16.4	16.7	0.02
3	29.9	30.8	31.4	29.9	23.5	28.4	29.0	0.10
4	53.4	51.6	-[b]	52.1	53.7	51.2	52.4	0.02
5	55.1	61.3	-[b]	57.0	59.4	61.4	58.8	0.05
6	87.3	80.7	-[b]	81.7	71.3	76.9	79.6	0.07
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	102	93.7	80.0	91.8	90.3	94.8	92.0	0.08

(b) Mass per time-based CO_2 emission rate (g/s)

Throttle Notch Position	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips	
	Train 77	Train 78	Train 75	Train 75	Train 75	Train 75	Avg	CV[a]
Low Idle	9	9	8	9	8	10	9	0.1
High Idle	14	15	17	14	16	16	15	0.1
Dynamic Brake	22	19	32	24	23	20	23	0.2
1	14	14	14	15	13	16	14	0.1
2	52	52	25	51	39	49	45	0.2
3	93	96	98	93	73	88	90	0.1
4	167	161	-[b]	162	168	160	163	0.0
5	172	191	-[b]	179	167	191	180	0.1
6	273	252	-[b]	255	222	239	248	0.1
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	316	292	249	285	280	295	286	0.1

Table E-9 Continued on next page.

Table E-9 Continued from previous page.

(c) Mass per time-based CO emission rate (g/s)

Throttle Notch Position	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips	
	Train 77	Train 78	Train 75	Train 75	Train 75	Train 75	Avg	CV[a]
Low Idle	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	0.9
High Idle	*0.0*	*0.0*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	0.9
Dynamic Brake	*0.0*	*0.0*	*0.1*	*0.0*	*0.0*	*0.0*	*0.0*	0.9
1	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	0.8
2	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	1.1
3	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	0.9
4	*0.0*	*0.0*	-[b]	*0.0*	*0.0*	*0.0*	*0.0*	0.8
5	*0.1*	*0.0*	-[b]	*0.1*	*0.1*	0.2	*0.1*	0.7
6	*0.1*	*0.0*	-[b]	*0.1*	*0.0*	0.3	*0.1*	1.0
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	0.7	0.7	0.5	0.7	1.1	0.7	0.7	0.2

Values in italics correspond to estimates based on concentrations below-detection limit

(d) Mass per time-based THC emission rate (g/s)

Throttle Notch Position	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips	
	Train 77	Train 78	Train 75	Train 75	Train 75	Train 75	Avg	CV[a]
Low Idle	0.1	0.2	0.3	0.1	0.2	0.2	0.2	0.29
High Idle	*0.1*	0.2	0.2	0.1	0.3	0.4	0.2	0.47
Dynamic Brake	*0.1*	*0.1*	0.3	0.2	0.7	0.6	0.3	0.80
1	*0.1*	0.1	0.4	0.1	0.2	0.2	0.2	0.72
2	*0.1*	0.1	0.3	0.2	*0.0*	0.3	0.2	0.76
3	*0.1*	0.2	0.5	0.5	0.5	0.5	0.4	0.49
4	*0.2*	0.5	-[b]	0.5	*0.2*	0.7	0.4	0.59
5	*0.0*	*0.1*	-[b]	0.4	*0.0*	0.8	*0.3*	1.23
6	*0.2*	*0.1*	-[b]	*0.4*	0.6	0.9	0.4	0.71
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	*0.1*	*0.2*	0.6	*0.3*	0.5	0.6	0.4	0.51

[*] *HC measured with Axion PEMS have been multiplied with a correction factor shown in Table 6 to obtain THC.*

Table E-9 Continued on next page.

Table E-9 Continued from previous page.

(e) Mass per time-based NO_x emission rate (g/s)

Throttle Notch Position	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips	
	Train 77	Train 78	Train 75	Train 75	Train 75	Train 75	Avg	CV[a]
Low Idle	0.3	0.2	0.2	0.3	0.3	0.3	0.3	0.10
High Idle	0.4	0.4	1.3	0.4	0.8	0.6	0.7	0.54
Dynamic Brake	0.4	0.4	0.8	0.5	0.5	0.5	0.5	0.24
1	0.5	0.5	0.4	0.5	0.4	0.5	0.5	0.09
2	1.5	1.6	0.6	1.5	1.1	1.5	1.3	0.30
3	3.0	3.3	3.4	3.3	2.5	3.1	3.1	0.11
4	5.1	5.1	-[b]	5.1	5.4	5.1	5.1	0.03
5	5,9	6.1	-[b]	6.3	6.4	6.3	6.3	0.02
6	7.9	7.4	-[b]	7.4	7.7	6.8	7.4	0.06
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	7.2	6.5	5.7	6.5	6.2	7.1	6.5	0.09

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of six trips*
[*]NO measured wit Axion PEMS have been multiplied with a correction factor shown in Table 5 to obtain NO_x.

(f) Mass per time-based PM emission rate (g/s)

Throttle Notch Position	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	6 Trips	
	Train 77	Train 78	Train 75	Train 75	Train 75	Train 75	Avg	CV[a]
Low Idle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
High Idle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
Dynamic Brake	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5
3	0.1	0.1	0.0	0.0	0.1	0.1	0.0	0.5
4	0.1	0.1	-[b]	0.1	0.1	0.1	0.1	0.0
5	0.1	0.1	-[b]	0.1	0.1	0.1	0.1	0.1
6	0.1	0.1	-[b]	0.1	0.1	0.1	0.1	0.2
7	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]	-[b]
8	0.2	0.2	0.0	0.1	0.3	0.2	0.2	0.5

[a] *CV = Coefficient of Variation (Ratio of standard deviation and mean) of six trips*
[*]PM emission rates estimated with Axion measurements have been multiplied by a factor of 5 to account for total PM.
[b] *No steady-state data available for select notch position*

TABLE E-10. Steady-state Notch-average Engine Activity Variables for Locomotive NC 1984 for Over-the-Rail Measurements of Double- and single-powered Push/Pull Train Consists Conducted between June 18 and June 20, 2019: (a) Engine RPM; (b) Intake Air Temperature; and (c) Manifold Absolute Pressure.

(a) Engine Revolutions Per Minute (RPM)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	219	219	-[b]	219	0.00	219	-[b]	219	219	0.00
High Idle	268	268	268	268	0.00	268	268	268	268	0.00
Dyn Brk	470	-[b]	484	477	0.02	392	379	-[b]	386	0.03
1	268	269	268	268	0.00	268	269	268	268	0.00
2	389	389	389	389	0.00	389	389	390	389	0.00
3	509	509	509	509	0.00	509	509	509	509	0.00
4	702	703	703	703	0.00	702	702	703	702	0.00
5	726	728	726	727	0.00	726	727	727	727	0.00
6	819	819	820	819	0.00	817	819	819	818	0.00
7	858	-[b]	859	859	0.00	870	-[b]	-[b]	870	-
8	902	900	901	901	0.00	901	901	900	901	0.00

(b) Intake Air Temperature(K)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Train 75	Train 75
Low Idle	351	352	-[b]	352	0.01	355	-[b]	350	353	0.04
High Idle	356	354	358	356	0.02	355	354	352	354	0.02
Dyn Brk	357	-[b]	358	358	0.01	356	353	-[b]	355	0.03
1	354	355	359	356	0.03	355	354	354	354	0.00
2	356	356	359	357	0.02	355	356	354	355	0.01
3	358	358	365	360	0.04	356	356	356	356	0.00
4	358	361	363	361	0.03	362	357	356	358	0.04
5	359	364	360	361	0.03	360	358	357	358	0.02
6	362	365	364	364	0.02	363	359	358	360	0.03
7	361	-[b]	366	364	0.03	356	-[b]	-[b]	356	-
8	366	363	365	365	0.01	362	360	360	361	0.01

Table E-10 Continued on next page.

Table E-10 Continued from previous page.

(c) Manifold Absolute Pressure (kPa)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Train 75	Train 75
Low Idle	101	101	-[b]	101	0.00	100	-[b]	100	100	0.00
High Idle	103	103	102	103	0.01	103	103	102	102	0.01
Dyn Brk	120	-[b]	120	120	0.00	110	110	-[b]	110	0.00
1	103	103	103	103	0.00	103	103	102	102	0.01
2	111	111	110	111	0.01	110	110	110	110	0.00
3	122	122	121	122	0.00	122	122	120	121	0.01
4	150	150	150	150	0.00	149	149	149	149	0.00
5	155	155	153	154	0.01	155	155	154	155	0.00
6	176	176	176	176	0.00	175	175	175	175	0.00
7	203	-[b]	203	203	0.00	200	-[b]	-[b]	200	-
8	211	211	216	212	0.01	206	206	203	205	0.01

[a] *CV = coefficient of variation (standard deviation divided by mean)*
[b] *No steady-state data for the given notch position.*

The notch-average IAT for the double-powered consist varied from 353 K at low idle to 361 K at notch 8. Notch-average IAT for the double-powered consist had inter-trip CV of 0.04 or lower for each notch position. Thus, the IAT measurements were highly repeatable. Notch-average IAT for the single-powered consist varied from 352 K at low idle to 365 K at notch 8. Notch-average IAT for the single-powered consist had inter-trip CV of 0.04 or lower for each notch position. Thus, the IAT measurements were highly repeatable.

The notch-average MAP for a given notch position was within 2 kPa for the double- and single-powered consists for each notch position, except for dynamic brake, notch 7 and notch 8. Therefore, notch-average MAP for a given notch position were approximately similar for the two consists, except for dynamic brake notch 7 and notch 8. For the double-powered consist, notch-average MAP varied from 100 kPa at low idle to 205 kPa at notch 8. For the single-powered consist, notch-average MAP varied from 101 kPa at low idle to 212 kPa at notch 8. For both consists, notch-average MAP increased monotonically from low idle to notch 8, except for dynamic brake. Single-powered consist had 3 kPa to 7 kPa the higher MAP at notches 7 and 8 versus double-powered consist.

Steady-State Exhaust Gas and PM Concentrations

The steady-state notch-average measured exhaust concentrations of CO_2, CO, HC, NO and PM measured using an Axion PEMS are summarized in Table E-11. The steady-state notch-average CO_2 concentrations for the double-powered consist varied from 0.53 vol % at low idle to 5.92 vol % at notch 8 typically increased with notch position. The notch-average steady-state CO_2

concentrations varied from 0.68 vol % at low idle to 7.03 vol % at notch 7 for the single-powered consist and typically increased with notch position. The average CO_2 concentration at notch 8 was 6.08 vol %. Notch-average CO_2 concentrations were not statistically significantly different for double- versus single-powered consist for each notch position. Though not statistically significant, notch-average CO_2 concentrations for a given notch position were 2 to 6 percent lower for double- versus single-powered consist implying a higher air to fuel ratio and a lower fuel flow rate. The measurements were repeatable for a given notch position based on inter-trip CV of 0.11 or lower. CV was typically higher for notches 3 or lower compared to notches 4 and higher. However, notch-average CO_2 emission rates were also low for notches 3 or lower compared to notches 4 through 8.

Notch-average CO concentrations were typically below the detection limits of the Axion PEMS for most notches and trips. The inter-trip CVs for a given notch position was typically higher for notches with low emission rates and that were based on average concentrations below the detection limit of the PEMS. For notches 7 and 8, for which measured notch-average CO concentrations were typically above the detection limit, measurements were repeatable based on inter-trip CV of 0.11 or lower. For low idle through notch 1, CO concentrations were the same, within the precision of the measurements, for a given notch position for double- versus single-powered consist. For notches 2 through 8, differences in CO concentrations for double- versus single-powered were not statistically significant. Notch-average HC concentrations were below the detection limit of the Axion PEMS for all notch positions and all one-way trips. No trend in notch-average HC concentrations was observed for double- versus single-powered consist.

TABLE E-11. Steady-state Notch-average Concentrations for Locomotive NC 1984 for Over-the-Rail Measurements of Push/Pull Train Consists Conducted between June 18 and June 20, 2019: (a) CO_2; (b) CO; (c) HC; (d) NO; and (e) PM.

(a) CO_2 concentration (vol %)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	0.73	0.68	-[b]	0.70	0.05	0.53	-[b]	0.58	0.55	0.07
High Idle	0.68	0.65	0.64	0.66	0.03	0.57	0.67	0.64	0.62	0.08
Dyn Brk	0.86	-[b]	0.86	0.86	0.00	0.70	0.77	-[b]	0.73	0.07
1	0.76	0.82	0.91	0.83	0.09	0.64	0.73	0.76	0.71	0.09
2	2.54	2.58	2.10	2.41	0.11	2.30	2.43	2.32	2.35	0.03
3	3.54	3.61	3.22	3.46	0.06	3.56	3.56	3.65	3.59	0.01
4	4.02	3.97	4.17	4.05	0.03	3.98	3.86	3.86	3.90	0.02
5	4.77	4.86	4.27	4.63	0.07	4.53	4.60	4.44	4.52	0.02
6	5.74	5.78	5.64	5.72	0.01	5.53	4.92	5.47	5.31	0.06
7	7.03	-[b]	6.71	6.87	0.03	3.40	-[b]	-[b]	3.40	-
8	6.15	5.96	6.12	6.08	0.02	6.01	5.89	5.87	5.92	0.01

Table E-11 Continued on next page.

Table E-11 Continued from previous page.

(b) CO concentration (vol %)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	*0.000*	*0.002*	-[b]	*0.001*	*1.17*	-[d]	-[b]	*0.002*	*0.002*	-
High Idle	*0.001*	*0.001*	*0.000*	*0.001*	*0.45*	*0.000*	*0.001*	*0.001*	*0.001*	*0.41*
Dyn Brk	*0.001*	-[b]	*0.001*	*0.001*	*0.20*	*0.000*	*0.001*	-[b]	*0.000*	*0.49*
1	*0.001*	*0.002*	*0.001*	*0.001*	*0.34*	*0.001*	*0.001*	*0.001*	*0.001*	*0.30*
2	*0.002*	*0.001*	*0.004*	*0.002*	*0.68*	*0.000*	*0.002*	*0.000*	*0.001*	*1.34*
3	*0.002*	*0.001*	*0.005*	*0.002*	*0.80*	*0.000*	*0.004*	*0.000*	*0.001*	*1.50*
4	*0.002*	*0.005*	*0.005*	*0.004*	*0.38*	*0.003*	*0.004*	*0.001*	*0.002*	*0.58*
5	*0.003*	*0.006*	*0.001*	*0.004*	*0.69*	*0.001*	*0.003*	*0.001*	*0.002*	*0.86*
6	0.009	0.013	*0.007*	0.010	0.30	0.013	*0.006*	*0.006*	0.008	0.47
7	0.070	-[b]	0.058	0.064	0.14	-[d]	-[b]	-[b]	-	-
8	0.043	0.047	0.047	0.046	0.04	0.049	0.054	0.054	0.053	0.05

**The values in italics are below the detection limit of the instrument (0.008 vol % for CO).*

(c) HC concentration (ppm)[c]

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	*5*	*3*	-[b]	*4*	*0.38*	*9*	-[b]	*5*	*7*	*0.36*
High Idle	*7*	*5*	*3*	*5*	*0.42*	*6*	*10*	*7*	*8*	*0.27*
Dyn Brk	*4*	-[b]	*5*	*4*	*0.17*	*4*	*9*	-[b]	*7*	*0.54*
1	*7*	*4*	*3*	*5*	*0.38*	*3*	*2*	*9*	*5*	*0.81*
2	*5*	*4*	*5*	*5*	*0.11*	*5*	*1*	*7*	*4*	*0.72*
3	*3*	*3*	*3*	*3*	*0.09*	*3*	*5*	*5*	*4*	*0.25*
4	*5*	*4*	*6*	*5*	*0.25*	*4*	*2*	*6*	*4*	*0.48*
5	*5*	*4*	*11*	*7*	*0.57*	*5*	*8*	*4*	*6*	*0.35*
6	*2*	*4*	*6*	*4*	*0.43*	*1*	*6*	*3*	*3*	*0.71*
7	*5*	-[b]	*3*	*4*	*0.34*	*2*	-[b]	-[b]	*2*	-
8	*4*	*3*	*2*	*3*	*0.34*	*7*	*3*	*3*	*4*	*0.55*

**The values in italics are below the detection limit of the instrument (13 ppm for HC).*

Table E-11 Continued on next page.

Table E-11 Continued from previous page.

(d) NO concentration (ppm)[c]

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	204	198	-[b]	201	0.02	179	-[b]	160	170	0.08
High Idle	179	180	189	183	0.03	188	184	169	180	0.06
Dyn Brk	169	-[b]	182	175	0.05	189	169	-[b]	179	0.08
1	216	276	292	261	0.15	206	271	230	236	0.14
2	659	690	593	647	0.08	689	639	600	643	0.07
3	961	1058	919	980	0.07	1130	1049	1089	1089	0.04
4	1011	1094	1138	1081	0.06	1216	1052	1063	1111	0.08
5	1201	1390	1153	1248	0.10	1356	1284	1196	1279	0.06
6	1333	1439	1337	1370	0.04	1368	1248	1308	1308	0.05
7	1199	-[b]	1260	1230	0.04	915	-[b]	-[b]	915	-
8	1163	1087	1119	1123	0.03	1201	1053	1028	1094	0.09

(e) PM Concentration (mg/m^3)[c]

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	9.01	11.01	-[b]	10.01	0.14	10.81	-[b]	12.21	11.51	0.09
High Idle	8.00	9.60	11.20	9.60	0.17	9.60	9.80	10.20	9.87	0.03
Dyn Brk	6.93	-[b]	8.93	7.93	0.18	10.33	10.53	-[b]	10.43	0.01
1	8.52	8.92	11.32	9.59	0.16	9.12	9.92	10.32	9.79	0.06
2	8.83	10.63	11.03	10.17	0.12	10.03	10.43	10.23	10.23	0.02
3	9.83	10.43	12.83	11.03	0.14	12.23	11.23	11.23	11.57	0.05
4	10.14	10.54	12.14	10.94	0.10	12.34	13.34	12.54	12.74	0.04
5	8.84	10.64	11.84	10.44	0.14	10.04	11.84	10.24	10.71	0.09
6	10.11	10.71	12.71	11.17	0.12	12.31	13.31	13.71	13.11	0.06
7	15.80	-[b]	18.60	17.20	0.12	19.60	-[b]	-[b]	19.60	-
8	12.24	13.84	14.64	13.58	0.09	14.84	14.84	15.04	14.91	0.01

[a] *CV = coefficient of variation (standard deviation divided by mean)*
[b] *No steady-state data for the given notch position.*
[c] *HC, NO and PM concentrations reported are without bias corrections, as measured by Axion PEMS*
[d] *Measurements less than zero*

The steady-state notch-average NO concentrations for double-powered consist varied between 160 ppm at low idle and 1,368 ppm at notch 6. Notch-average NO concentrations for the single-powered consist between 180 ppm at high idle and 1,439 ppm at notch 6. Notch-average NO concentration typically increased with notch position from high idle through notch 6 for each consist. Notch-average NO concentrations were repeatable for a given notch position and operation based on inter-trip CV of 0.10 or lower for both consists, except at notch 1.

Notch 1 had the inter-trip CV of 0.15 and 0.14 for double- and single-powered consist, respectively. However, the measured average NO concentrations were low for notch 1 compared to higher notch positions. Measured notch-average NO concentrations were within 100 ppm for a given notch potion for double- versus single-powered consist, except at notch 7. However, the differences were not statistically significant. The large difference for notch 7 was likely an artifact of having relatively few seconds of steady-state data.

The steady-state notch-average PM concentrations for the double-powered consist varied from 10 $\mu g/m^3$ at high idle to 20 $\mu g/m^3$ at notch 8. The steady-state notch-average PM concentrations for single-powered consist varied between 7 $\mu g/m^3$ at dynamic brake and 19 $\mu g/m^3$ at notch 7. Notch-average PM concentrations typically increased with the notch position from high idle through notch 8, except at notch 7. Measured concentrations at notch 7 were typically based on limited amount of steady-state data, typically 10 seconds or fewer, and therefore have larger random sampling error for the mean value compared to other notches.

Steady-State Fuel Use and Emission Rates

The steady-state notch-average fuel use rate and emission rates of CO_2, CO, HC, NO_x and PM are summarized in Table E-12. The notch-average fuel use rate increased with increasing notch position for both double- and single-powered consists. Notch-average fuel use rates for a given notch position for low idle, high idle and notches 1 through 5 were within 4 percent for double- versus single-powered consist. Notch-average fuel use rates for a given notch position for notches 6 through 8 were 5 percent to 10 percent lower for double- versus single-powered consist. Measured CO_2 exhaust concentrations for these notch positions were typically 2 to 6 percent lower for double- versus single-powered consist, resulting in lower fuel flow rate for double-powered consist. At notch 8, the MAP for double-powered consist was 4 percent lower compared to single-powered consist whereas, RPM and IAT were within 0.5 percent of each other. As a result, the mass air flow rate at notch 8 for double-powered consist was 5 percent lower compared to single-powered consist, which resulted in a lower fuel use rate at notch 8. Notch-average fuel use rates were highly repeatable at a given notch position for both double- and single-powered consists, as indicated by the inter-trip CV of 0.08 or lower. Notch-average CO_2 emission rates have the same trend as fuel use rate. Notch-average CO_2 emission rates were also repeatable.

The notch-average CO emission rates for low idle through notch 6 were typically based on CO concentrations below the detection limit of Axion PEMS. Although the CVs for inter-trip variability in these rates were as high as 1.50, these emission rates were low. CO emission rates at notch 8 were highly repeatable for double- and single-powered consists with inter-trip CV of 0.07 and 0.05, respectively. Inter-trip variability in CO emission rates at notch 7 was due to few seconds of measured steady-state data.

TABLE E-12. Steady-state Notch-average Engine Output, Fuel Use and Emission Rates for Locomotive NC 1871 for Over-the-Rail Measurements of Push/Pull Train Consists Conducted between June 18 and June 20, 2019: (a) Double-powered; and (b) Single-powered: (a) fuel use rate; (b) CO_2 emission rate; (c) CO emission rate; (d) THC emission rate; (e) NO_x emission rate; and (f) PM emission rate.

(a) Mass per time-based fuel use rate (g/s)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	3	3	-[b]	3	0.06	2	-[b]	2	2	0.07
High Idle	3	3	3	3	0.03	3	3	3	3	0.07
Dyn Brk	6	-[b]	8	7	0.14	4	5	-[b]	4	0.03
1	3	4	4	4	0.11	3	3	3	3	0.08
2	15	16	13	15	0.08	14	15	14	14	0.03
3	28	28	27	27	0.03	28	28	28	28	0.01
4	47	46	49	47	0.04	46	45	45	45	0.01
5	58	58	54	57	0.04	55	56	54	55	0.02
6	83	83	85	84	0.01	79	72	80	77	0.06
7	117	-[b]	112	115	0.03	57	-[b]	-[b]	57	-
8	108	105	116	109	0.05	106	104	102	104	0.02

(b) Mass per time-based CO_2 emission rate (g/s)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	6	6	-[b]	6	0.00	6	-[b]	7	7	0.11
High Idle	9	9	9	9	0.02	8	9	9	9	0.08
Dyn Brk	20	-[b]	21	21	0.05	13	14	-[b]	14	0.04
1	11	11	13	12	0.10	9	10	10	10	0.08
2	48	48	41	46	0.09	44	46	43	44	0.03
3	87	88	82	85	0.03	88	87	89	88	0.01
4	145	142	153	147	0.04	143	140	140	141	0.01
5	180	182	168	177	0.04	173	174	169	172	0.02
6	259	258	264	260	0.01	248	224	249	240	0.06
7	363	-[b]	348	355	0.03	179	-[b]	-[b]	179	-
8	335	325	356	339	0.05	329	320	316	322	0.02

Table E-12 Continued on next page.

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(c) Mass per time-based CO emission rate (g/s)

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	*0.01*	*0.01*	-[b]	*0.01*	*0.00*	*0.01*	-[b]	*0.01*	*0.01*	*0.00*
High Idle	*0.01*	*0.01*	*0.00*	*0.01*	*0.43*	*0.00*	*0.01*	*0.01*	*0.01*	*0.40*
Dyn Brk	*0.02*	-[b]	*0.01*	*0.02*	*0.14*	*0.00*	*0.01*	-[b]	*0.01*	*0.47*
1	*0.01*	*0.02*	*0.01*	*0.01*	*0.33*	*0.01*	*0.01*	*0.01*	*0.01*	*0.30*
2	*0.02*	*0.01*	*0.05*	*0.03*	*0.71*	*0.00*	*0.03*	*0.00*	*0.01*	*1.34*
3	*0.02*	*0.02*	*0.08*	*0.04*	*0.83*	*0.00*	*0.06*	*0.00*	*0.02*	*1.50*
4	*0.05*	*0.11*	*0.12*	*0.10*	*0.38*	*0.07*	*0.08*	*0.02*	*0.06*	*0.58*
5	*0.08*	*0.15*	*0.03*	*0.09*	*0.67*	*0.02*	*0.08*	*0.02*	*0.04*	*0.86*
6	0.27	0.38	*0.22*	*0.29*	*0.28*	0.37	*0.18*	*0.17*	*0.24*	*0.46*
7	2.31	-[b]	1.90	2.10	0.14	2.22	-[b]	-[b]	2.22	-
8	1.51	1.61	1.73	1.62	0.07	1.72	1.87	1.87	1.82	0.05

Values in italics correspond to estimates based on concentrations below-detection limit

(d) Mass per time-based THC emission rate (g/s)[c]

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	*0.0*	*0.0*	-[b]	*0.0*	-	*0.0*	-[b]	*0.0*	*0.0*	-
High Idle	*0.0*	*0.0*	*0.6*	*0.2*	*1.4*	*0.2*	*0.1*	*0.0*	*0.1*	*0.6*
Dyn Brk	*0.0*	-[b]	*4.7*	*2.4*	*1.4*	*0.3*	*0.1*	-[b]	*0.2*	*0.9*
1	*0.0*	*0.0*	*0.4*	*0.2*	*1.4*	*0.1*	*0.1*	*0.1*	*0.1*	*0.2*
2	*0.0*	*0.0*	*1.1*	*0.4*	*1.5*	*0.3*	*0.9*	*0.1*	*0.4*	*1.0*
3	*0.0*	*0.0*	*1.1*	*0.4*	*1.6*	*0.1*	*0.1*	*0.1*	*0.1*	*0.4*
4	*0.1*	*0.1*	*1.2*	*0.4*	*1.4*	*0.1*	*0.6*	*0.1*	*0.3*	*1.2*
5	*0.1*	*0.1*	*1.6*	*0.6*	*1.5*	*0.1*	*0.2*	*0.1*	*0.1*	*0.3*
6	*0.1*	*0.1*	*2.3*	*0.8*	*1.6*	*0.0*	*0.8*	*0.1*	*0.3*	*1.5*
7	*0.1*	-[b]	*0.0*	*0.1*	*1.3*	*0.1*	-[b]	-[b]	*0.1*	-
8	*0.1*	*0.1*	*3.5*	*1.2*	*1.6*	*0.2*	*1.1*	*0.1*	*0.5*	*1.2*

Values in italics correspond to estimates based on concentrations below-detection limit

Table E-12 Continued on next page.

Table E-12 Continued from previous page.

(e) Mass per time-based NO_x emission rate (g/s)[c]

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	0.3	0.3	-[b]	0.3	0.00	0.2	-[b]	0.2	0.2	0.00
High Idle	0.3	0.3	0.3	0.3	0.06	0.3	0.3	0.3	0.3	0.06
Dyn Brk	0.4	-[b]	0.5	0.5	0.11	0.4	0.3	-[b]	0.4	0.11
1	0.3	0.4	0.5	0.4	0.16	0.3	0.4	0.3	0.4	0.14
2	1.4	1.4	1.3	1.4	0.06	1.4	1.3	1.2	1.3	0.08
3	2.6	2.8	2.6	2.7	0.05	3.1	2.8	2.9	2.9	0.04
4	4.0	4.3	4.6	4.3	0.07	4.8	4.2	4.2	4.4	0.08
5	5.0	5.7	5.0	5.2	0.08	5.7	5.4	5.0	5.4	0.07
6	6.6	7.1	6.9	6.9	0.03	6.7	6.3	6.5	6.5	0.04
7	6.8	-[b]	7.2	7.0	0.04	5.3	-[b]	-[b]	5.3	-
8	7.0	6.5	7.2	6.9	0.05	7.2	6.3	6.1	6.5	0.09

(f) Mass per time-based PM emission rate (g/s)[c]

Throttle Notch Position	Single-powered Consist					Double-powered Consist				
	18-Jun	19-Jun	20-Jun	3 Trips		18-Jun	19-Jun	20-Jun	3 Trips	
	Train 75	Train 75	Train 75	Avg	CV[a]	Train 76	Train 76	Train 76	Avg	CV[a]
Low Idle	0.03	0.04	-[b]	0.04	0.31	0.03	-[b]	0.03	0.03	0.00
High Idle	0.03	0.02	0.04	0.03	0.30	0.04	0.04	0.04	0.04	0.15
Dyn Brk	0.05	-[b]	0.06	0.06	0.25	0.06	0.05	-[b]	0.06	0.22
1	0.03	0.04	0.04	0.04	0.29	0.04	0.06	0.04	0.05	0.18
2	0.05	0.04	0.03	0.04	0.18	0.06	0.06	0.08	0.06	0.19
3	0.07	0.08	0.10	0.08	0.19	0.07	0.08	0.10	0.08	0.16
4	0.10	0.14	0.11	0.12	0.17	0.11	0.17	0.11	0.13	0.31
5	0.10	0.08	0.07	0.08	0.19	0.11	0.19	0.16	0.15	0.23
6	0.13	0.18	0.13	0.14	0.28	0.14	0.09	0.11	0.12	0.16
7	0.23	-[b]	0.28	0.26	0.14	0.16	-[b]	-[b]	0.16	-
8	0.19	0.15	0.10	0.15	0.31	0.21	0.25	0.27	0.24	0.13

[a] *CV = coefficient of variation (standard deviation divided by mean)*

[b] *No steady-state data for the given notch position.*

[c] *HC emission rates estimated with Axion PEMS-measured HC concentrations have been multiplied with a correction factor shown in Table 8 to obtain THC emission rates. NO emission rates estimated with Axion PEMS-measured NO concentrations have been multiplied with a correction factor shown in Table 8 to obtain NO_x emission rates. PM emission rates estimated with Axion PEMS-measured PM concentrations have been multiplied with a correction factor of 5 to obtain PM emission rates.*

[d] *Measurements less than zero*

[e] *Invalid measurements: PM sensor failed. Concentrations were extremely low compared to other measurements*

Notch-average HC emission rates were based on average HC concentrations below the detection limit of the PEMS for all notches and all trips, resulting in large variability. However, emission rates were low. The notch-average NO_x emission rates increased monotonically from idle through notch 7 for both double- and single-powered consists. NO_x emission rates for notches 6 through 8 were 5 percent to 10 percent lower for double- versus single-powered consist. Notch-average NO_x emission rates were repeatable at a given notch position for both double- and single-powered consists based on inter-trip CV of 0.09 or lower except for dynamic brake and notch 1, which have low NO_x emission rates. The inter-trip CV for a given notch position was 0.16 or lower for each position and for the double- and single-powered consist.

The notch-average PM emission rates increased monotonically from idle through notch 7 for both double- and single-powered consists. For a given notch position for notches low idle through notch 6, notch-average PM emission rates were within 5 percent of each other for the double- versus single-powered consist. For notch 8, PM emission rates for the double-powered consist were 60 percent higher than a single-powered consist. The inter-trip CVs for a given notch position for the double-powered consist were 0.20 or lower for 7 of the 11 notch positions. The inter-trip CVs for the single-powered consist were 0.20 or lower for 5 of the 11 notch positions.

The steady-state notch-average NO_x emission rates varied from 0.2 g/s at low idle to 10.0 g/s at notch 7. Notch-average NO_x emission rates increased monotonically from low idle through notch 7. The average NO_x emission rate was 8.4 g/s at notch 8. The inter-trip CV of notch-average NO_x emission rates for a given notch position were 0.20 or lower for each notch position. Thus, these measurements were repeatable. The steady-state notch-average PM emission rates varied from 0.02 g/s at low idle to 0.22 g/s at notch 7. Notch-average PM emission rates increased monotonically from low idle through notch 7. The average PM emission rate was 0.15 g/s at notch 8. The inter-trip CV of notch-average PM emission rates for a given notch position were 0.20 or lower for each notch position. Thus, these measurements were repeatable.

The steady-state notch-average fuel use rate varied from 2 g/s at low idle to 105 g/s at notch 8. Notch-average fuel use rate increased monotonically from low idle through notch 8. The inter-trip CV of notch-average fuel use rates for a given notch position were 0.21 or lower for each notch position. Thus, these measurements were repeatable. Notch-average CO_2 emission rates varied from 6 g/s at low idle to 328 g/s at notch 8. Notch-average CO_2 emission rates had similar trends as fuel use rate. For the single-powered consist, the fuel use rate at notch 8 was 10 percent higher compared to the fuel use rate at notch 8 for the double-powered consist.

The notch-average CO and HC emission rates for the single-powered consist for a given notch position were not statistically significantly different than for the double-powered consist. Notch-average NO_x and PM emission rates for the single-powered consist for a given notch position were not statistically significantly different than for the double-powered consist, except at notch 8. At notch 8, NO_x and PM emission rates for the single-powered consist were higher than the double-powered consist due to higher measured concentrations and exhaust flow rate. Measured exhaust concentrations and FUER were 5 percent to 10 percent lower at notch 8 for the double-powered versus single-powered consist. Operators typically spent the highest or the second highest percentage of time in notch 8 and notch 8 has the highest fuel use rate versus all notch positions.

References

Graver, B.M., Frey, H., 2013. Comparison of Locomotive Emissions Measured During Dynamometer Versus Rail Yard Engine Load Tests. Transp. Res. Rec. J. Transp. Res. Board 23–33.

Hay, W.W., 1982. Railroad engineering. John Wiley & Sons.

Appendix F. Locomotive Power Demand Model

In this Appendix, fuel use and emission rates (FUER) for the Head End Power (HEP) engines and calibration and validation parameters with and without lagged error terms for each locomotive, consist and fuel are presented.

FUER for HEP engines of six of the eight NCDOT locomotives were measured in prior work. FUER were measured based on rail yard measurements. These locomotives include the two F59PHI locomotives, and four F59PH locomotives with mechanically-governed fuel injection. HEP engine FUER for the two F59PH locomotives with electronically governed fuel injection have not been quantified yet. Therefore, for these two locomotives, HEP engine FUER were assumed to be the average FUER based on other six NCDOT locomotives. HEP engine FUER for locomotives operated on ultra-low sulfur diesel (ULSD) and B20 biodiesel are given in Tables F-1 and F-2, respectively.

For autocorrelated data with autocorrelated errors, such as the LPD model data, the data can be well-described by a model that accounts for autocorrelation. Such models are time series models that are calibrated based on past data. Such models are useful for predicting FUER for the remainder of a trajectory for which FUER are known for an initial part of the trajectory. These models cannot be applied to a completely different trajectory for which FUER are not known for any part. To predict FUER for any given trajectory, LPD models were calibrated without the lagged error terms. The estimated coefficients and diagnostic parameters in such a case would be biased. The order of lagged error term and weighting parameters are estimated in the next section. The extent of bias, if any, in models without lagged errors is quantified by comparison to models with lagged errors.

F.1 Lagged Error Terms

The order of the lagged error term is equal to the lag at which the autocorrelation coefficient drops to zero (Box *et al.*, 2015). The weighting parameter(s) of the lagged error term are estimated based on the relationship with autocorrelation as given in Equation 5-20.

The autocorrelation among residual errors and the weighting parameters for fuel use rate based on all one-way trips conducted for the single-locomotive consist with locomotive NC 1859 operated on ULSD are presented in Table F-3. At zero lag, the autocorrelation is always 1. For increasing lag, the autocorrelation drops to 0.05 at a lag of 5 seconds. Beyond 5 seconds, the autocorrelation was not statistically significantly different from zero. Therefore, the order of the lagged error terms was determined to be 5. Weighting parameters for the lagged error terms varied between 0.92 at a lag of 1 second to 0.12 at a lag of 5 seconds and decreased monotonically. Each of the weighting parameter was positive and the sum of all the parameters was greater than one. Therefore, this sum of all lagged error terms was typically greater than any individual lagged error term. Similar autocorrelations and weighting parameters were estimated for emission rates and for other combinations of locomotives, consist, and fuels.

To compare the distribution of residual errors with and without lagged error terms, histogram plots of the residual errors in fuel use rate for the single-locomotive consist with locomotive NC 1859 operated on ULSD are compared in Figure F-1. The residual errors for the model with the lagged errors are normally distributed and centered around zero. Thus, the residual errors for the model with lagged error terms resembles white noise. For the model without lagged error terms, the residuals were neither normally distributed nor centered around zero. Thus, statistically, models with lagged error terms are more appropriate models to describe autocorrelated data, but are not useful for making predictions.

F.2 Model Calibration

The calibrated model parameters with and without error terms are given in this section.

F.2.1 With Lagged Error Terms

The calibration parameters and diagnostic statistics for each leave-one-out (LOO) cross-validation case, and for the final model with the lagged error terms for 12 combinations of locomotive, consist, and fuel are given in Tables F-4 through F-15.

F.2.2 Without Lagged Error Terms

The calibration parameters and diagnostic statistics for each LOO cross-validation case, and for the final model without the lagged error terms for 11 combinations of locomotive, consist, and fuel are given Tables F-16 through F-26. The calibration parameters and diagnostic statistics for each LOO cross-validation case, and for the final model without the lagged error terms for the single-locomotive consist with NC 1859 operated on ULSD were given in Table 5-6.

F.3 Model Validation

The validation model parameters with and without error terms are given in this section.

F.3.1 With Lagged Error Terms

The validation parameters and diagnostic statistics for each leave-one-out (LOO) cross-validation case, and for the final model with the lagged error terms for 12 combinations of locomotive, consist, and fuel are given in Tables F-27 through F-38.

F.3.2 Without Lagged Error Terms

The validation parameters and diagnostic statistics for each LOO cross-validation case, and for the final model without the lagged error terms for 11 combinations of locomotive, consist, and fuel are given Tables F-39 through F-49. The calibration parameters and diagnostic statistics for each LOO cross-validation case, and for the final model without the lagged error terms for the single-locomotive consist with NC 1859 operated on ULSD were given in Table 5-7.

TABLE F-1. Fuel Use and Emission Rates versus Engine Output of the Head End Power Engines of the NCDOT Locomotives operated on Ultra-low Sulfur Diesel based on Rail Yard Measurements

Locomotive	Engine Output (hp)	Fuel Use and Emission Rates (g/s)					
		Fuel Use Rate	CO_2 Emission Rate	CO Emission Rate	HC Emission Rate	NO_x Emission Rate	PM Emission Rate
NC 1755	83	5.7	20	0.071	0.021	0.22	0.014
	126	7.8	24	0.026	0.018	0.25	0.015
	349	18.4	64	0.003	0.028	0.43	0.041
	532	24.9	85	0.000	0.028	0.61	0.033
	692	32.7	111	0.005	0.040	1.04	0.042
NC 1797	83	5.8	21	0.058	0.030	0.20	0.015
	158	9.7	32	0.022	0.034	0.34	0.021
	378	18.8	60	0.008	0.057	0.40	0.033
	544	23.5	71	0.002	0.062	0.66	0.024
	742	32.9	118	0.045	0.070	1.09	0.035
NC 1893	73	5.9	18	0.073	0.015	0.21	0.014
	115	6.9	21	0.022	0.007	0.21	0.016
	341	17.8	56	0.005	0.011	0.38	0.033
	525	24.4	80	0.000	0.012	0.51	0.029
	688	32.5	106	0.001	0.013	0.92	0.032
NC 1810	132	5.4	17	0.044	0.024	0.21	0.019
	197	10.1	32	0.022	0.026	0.41	0.020
	391	20.3	63	0.004	0.037	0.49	0.036
	529	24.6	84	0.003	0.043	0.84	0.034
	698	33.7	112	0.023	0.035	1.30	0.062
NC 1859	129	5.5	17	0.072	0.033	0.22	0.011
	157	7.4	26	0.026	0.024	0.27	0.011
	344	16.5	52	0.007	0.041	0.41	0.019
	480	21.7	70	0.005	0.052	0.57	0.020
	612	29.7	98	0.022	0.077	1.00	0.032
NC 1869	114	5.9	19	0.070	0.023	0.20	0.013
	168	8.5	28	0.021	0.018	0.27	0.015
	359	17.8	62	0.002	0.032	0.38	0.024
	516	23.7	73	0.000	0.040	0.65	0.022
	692	33.4	115	0.006	0.037	1.06	0.033
NC 1871 and NC 1984[a]	102	5.7	19	0.065	0.024	0.21	0.014
	154	8.4	27	0.023	0.021	0.29	0.016
	360	18.3	60	0.005	0.034	0.41	0.031
	521	23.8	77	0.002	0.039	0.64	0.027
	687	32.5	110	0.017	0.045	1.07	0.039

[a] *FUER for HEP engines of locomotives NC 1871 and NC 1984 are not measured yet. Therefore, FUER and engine output for these locomotives were assumed as average of other locomotives for which HEP engine FUER were measured.*

TABLE F-2. Fuel Use and Emission Rates versus Engine Output of the Head End Power Engines of the NCDOT Locomotives operated on B20 Biodiesel based on Rail Yard Measurements

Locomotive	Engine Output (hp)	Fuel Use and Emission Rates (g/s)					
		Fuel Use Rate	CO_2 Emission Rate	CO Emission Rate	HC Emission Rate	NO_x Emission Rate	PM Emission Rate
NC 1755	81	5.8	21	0.043	0.036	0.17	0.013
	148	9.7	31	0.011	0.033	0.27	0.015
	358	19.3	59	0.003	0.051	0.38	0.021
	540	25.7	79	0.000	0.042	0.53	0.026
	713	34.3	116	0.032	0.053	0.93	0.038
NC 1797	78	6.0	20	0.056	0.025	0.18	0.011
	160	9.9	30	0.018	0.030	0.33	0.015
	383	19.4	65	0.008	0.045	0.38	0.021
	553	24.4	79	0.009	0.037	0.61	0.015
	770	34.8	111	0.190	0.036	0.98	0.028
NC 1893	70	6.0	20	0.051	0.025	0.19	0.014
	138	8.9	32	0.015	0.020	0.28	0.021
	337	17.7	58	0.009	0.035	0.40	0.033
	530	25.1	85	0.006	0.032	0.56	0.034
	701	33.6	105	0.011	0.033	1.01	0.043
NC 1810	125	5.7	19	0.045	0.016	0.18	0.010
	195	10.2	36	0.016	0.018	0.35	0.015
	383	20.0	65	0.006	0.024	0.40	0.026
	524	24.6	86	0.007	0.020	0.68	0.022
	705	34.7	107	0.027	0.024	1.12	0.029
NC 1859	123	5.7	18	0.062	0.029	0.22	0.009
	151	6.9	22	0.016	0.024	0.26	0.009
	348	17.2	59	0.003	0.039	0.42	0.015
	484	22.1	73	0.004	0.044	0.58	0.015
	624	30.6	104	0.028	0.066	1.01	0.023
NC 1869	109	6.1	21	0.058	0.014	0.20	0.010
	184	9.9	30	0.025	0.010	0.37	0.011
	365	18.5	65	0.011	0.015	0.43	0.017
	520	24.3	87	0.003	0.014	0.72	0.016
	701	34.4	118	0.015	0.014	1.19	0.029
NC 1871 and NC 1984[a]	98	5.9	20	0.052	0.024	0.19	0.011
	163	9.3	30	0.017	0.023	0.31	0.014
	362	18.7	62	0.007	0.035	0.40	0.022
	525	24.4	81	0.005	0.032	0.61	0.021
	702	33.7	110	0.051	0.038	1.04	0.032

[a] *FUER for HEP engines of locomotives NC 1871 and NC 1984 are not measured yet. Therefore, FUER and engine output for these locomotives were assumed as average of other locomotives for which HEP engine FUER were measured.*

TABLE F-3. Autocorrelation and Weighting Parameters for the Lagged Error Terms of the Locomotive Power Demand Model for Fuel Use Rate based on All One-way Trips conducted for the Single-Locomotive Consist with Locomotive NC 1859 operated on Ultra-Low Sulfur Diesel.

Lag (s)	Autocorrelation	Weighting Parameter
0	1.00	-
1	0.81	0.92
2	0.65	0.76
3	0.32	0.65
4	0.21	0.22
5	0.05	0.12

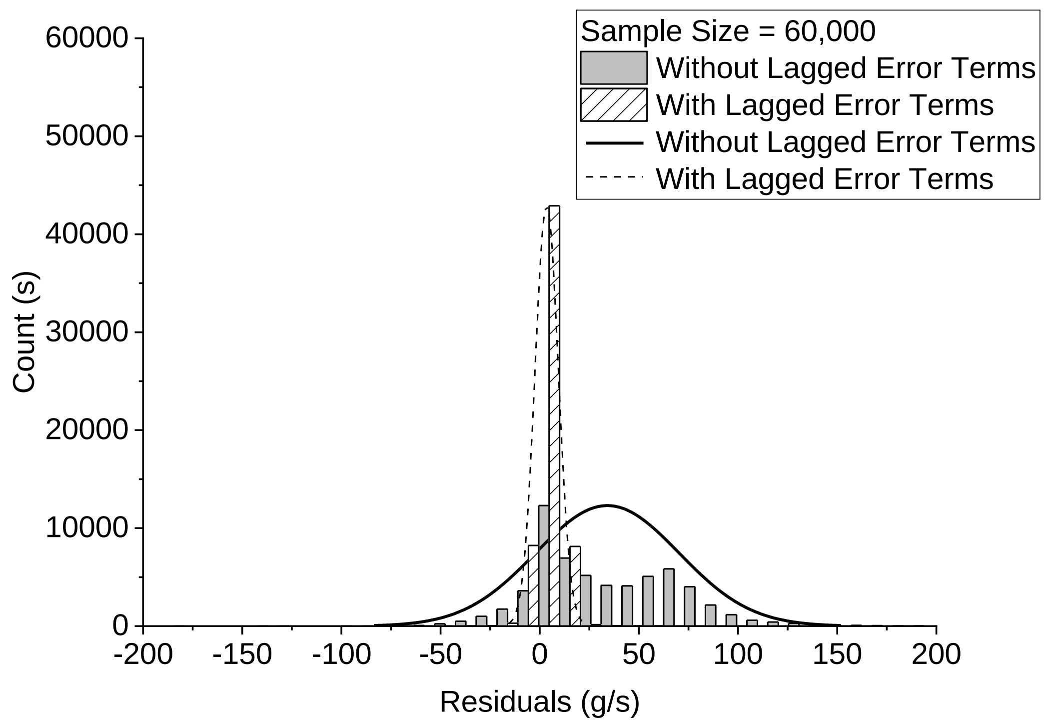

FIGURE F-1. Comparison of the Distribution of the Residual Errors for an Example Case of the Locomotive Power Demand Model Calibrated With and Without Lagged Error Terms for Fuel Use Rate for a Single-Locomotive Consist with NC 1859 operated on Ultra-Low Sulfur Diesel.

TABLE F-4. Calibrated Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1859 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.029	[0.028, 0.029]	0.000069	0.75
	1,3,4,5,6	2	0.029	[0.029, 0.029]	0.000066	0.78
	1,2,4,5,6	3	0.029	[0.029, 0.030]	0.000073	0.77
	1,2,3,5,6	4	0.028	[0.028, 0.029]	0.000067	0.79
	1,2,3,4,6	5	0.029	[0.029, 0.030]	0.000065	0.79
	1,2,3,4,5	6	0.029	[0.029, 0.029]	0.000063	0.77
	Final Model		0.029	[0.029, 0.029]	0.000067	0.77
CO_2 Emission Rate	2,3,4,5,6	1	0.089	[0.088, 0.090]	0.00022	0.75
	1,3,4,5,6	2	0.092	[0.091, 0.093]	0.00023	0.80
	1,2,4,5,6	3	0.089	[0.088, 0.090]	0.00021	0.81
	1,2,3,5,6	4	0.094	[0.093, 0.095]	0.00020	0.81
	1,2,3,4,6	5	0.091	[0.090, 0.092]	0.00021	0.78
	1,2,3,4,5	6	0.092	[0.091, 0.093]	0.00022	0.77
	Final Model		0.091	[0.090, 0.092]	0.00022	0.78
CO Emission Rate	2,3,4,5,6	1	0.00010	[0.00010, 0.00011]	0.00000076	0.47
	1,3,4,5,6	2	0.00011	[0.00011, 0.00011]	0.00000078	0.49
	1,2,4,5,6	3	0.00010	[0.00010, 0.00011]	0.00000076	0.48
	1,2,3,5,6	4	0.00011	[0.00011, 0.00011]	0.00000072	0.49
	1,2,3,4,6	5	0.00011	[0.00011, 0.00011]	0.00000070	0.49
	1,2,3,4,5	6	0.00010	[0.00011, 0.00011]	0.00000071	0.46
	Final Model		0.00011	[0.00011, 0.00011]	0.00000074	0.48

The LPD model was calibrated based on Equation 5-19.

Table F-4 Continued on next page.

Table F-4 Continued from previous page.

<table>
<tr><th>Species</th><th>Calibration Trips</th><th>Validation Trip</th><th>Proportionality Constant (g/kW)</th><th>95 % Confidence Interval (g/kW)</th><th>Standard Error in Proportionality Constant (g/kW)</th><th>Goodness of Fit (R²)</th></tr>
<tr><td rowspan="7">HC Emission Rate</td><td>2,3,4,5,6</td><td>1</td><td>0.000038</td><td>[0.000036, 0.000040]</td><td>0.0000025</td><td>0.06</td></tr>
<tr><td>1,3,4,5,6</td><td>2</td><td>0.000030</td><td>[0.000029, 0.000031]</td><td>0.0000023</td><td>0.05</td></tr>
<tr><td>1,2,4,5,6</td><td>3</td><td>0.000034</td><td>[0.000033, 0.000036]</td><td>0.0000026</td><td>0.06</td></tr>
<tr><td>1,2,3,5,6</td><td>4</td><td>0.000031</td><td>[0.000030, 0.000033]</td><td>0.0000025</td><td>0.06</td></tr>
<tr><td>1,2,3,4,6</td><td>5</td><td>0.000037</td><td>[0.000036, 0.000039]</td><td>0.0000025</td><td>0.06</td></tr>
<tr><td>1,2,3,4,5</td><td>6</td><td>0.000029</td><td>[0.000028, 0.000031]</td><td>0.0000024</td><td>0.04</td></tr>
<tr><td colspan="2">Final Model</td><td>0.000033</td><td>[0.000032, 0.000035]</td><td>0.0000025</td><td>0.05</td></tr>
<tr><td rowspan="7">NO_x Emission Rate</td><td>2,3,4,5,6</td><td>1</td><td>0.0016</td><td>[0.0016, 0.0016]</td><td>0.0000075</td><td>0.86</td></tr>
<tr><td>1,3,4,5,6</td><td>2</td><td>0.0015</td><td>[0.0015, 0.0015]</td><td>0.0000076</td><td>0.85</td></tr>
<tr><td>1,2,4,5,6</td><td>3</td><td>0.0015</td><td>[0.0015, 0.0015]</td><td>0.0000074</td><td>0.86</td></tr>
<tr><td>1,2,3,5,6</td><td>4</td><td>0.0015</td><td>[0.0015, 0.0015]</td><td>0.0000074</td><td>0.85</td></tr>
<tr><td>1,2,3,4,6</td><td>5</td><td>0.0016</td><td>[0.0016, 0.0016]</td><td>0.0000073</td><td>0.85</td></tr>
<tr><td>1,2,3,4,5</td><td>6</td><td>0.0015</td><td>[0.0015, 0.0015]</td><td>0.0000075</td><td>0.84</td></tr>
<tr><td colspan="2">Final Model</td><td>0.0016</td><td>[0.0015, 0.0016]</td><td>0.0000074</td><td>0.85</td></tr>
<tr><td rowspan="7">PM Emission Rate</td><td>2,3,4,5,6</td><td>1</td><td>0.000048</td><td>[0.000047, 0.000047]</td><td>0.00000013</td><td>0.59</td></tr>
<tr><td>1,3,4,5,6</td><td>2</td><td>0.000049</td><td>[0.000048, 0.000049]</td><td>0.00000014</td><td>0.59</td></tr>
<tr><td>1,2,4,5,6</td><td>3</td><td>0.000048</td><td>[0.000047, 0.000048]</td><td>0.00000009</td><td>0.59</td></tr>
<tr><td>1,2,3,5,6</td><td>4</td><td>0.000048</td><td>[0.000047, 0.000048]</td><td>0.00000012</td><td>0.58</td></tr>
<tr><td>1,2,3,4,6</td><td>5</td><td>0.000046</td><td>[0.000045, 0.000046]</td><td>0.00000000</td><td>0.56</td></tr>
<tr><td>1,2,3,4,5</td><td>6</td><td>0.000044</td><td>[0.000043, 0.000044]</td><td>0.00000000</td><td>0.56</td></tr>
<tr><td colspan="2">Final Model</td><td>0.000047</td><td>[0.000046, 0.000047]</td><td>0.00000008</td><td>0.58</td></tr>
</table>

TABLE F-5. Calibrated Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1797 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5	1	0.035	[0.035, 0.035]	0.000075	0.88
	1,3,4,5	2	0.033	[0.032, 0.033]	0.000073	0.88
	1,2,4,5	3	0.034	[0.033, 0.034]	0.000078	0.87
	1,2,3,5	4	0.034	[0.034, 0.034]	0.000074	0.88
	1,2,3,4	5	0.032	[0.031, 0.032]	0.000069	0.88
	Final Model		0.034	[0.033, 0.033]	0.000074	0.88
CO_2 Emission Rate	2,3,4,5	1	0.112	[0.111, 0.112]	0.00024	0.88
	1,3,4,5	2	0.105	[0.104, 0.105]	0.00023	0.88
	1,2,4,5	3	0.108	[0.107, 0.108]	0.00025	0.87
	1,2,3,5	4	0.109	[0.108, 0.109]	0.00023	0.88
	1,2,3,4	5	0.101	[0.101, 0.101]	0.00022	0.88
	Final Model		0.107	[0.106, 0.107]	0.000234	0.88
CO Emission Rate	2,3,4,5	1	0.000153	[0.000151, 0.000155]	0.00000081	0.56
	1,3,4,5	2	0.000127	[0.000126, 0.000128]	0.00000074	0.51
	1,2,4,5	3	0.000150	[0.000149, 0.000152]	0.00000083	0.54
	1,2,3,5	4	0.000131	[0.000129, 0.000132]	0.00000083	0.46
	1,2,3,4	5	0.000134	[0.000132, 0.000136]	0.00000080	0.50
	Final Model		0.000139	[0.000137, 0.000141]	0.00000080	0.51

The LPD model was calibrated based on Equation 5-19.

Table F-5 Continued on next page.

Table F-5 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5	1	0.000131	[0.000125, 0.000136]	0.00000272	0.07
	1,3,4,5	2	0.000080	[0.000075, 0.000085]	0.00000244	0.04
	1,2,4,5	3	0.000137	[0.000132, 0.000143]	0.00000279	0.08
	1,2,3,5	4	0.000082	[0.000077, 0.000088]	0.00000274	0.03
	1,2,3,4	5	0.000126	[0.000121, 0.000131]	0.00000267	0.07
	Final Model		0.000111	[0.000106, 0.000117]	0.00000267	0.06
NO_x Emission Rate	2,3,4,5	1	0.0024	[0.0023, 0.0024]	0.0000082	0.75
	1,3,4,5	2	0.0023	[0.0022, 0.0023]	0.0000080	0.74
	1,2,4,5	3	0.0024	[0.0023, 0.0024]	0.0000084	0.74
	1,2,3,5	4	0.0024	[0.0024, 0.0024]	0.0000080	0.76
	1,2,3,4	5	0.0023	[0.0022, 0.0022]	0.0000082	0.73
	Final Model		0.0024	[0.0023, 0.0023]	0.0000081	0.75
PM Emission Rate	2,3,4,5	1	0.000028	[0.000027, 0.000028]	0.000000141	0.58
	1,3,4,5	2	0.000029	[0.000028, 0.000029]	0.000000139	0.60
	1,2,4,5	3	0.000030	[0.000029, 0.000030]	0.000000146	0.59
	1,2,3,5	4	0.000031	[0.000030, 0.000031]	0.000000146	0.61
	1,2,3,4	5	0.000028	[0.000028, 0.000028]	0.000000096	0.75
	Final Model		0.000029	[0.000028, 0.000029]	0.000000134	0.63

TABLE F-6. Calibrated Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1810 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.029	[0.029, 0.029]	0.000070	0.85
	1,3,4,5,6	2	0.029	[0.028, 0.029]	0.000073	0.83
	1,2,4,5,6	3	0.028	[0.027, 0.028]	0.000071	0.84
	1,2,3,5,6	4	0.028	[0.027, 0.028]	0.000072	0.83
	1,2,3,4,6	5	0.029	[0.028, 0.028]	0.000077	0.82
	1,2,3,4,5	6	0.028	[0.028, 0.028]	0.000076	0.82
	Final Model		0.029	[0.028, 0.028]	0.000073	0.83
CO_2 Emission Rate	2,3,4,5,6	1	0.093	[0.092, 0.093]	0.00022	0.85
	1,3,4,5,6	2	0.092	[0.091, 0.092]	0.00023	0.84
	1,2,4,5,6	3	0.089	[0.088, 0.089]	0.00023	0.84
	1,2,3,5,6	4	0.088	[0.087, 0.088]	0.00023	0.83
	1,2,3,4,6	5	0.090	[0.090, 0.090]	0.00024	0.82
	1,2,3,4,5	6	0.090	[0.089, 0.090]	0.00024	0.82
	Final Model		0.090	[0.089, 0.090]	0.00023	0.83
CO Emission Rate	2,3,4,5,6	1	0.000280	[0.000277, 0.000283]	0.00000147	0.55
	1,3,4,5,6	2	0.000266	[0.000264, 0.000269]	0.00000141	0.53
	1,2,4,5,6	3	0.000278	[0.000275, 0.000281]	0.00000150	0.54
	1,2,3,5,6	4	0.000254	[0.000251, 0.000257]	0.00000138	0.53
	1,2,3,4,6	5	0.000278	[0.000275, 0.000281]	0.00000154	0.52
	1,2,3,4,5	6	0.000254	[0.000252, 0.000257]	0.00000139	0.53
	Final Model		0.000268	[0.000266, 0.000271]	0.00000145	0.53

Table F-6 Continued on next page.

Table F-6 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.000245	[0.000241, 0.000250]	0.00000219	0.30
	1,3,4,5,6	2	0.000191	[0.000187, 0.000195]	0.00000202	0.22
	1,2,4,5,6	3	0.000229	[0.000225, 0.000233]	0.00000215	0.27
	1,2,3,5,6	4	0.000195	[0.000191, 0.000199]	0.00000192	0.26
	1,2,3,4,6	5	0.000234	[0.000230, 0.000239]	0.00000224	0.27
	1,2,3,4,5	6	0.000171	[0.000167, 0.000175]	0.00000189	0.21
	Final Model		0.000211	[0.000207, 0.000215]	0.00000207	0.26
NO_x Emission Rate	2,3,4,5,6	1	0.0011	[0.0011, 0.0011]	0.0000027	0.85
	1,3,4,5,6	2	0.0011	[0.0011, 0.0011]	0.0000028	0.84
	1,2,4,5,6	3	0.0011	[0.0010, 0.0010]	0.0000027	0.84
	1,2,3,5,6	4	0.0011	[0.0010, 0.0010]	0.0000028	0.83
	1,2,3,4,6	5	0.0011	[0.0010, 0.0011]	0.0000029	0.83
	1,2,3,4,5	6	0.0011	[0.0010, 0.0011]	0.0000029	0.83
	Final Model		0.0011	[0.0010, 0.0011]	0.0000028	0.84
PM Emission Rate	2,3,4,5,6	1	0.000067	[0.000066, 0.000067]	0.00000025	0.69
	1,3,4,5,6	2	0.000066	[0.000065, 0.000066]	0.00000027	0.65
	1,2,4,5,6	3	0.000067	[0.000066, 0.000067]	0.00000026	0.68
	1,2,3,5,6	4	0.000066	[0.000065, 0.000066]	0.00000027	0.66
	1,2,3,4,6	5	0.000067	[0.000066, 0.000067]	0.00000027	0.67
	1,2,3,4,5	6	0.000065	[0.000064, 0.000065]	0.00000028	0.64
	Final Model		0.000066	[0.000065, 0.000066]	0.00000027	0.67

TABLE F-7. Calibrated Locomotive Power Demand Model Parameters with Lagged Error Terms for the Tandem-Locomotive Consist with Locomotive NC 1859 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5	1	0.026	[0.026, 0.026]	0.000077	0.82
	1,3,4,5	2	0.027	[0.026, 0.026]	0.000076	0.83
	1,2,4,5	3	0.027	[0.026, 0.026]	0.000069	0.85
	1,2,3,5	4	0.027	[0.026, 0.026]	0.000070	0.85
	1,2,3,4	5	0.027	[0.027, 0.027]	0.000065	0.87
	Final Model		0.027	[0.026, 0.026]	0.000072	0.84
CO_2 Emission Rate	2,3,4,5	1	0.083	[0.082, 0.083]	0.00024	0.82
	1,3,4,5	2	0.085	[0.084, 0.085]	0.00024	0.83
	1,2,4,5	3	0.085	[0.084, 0.085]	0.00022	0.85
	1,2,3,5	4	0.085	[0.084, 0.085]	0.00022	0.85
	1,2,3,4	5	0.087	[0.086, 0.087]	0.00021	0.87
	Final Model		0.085	[0.084, 0.085]	0.00022	0.84
CO Emission Rate	2,3,4,5	1	0.000098	[0.000097, 0.000100]	0.00000057	0.53
	1,3,4,5	2	0.000102	[0.000101, 0.000103]	0.00000053	0.59
	1,2,4,5	3	0.000094	[0.000092, 0.000095]	0.00000057	0.51
	1,2,3,5	4	0.000098	[0.000097, 0.000099]	0.00000058	0.53
	1,2,3,4	5	0.000094	[0.000093, 0.000095]	0.00000057	0.52
	Final Model		0.000097	[0.000096, 0.000098]	0.00000056	0.54

Table F-7 Continued on next page.

Table F-7 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5	1	0.000023	[0.000022, 0.000024]	0.00000050	0.08
	1,3,4,5	2	0.000024	[0.000023, 0.000024]	0.00000043	0.10
	1,2,4,5	3	0.000022	[0.000021, 0.000023]	0.00000037	0.12
	1,2,3,5	4	0.000027	[0.000026, 0.000028]	0.00000050	0.10
	1,2,3,4	5	0.000027	[0.000026, 0.000028]	0.00000050	0.10
	Final Model		0.000025	[0.000024, 0.000025]	0.00000046	0.10
NO_x Emission Rate	2,3,4,5	1	0.0013	[0.0013, 0.0013]	0.0000042	0.79
	1,3,4,5	2	0.0013	[0.0013, 0.0013]	0.0000042	0.80
	1,2,4,5	3	0.0014	[0.0014, 0.0014]	0.0000040	0.83
	1,2,3,5	4	0.0014	[0.0013, 0.0013]	0.0000040	0.82
	1,2,3,4	5	0.0014	[0.0014, 0.0014]	0.0000039	0.84
	Final Model		0.0014	[0.0013, 0.0013]	0.0000041	0.82
PM Emission Rate	2,3,4,5	1	0.000035	[0.000035, 0.000035]	0.00000011	0.80
	1,3,4,5	2	0.000038	[0.000038, 0.000038]	0.00000012	0.78
	1,2,4,5	3	0.000039	[0.000039, 0.000039]	0.00000012	0.78
	1,2,3,5	4	0.000039	[0.000038, 0.000039]	0.00000012	0.79
	1,2,3,4	5	0.000039	[0.000039, 0.000039]	0.00000011	0.81
	Final Model		0.000038	[0.000037, 0.000038]	0.00000012	0.79

TABLE F-8. Calibrated Locomotive Power Demand Model Parameters with Lagged Error Terms for the Single-Locomotive Consist with Locomotive NC 1893 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.027	[0.026, 0.026]	0.000059	0.87
	1,3,4,5,6	2	0.025	[0.024, 0.025]	0.000061	0.85
	1,2,4,5,6	3	0.026	[0.026, 0.026]	0.000060	0.87
	1,2,3,5,6	4	0.025	[0.025, 0.025]	0.000056	0.86
	1,2,3,4,6	5	0.025	[0.025, 0.025]	0.000061	0.86
	1,2,3,4,5	6	0.024	[0.024, 0.024]	0.000059	0.85
	Final Model		0.025	[0.025, 0.025]	0.000059	0.86
CO_2 Emission Rate	2,3,4,5,6	1	0.085	[0.085, 0.085]	0.00019	0.87
	1,3,4,5,6	2	0.080	[0.079, 0.080]	0.00020	0.85
	1,2,4,5,6	3	0.085	[0.084, 0.085]	0.00019	0.87
	1,2,3,5,6	4	0.080	[0.080, 0.080]	0.00018	0.86
	1,2,3,4,6	5	0.081	[0.080, 0.081]	0.00019	0.86
	1,2,3,4,5	6	0.077	[0.077, 0.077]	0.00019	0.85
	Final Model		0.082	[0.081, 0.081]	0.00019	0.86
CO Emission Rate	2,3,4,5,6	1	0.000065	[0.000064, 0.000066]	0.00000028	0.64
	1,3,4,5,6	2	0.000066	[0.000066, 0.000067]	0.00000028	0.64
	1,2,4,5,6	3	0.000066	[0.000066, 0.000067]	0.00000028	0.66
	1,2,3,5,6	4	0.000063	[0.000063, 0.000064]	0.00000025	0.66
	1,2,3,4,6	5	0.000064	[0.000063, 0.000065]	0.00000028	0.64
	1,2,3,4,5	6	0.000069	[0.000069, 0.000070]	0.00000028	0.68
	Final Model		0.000066	[0.000065, 0.000066]	0.00000028	0.65

Table F-8 Continued on next page.

Table F-8 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.000019	[0.000018, 0.000019]	0.00000033	0.09
	1,3,4,5,6	2	0.000021	[0.000021, 0.000022]	0.00000033	0.12
	1,2,4,5,6	3	0.000019	[0.000018, 0.000019]	0.00000033	0.10
	1,2,3,5,6	4	0.000014	[0.000014, 0.000015]	0.00000027	0.08
	1,2,3,4,6	5	0.000018	[0.000018, 0.000019]	0.00000032	0.10
	1,2,3,4,5	6	0.000005	[0.000005, 0.000006]	0.00000026	0.01
	Final Model		0.000016	[0.000015, 0.000017]	0.00000031	0.08
NO_x Emission Rate	2,3,4,5,6	1	0.0013	[0.0013, 0.0013]	0.0000030	0.87
	1,3,4,5,6	2	0.0013	[0.0012, 0.0012]	0.0000031	0.85
	1,2,4,5,6	3	0.0013	[0.0013, 0.0013]	0.0000032	0.85
	1,2,3,5,6	4	0.0013	[0.0012, 0.0012]	0.0000029	0.85
	1,2,3,4,6	5	0.0013	[0.0012, 0.0012]	0.0000031	0.85
	1,2,3,4,5	6	0.0012	[0.0012, 0.0012]	0.0000030	0.85
	Final Model		0.0013	[0.0012, 0.0012]	0.0000031	0.85

TABLE F-9. Calibrated Locomotive Power Demand Model Parameters with Lagged Error Terms for Double-Powered Consist with Locomotive NC 1871 operated on Ultra-low Sulfur Diesel based on Jan-Feb 2019 Measurements.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.027	[0.026, 0.027]	0.00012	0.79
	2,6	4	0.027	[0.026, 0.028]	0.00014	0.79
	2,4	6	0.027	[0.026, 0.027]	0.00012	0.79
	Final Model		0.027	[0.026, 0.028]	0.00012	0.79
CO_2 Emission Rate	4,6	2	0.085	[0.084, 0.085]	0.00039	0.79
	2,6	4	0.085	[0.084, 0.086]	0.00039	0.79
	2,4	6	0.085	[0.084, 0.086]	0.00039	0.79
	Final Model		0.085	[0.084, 0.086]	0.00039	0.79
CO Emission Rate	4,6	2	0.000092	[0.000088, 0.000095]	0.0000018	0.16
	2,6	4	0.000092	[0.000089, 0.000096]	0.0000018	0.16
	2,4	6	0.000092	[0.000089, 0.000096]	0.0000018	0.16
	Final Model		0.000092	[0.000088, 0.000096]	0.0000018	0.16
HC Emission Rate	4,6	2	0.000024	[0.000023, 0.000025]	0.00000057	0.12
	2,6	4	0.000024	[0.000023, 0.000025]	0.00000053	0.14
	2,4	6	0.000024	[0.000023, 0.000026]	0.00000055	0.13
	Final Model		0.000024	[0.000024, 0.000025]	0.00000055	0.13
NO_x Emission Rate	4,6	2	0.0026	[0.0026, 0.0027]	0.000012	0.77
	2,6	4	0.0026	[0.0026, 0.0026]	0.000012	0.77
	2,4	6	0.0026	[0.0026, 0.0027]	0.000012	0.77
	Final Model		0.0026	[0.0026, 0.0027]	0.000012	0.77
PM Emission Rate	4,6	2	0.000038	[0.000038, 0.000039]	0.00000014	0.68
	2,6	4	0.000038	[0.000038, 0.000039]	0.00000015	0.69
	2,4	6	0.000038	[0.000038, 0.000039]	0.00000013	0.65
	Final Model		0.000038	[0.000038, 0.000039]	0.00000014	0.67

TABLE F-10. Calibrated Locomotive Power Demand Model Parameters with Lagged Error Terms for the Single-Powered Consist with Locomotive NC 1871 operated on Ultra-low Sulfur Diesel based on Jan-Feb 2019 Measurements.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.032	[0.031, 0.032]	0.00015	0.75
	2,6	4	0.031	[0.031, 0.032]	0.00011	0.75
	2,4	6	0.032	[0.031, 0.032]	0.00012	0.75
	Final Model		0.032	[0.032, 0.032]	0.00013	0.75
CO_2 Emission Rate	4,6	2	0.102	[0.101, 0.102]	0.000482	0.75
	2,6	4	0.102	[0.101, 0.103]	0.000481	0.75
	2,4	6	0.102	[0.101, 0.102]	0.000483	0.75
	Final Model		0.102	[0.101, 0.102]	0.000482	0.75
CO Emission Rate	4,6	2	0.000190	[0.000186, 0.000194]	0.00000211	0.35
	2,6	4	0.000191	[0.000187, 0.000195]	0.00000210	0.36
	2,4	6	0.000191	[0.000187, 0.000195]	0.00000211	0.35
	Final Model		0.000191	[0.000187, 0.000195]	0.00000211	0.35
HC Emission Rate	4,6	2	0.000006	[0.000004, 0.000007]	0.00000063	0.01
	2,6	4	0.000006	[0.000005, 0.000007]	0.00000064	0.01
	2,4	6	0.000006	[0.000004, 0.000007]	0.00000063	0.01
	Final Model		0.000006	[0.000004, 0.000007]	0.00000063	0.01
NO_x Emission Rate	4,6	2	0.0030	[0.0029, 0.0030]	0.0000141	0.75
	2,6	4	0.0030	[0.0029, 0.0030]	0.0000141	0.75
	2,4	6	0.0030	[0.0029, 0.0030]	0.0000141	0.75
	Final Model		0.0030	[0.0029, 0.0030]	0.0000141	0.75
PM Emission Rate	4,6	2	0.000045	[0.000044, 0.000045]	0.000000148	0.66
	2,6	4	0.000045	[0.000044, 0.000045]	0.000000135	0.68
	2,4	6	0.000045	[0.000044, 0.000045]	0.000000143	0.67
	Final Model		0.000045	[0.000044, 0.000045]	0.000000142	0.67

TABLE F-11. Calibrated Locomotive Power Demand Model Parameters with Lagged Error Terms for Double-Powered Consist with Locomotive NC 1984 operated on Ultra-low Sulfur Diesel based on June 2019.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.019	[0.018, 0.019]	0.00012	0.67
	2,6	4	0.019	[0.018, 0.019]	0.00012	0.67
	2,4	6	0.019	[0.018, 0.019]	0.00012	0.67
	Final Model		0.019	[0.019, 0.019]	0.00012	0.67
CO_2 Emission Rate	4,6	2	0.060	[0.059, 0.060]	0.00040	0.67
	2,6	4	0.060	[0.059, 0.060]	0.00040	0.67
	2,4	6	0.060	[0.059, 0.060]	0.00040	0.67
	Final Model		0.060	[0.059, 0.060]	0.00040	0.67
CO Emission Rate	4,6	2	0.000277	[0.000268, 0.000286]	0.00000456	0.26
	2,6	4	0.000277	[0.000268, 0.000286]	0.00000451	0.26
	2,4	6	0.000277	[0.000268, 0.000286]	0.00000453	0.26
	Final Model		0.000277	[0.000268, 0.000286]	0.00000453	0.26
HC Emission Rate	4,6	2	0.000051	[0.000043, 0.000059]	0.00000419	0.01
	2,6	4	0.000052	[0.000043, 0.000060]	0.00000419	0.01
	2,4	6	0.000051	[0.000043, 0.000060]	0.00000420	0.01
	Final Model		0.000051	[0.000043, 0.000060]	0.00000419	0.01
NO_x Emission Rate	4,6	2	0.0014	[0.0013, 0.0013]	0.0000090	0.68
	2,6	4	0.0014	[0.0013, 0.0013]	0.0000090	0.68
	2,4	6	0.0014	[0.0013, 0.0013]	0.0000090	0.68
	Final Model		0.0014	[0.0013, 0.0013]	0.0000090	0.68
PM Emission Rate	4,6	2	0.000036	[0.000035, 0.000037]	0.00000044	0.62
	2,6	4	0.000037	[0.000035, 0.000037]	0.00000043	0.62
	2,4	6	0.000037	[0.000035, 0.000037]	0.00000041	0.62
	Final Model		0.000036	[0.000035, 0.000037]	0.00000043	0.62

TABLE F-12. Calibrated Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Powered Consist with Locomotive NC 1984 operated on Ultra-low Sulfur Diesel based on June 2019.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.028	[0.027, 0.029]	0.00012	0.77
	2,6	4	0.028	[0.027, 0.027]	0.00012	0.77
	2,4	6	0.028	[0.027, 0.028]	0.00012	0.77
	Final Model		0.028	[0.027, 0.028]	0.00012	0.77
CO_2 Emission Rate	4,6	2	0.087	[0.086, 0.088]	0.00040	0.77
	2,6	4	0.087	[0.086, 0.088]	0.00040	0.77
	2,4	6	0.087	[0.086, 0.088]	0.00040	0.77
	Final Model		0.087	[0.086, 0.088]	0.00040	0.77
CO Emission Rate	4,6	2	0.000417	[0.000409, 0.000424]	0.00000361	0.48
	2,6	4	0.000416	[0.000409, 0.000423]	0.00000361	0.48
	2,4	6	0.000416	[0.000409, 0.000423]	0.00000361	0.48
	Final Model		0.000416	[0.000409, 0.000423]	0.00000361	0.48
HC Emission Rate	4,6	2	0.000152	[0.000138, 0.000166]	0.00000729	0.03
	2,6	4	0.000152	[0.000138, 0.000166]	0.00000715	0.03
	2,4	6	0.000151	[0.000138, 0.000165]	0.00000691	0.03
	Final Model		0.000152	[0.000138, 0.000166]	0.00000712	0.03
NO_x Emission Rate	4,6	2	0.0019	[0.00185, 0.00188]	0.0000086	0.77
	2,6	4	0.0019	[0.00185, 0.00188]	0.0000086	0.77
	2,4	6	0.0019	[0.00185, 0.00188]	0.0000086	0.77
	Final Model		0.0019	[0.00185, 0.00188]	0.0000086	0.77
PM Emission Rate	4,6	2	0.000042	[0.000040, 0.000042]	0.00000047	0.70
	2,6	4	0.000042	[0.000041, 0.000042]	0.00000047	0.70
	2,4	6	0.000042	[0.000040, 0.000042]	0.00000046	0.70
	Final Model		0.000042	[0.000040, 0.000042]	0.00000047	0.70

TABLE F-13. Calibrated Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1810 operated on B20 Biodiesel Blend.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.036	[0.035, 0.036]	0.000077	0.87
	1,3,4,5,6	2	0.036	[0.036, 0.036]	0.000077	0.87
	1,2,4,5,6	3	0.036	[0.035, 0.035]	0.000079	0.87
	1,2,3,5,6	4	0.036	[0.036, 0.036]	0.000078	0.87
	1,2,3,4,6	5	0.037	[0.036, 0.036]	0.000078	0.87
	1,2,3,4,5	6	0.037	[0.037, 0.037]	0.000076	0.88
	Final Model		0.036	[0.036, 0.036]	0.000078	0.87
CO_2 Emission Rate	2,3,4,5,6	1	0.111	[0.111, 0.111]	0.00024	0.87
	1,3,4,5,6	2	0.113	[0.112, 0.113]	0.00024	0.87
	1,2,4,5,6	3	0.111	[0.110, 0.111]	0.00024	0.87
	1,2,3,5,6	4	0.112	[0.111, 0.112]	0.00024	0.87
	1,2,3,4,6	5	0.113	[0.113, 0.113]	0.00024	0.87
	1,2,3,4,5	6	0.115	[0.114, 0.115]	0.00024	0.88
	Final Model		0.113	[0.112, 0.113]	0.000241	0.87
CO Emission Rate	2,3,4,5,6	1	0.000397	[0.000391, 0.000402]	0.00000273	0.39
	1,3,4,5,6	2	0.000403	[0.000398, 0.000409]	0.00000290	0.38
	1,2,4,5,6	3	0.000381	[0.000376, 0.000385]	0.00000245	0.44
	1,2,3,5,6	4	0.000401	[0.000395, 0.000406]	0.00000289	0.38
	1,2,3,4,6	5	0.000413	[0.000409, 0.000418]	0.00000239	0.49
	1,2,3,4,5	6	0.000396	[0.000390, 0.000402]	0.00000284	0.38
	Final Model		0.000398	[0.000393, 0.000404]	0.00000270	0.41

Table F-13 Continued on next page.

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Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.000022	[0.000021, 0.000023]	0.00000050	0.06
	1,3,4,5,6	2	0.000028	[0.000027, 0.000030]	0.00000061	0.06
	1,2,4,5,6	3	0.000030	[0.000029, 0.000031]	0.00000063	0.07
	1,2,3,5,6	4	0.000024	[0.000022, 0.000025]	0.00000062	0.04
	1,2,3,4,6	5	0.000035	[0.000034, 0.000036]	0.00000064	0.09
	1,2,3,4,5	6	0.000026	[0.000025, 0.000027]	0.00000062	0.05
	Final Model		0.000028	[0.000026, 0.000029]	0.00000060	0.06
NO_x Emission Rate	2,3,4,5,6	1	0.0010	[0.0010, 0.0010]	0.0000025	0.84
	1,3,4,5,6	2	0.0010	[0.0010, 0.0010]	0.0000025	0.84
	1,2,4,5,6	3	0.0010	[0.0010, 0.0010]	0.0000024	0.85
	1,2,3,5,6	4	0.0010	[0.0010, 0.0010]	0.0000025	0.84
	1,2,3,4,6	5	0.0010	[0.0010, 0.0010]	0.0000026	0.84
	1,2,3,4,5	6	0.0010	[0.0010, 0.0010]	0.0000026	0.84
	Final Model		0.0010	[0.0010, 0.0010]	0.0000025	0.84
PM Emission Rate	2,3,4,5,6	1	0.000050	[0.000050, 0.000050]	0.00000019	0.69
	1,3,4,5,6	2	0.000046	[0.000045, 0.000046]	0.00000016	0.72
	1,2,4,5,6	3	0.000047	[0.000046, 0.000046]	0.00000016	0.73
	1,2,3,5,6	4	0.000052	[0.000051, 0.000052]	0.00000019	0.70
	1,2,3,4,6	5	0.000052	[0.000052, 0.000052]	0.00000019	0.71
	1,2,3,4,5	6	0.000051	[0.000050, 0.000051]	0.00000019	0.69
	Final Model		0.000050	[0.000049, 0.000050]	0.00000018	0.71

TABLE F-14. Calibrated Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1797 operated on B20 Biodiesel Blend.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.029	[0.029, 0.029]	0.000077	0.85
	1,3,4,5,6	2	0.029	[0.028, 0.029]	0.000076	0.85
	1,2,4,5,6	3	0.029	[0.028, 0.029]	0.000072	0.87
	1,2,3,5,6	4	0.026	[0.026, 0.026]	0.000071	0.85
	1,2,3,4,6	5	0.027	[0.027, 0.027]	0.000076	0.84
	1,2,3,4,5	6	0.028	[0.028, 0.028]	0.000075	0.85
	Final Model		0.028	[0.028, 0.028]	0.000075	0.85
CO_2 Emission Rate	2,3,4,5,6	1	0.090	[0.089, 0.090]	0.00024	0.85
	1,3,4,5,6	2	0.090	[0.089, 0.090]	0.00022	0.87
	1,2,4,5,6	3	0.082	[0.081, 0.081]	0.00022	0.85
	1,2,3,5,6	4	0.085	[0.084, 0.085]	0.00024	0.84
	1,2,3,4,6	5	0.087	[0.087, 0.087]	0.00023	0.85
	1,2,3,4,5	6	0.087	[0.087, 0.087]	0.00023	0.85
	Final Model		0.087	[0.087, 0.087]	0.00023	0.85
CO Emission Rate	2,3,4,5,6	1	0.000028	[0.000027, 0.000028]	0.00000029	0.27
	1,3,4,5,6	2	0.000029	[0.000028, 0.000030]	0.00000030	0.28
	1,2,4,5,6	3	0.000032	[0.000032, 0.000033]	0.00000031	0.30
	1,2,3,5,6	4	0.000029	[0.000029, 0.000030]	0.00000030	0.28
	1,2,3,4,6	5	0.000032	[0.000032, 0.000033]	0.00000031	0.30
	1,2,3,4,5	6	0.000029	[0.000029, 0.000030]	0.00000030	0.28
	Final Model		0.000029	[0.000029, 0.000030]	0.00000030	0.28

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Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.000124	[0.000120, 0.000128]	0.00000190	0.15
	1,3,4,5,6	2	0.000106	[0.000103, 0.000109]	0.00000170	0.13
	1,2,4,5,6	3	0.000127	[0.000123, 0.000130]	0.00000180	0.17
	1,2,3,5,6	4	0.000108	[0.000104, 0.000112]	0.00000183	0.13
	1,2,3,4,6	5	0.000133	[0.000129, 0.000136]	0.00000186	0.17
	1,2,3,4,5	6	0.000120	[0.000116, 0.000123]	0.00000182	0.15
	Final Model		0.000120	[0.000116, 0.000123]	0.00000182	0.15
NO_x Emission Rate	2,3,4,5,6	1	0.0022	[0.0022, 0.0022]	0.0000085	0.73
	1,3,4,5,6	2	0.0022	[0.0022, 0.0022]	0.0000081	0.75
	1,2,4,5,6	3	0.0021	[0.0020, 0.0020]	0.0000086	0.71
	1,2,3,5,6	4	0.0021	[0.0020, 0.0020]	0.0000085	0.71
	1,2,3,4,6	5	0.0022	[0.0021, 0.0021]	0.0000084	0.73
	1,2,3,4,5	6	0.0021	[0.0020, 0.0020]	0.0000086	0.71
	Final Model		0.0022	[0.0021, 0.0021]	0.0000084	0.73
PM Emission Rate	2,3,4,5,6	1	0.000029	[0.000028, 0.000029]	0.000000090	0.80
	1,3,4,5,6	2	0.000027	[0.000027, 0.000027]	0.000000096	0.77
	1,2,4,5,6	3	0.000026	[0.000025, 0.000025]	0.000000090	0.77
	1,2,3,5,6	4	0.000027	[0.000026, 0.000026]	0.000000090	0.78
	1,2,3,4,6	5	0.000024	[0.000023, 0.000027]	0.000000092	0.79
	1,2,3,4,5	6	0.000026	[0.000026, 0.000026]	0.000000093	0.77
	Final Model		0.000027	[0.000026, 0.000027]	0.000000094	0.78

TABLE F-15. Calibrated Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1859 operated on B20 Biodiesel Blend.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2-15	1	0.041	[0.041, 0.042]	0.000091	0.68
	1, 3-15	2	0.041	[0.041, 0.042]	0.000092	0.68
	1-2, 4-15	3	0.041	[0.040, 0.041]	0.000091	0.69
	1-3, 5-15	4	0.041	[0.040, 0.041]	0.000091	0.69
	1-4, 6-15	5	0.041	[0.041, 0.041]	0.000092	0.68
	1-5, 7-15	6	0.041	[0.041, 0.041]	0.000093	0.68
	1-6, 8-15	7	0.042	[0.041, 0.041]	0.000093	0.68
	1-7, 9-15	8	0.041	[0.040, 0.041]	0.000093	0.68
	1-8, 10-15	9	0.042	[0.041, 0.041]	0.000092	0.69
	1-9, 11-15	10	0.042	[0.041, 0.042]	0.000093	0.69
	1-10, 12-15	11	0.042	[0.041, 0.042]	0.000092	0.69
	1 -11, 13-15	12	0.042	[0.041, 0.043]	0.000091	0.69
	1-12, 14-15	13	0.041	[0.041, 0.042]	0.000093	0.68
	1-13, 15	14	0.042	[0.040, 0.042]	0.000091	0.70
	1-14	15	0.042	[0.041, 0.041]	0.000092	0.69
	Final Model		0.041	[0.040, 0.041]	0.000092	0.69
CO_2 Emission Rate	2-15	1	0.128	[0.127, 0.128]	0.000281	0.68
	1, 3-15	2	0.128	[0.127, 0.128]	0.000287	0.68
	1-2, 4-15	3	0.127	[0.126, 0.127]	0.000283	0.68
	1-3, 5-15	4	0.127	[0.126, 0.127]	0.000283	0.69
	1-4, 6-15	5	0.128	[0.127, 0.128]	0.000286	0.68
	1-5, 7-15	6	0.129	[0.128, 0.129]	0.000289	0.68
	1-6, 8-15	7	0.129	[0.128, 0.129]	0.000289	0.68
	1-7, 9-15	8	0.128	[0.127, 0.129]	0.000288	0.68
	1-8, 10-15	9	0.129	[0.128, 0.129]	0.000285	0.69
	1-9, 11-15	10	0.129	[0.128, 0.130]	0.000288	0.69
	1-10, 12-15	11	0.129	[0.128, 0.129]	0.000287	0.68
	1 -11, 13-15	12	0.129	[0.128, 0.129]	0.000284	0.69
	1-12, 14-15	13	0.128	[0.127, 0.128]	0.000287	0.68
	1-13, 15	14	0.131	[0.130, 0.131]	0.000282	0.70
	1-14	15	0.129	[0.128, 0.129]	0.000286	0.69
	Final Model		0.129	[0.127, 0.128]	0.000286	0.69

Table F-15 Continued on next page.

Table F-15 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
CO Emission Rate	2-15	1	0.000087	[0.000085, 0.000089]	0.00000080	0.11
	1, 3-15	2	0.000086	[0.000084, 0.000088]	0.00000081	0.11
	1-2, 4-15	3	0.000079	[0.000078, 0.000080]	0.00000072	0.11
	1-3, 5-15	4	0.000071	[0.000070, 0.000072]	0.00000058	0.14
	1-4, 6-15	5	0.000091	[0.000089, 0.000093]	0.00000082	0.12
	1-5, 7-15	6	0.000096	[0.000094, 0.000098]	0.00000083	0.13
	1-6, 8-15	7	0.000093	[0.000091, 0.000095]	0.00000083	0.12
	1-7, 9-15	8	0.000099	[0.000097, 0.000101]	0.00000083	0.13
	1-8, 10-15	9	0.000098	[0.000096, 0.000100]	0.00000083	0.13
	1-9, 11-15	10	0.000096	[0.000094, 0.000098]	0.00000083	0.12
	1-10, 12-15	11	0.000091	[0.000089, 0.000093]	0.00000083	0.11
	1 -11, 13-15	12	0.000094	[0.000092, 0.000096]	0.00000083	0.12
	1-12, 14-15	13	0.000087	[0.000085, 0.000089]	0.00000082	0.11
	1-13, 15	14	0.000096	[0.000094, 0.000098]	0.00000083	0.13
	1-14	15	0.000093	[0.000091, 0.000095]	0.00000083	0.12
	Final Model		0.000090	[0.000089, 0.000092]	0.00000080	0.12
HC Emission Rate	2-15	1	0.000184	[0.000181, 0.000187]	0.00000155	0.13
	1, 3-15	2	0.000178	[0.000175, 0.000181]	0.00000154	0.12
	1-2, 4-15	3	0.000163	[0.000160, 0.000166]	0.00000147	0.12
	1-3, 5-15	4	0.000155	[0.000152, 0.000158]	0.00000144	0.11
	1-4, 6-15	5	0.000174	[0.000171, 0.000177]	0.00000153	0.12
	1-5, 7-15	6	0.000198	[0.000195, 0.000201]	0.00000159	0.14
	1-6, 8-15	7	0.000188	[0.000185, 0.000191]	0.00000159	0.13
	1-7, 9-15	8	0.000202	[0.000199, 0.000205]	0.00000159	0.15
	1-8, 10-15	9	0.000187	[0.000184, 0.000190]	0.00000158	0.13
	1-9, 11-15	10	0.000200	[0.000197, 0.000203]	0.00000160	0.15
	1-10, 12-15	11	0.000167	[0.000164, 0.000170]	0.00000156	0.11
	1 -11, 13-15	12	0.000192	[0.000189, 0.000195]	0.00000159	0.14
	1-12, 14-15	13	0.000154	[0.000151, 0.000157]	0.00000150	0.10
	1-13, 15	14	0.000190	[0.000187, 0.000193]	0.00000157	0.14
	1-14	15	0.000167	[0.000164, 0.000170]	0.00000152	0.11
	Final Model		0.000180	[0.000177, 0.000183]	0.00000155	0.13

Table F-15 Continued on next page.

Table F-15 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
NO_x Emission Rate	2-15	1	0.00214	[0.00213, 0.00215]	0.0000042	0.76
	1, 3-15	2	0.00199	[0.00198, 0.00200]	0.0000043	0.75
	1-2, 4-15	3	0.00204	[0.00203, 0.00205]	0.0000041	0.73
	1-3, 5-15	4	0.00205	[0.00204, 0.00206]	0.0000039	0.71
	1-4, 6-15	5	0.00206	[0.00205, 0.00207]	0.0000040	0.71
	1-5, 7-15	6	0.00203	[0.00202, 0.00204]	0.0000041	0.71
	1-6, 8-15	7	0.00198	[0.00197, 0.00199]	0.0000043	0.73
	1-7, 9-15	8	0.00209	[0.00208, 0.00210]	0.0000040	0.68
	1-8, 10-15	9	0.00215	[0.00214, 0.00216]	0.0000041	0.75
	1-9, 11-15	10	0.00214	[0.00213, 0.00215]	0.0000039	0.76
	1-10, 12-15	11	0.00206	[0.00205, 0.00207]	0.0000039	0.76
	1 -11, 13-15	12	0.00218	[0.00217, 0.00219]	0.0000039	0.76
	1-12, 14-15	13	0.00209	[0.00208, 0.00210]	0.0000041	0.75
	1-13, 15	14	0.00204	[0.00203, 0.00205]	0.0000038	0.72
	1-14	15	0.00203	[0.00202, 0.00204]	0.0000041	0.71
	Final Model		0.00207	[0.00206, 0.00208]	0.0000040	0.73
PM Emission Rate	2-15	1	0.0000444	[0.0000441, 0.0000447]	0.000000164	0.56
	1, 3-15	2	0.0000457	[0.0000454, 0.0000460]	0.000000172	0.56
	1-2, 4-15	3	0.0000437	[0.0000434, 0.0000440]	0.000000167	0.55
	1-3, 5-15	4	0.0000444	[0.0000441, 0.0000447]	0.000000169	0.55
	1-4, 6-15	5	0.0000445	[0.0000442, 0.0000448]	0.000000168	0.56
	1-5, 7-15	6	0.0000447	[0.0000444, 0.0000450]	0.000000161	0.56
	1-6, 8-15	7	0.0000449	[0.0000446, 0.0000452]	0.000000160	0.56
	1-7, 9-15	8	0.0000455	[0.0000452, 0.0000458]	0.000000164	0.56
	1-8, 10-15	9	0.0000447	[0.0000444, 0.0000450]	0.000000160	0.56
	1-9, 11-15	10	0.0000465	[0.0000462, 0.0000469]	0.000000175	0.56
	1-10, 12-15	11	0.0000464	[0.0000461, 0.0000467]	0.000000173	0.56
	1 -11, 13-15	12	0.0000447	[0.0000444, 0.0000450]	0.000000160	0.56
	1-12, 14-15	13	0.0000444	[0.0000441, 0.0000447]	0.000000160	0.56
	1-13, 15	14	0.0000446	[0.0000443, 0.0000449]	0.000000168	0.56
	1-14	15	0.0000427	[0.0000424, 0.0000430]	0.000000165	0.55
	Final Model		0.0000448	[0.0000445, 0.0000451]	0.000000166	0.56

TABLE F-16. Calibrated Locomotive Power Demand Model Parameters without Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1797 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5	1	0.037	[0.037, 0.038]	0.000081	0.80
	1,3,4,5	2	0.035	[0.035, 0.036]	0.000083	0.79
	1,2,4,5	3	0.036	[0.036, 0.037]	0.000082	0.79
	1,2,3,5	4	0.036	[0.036, 0.037]	0.000081	0.84
	1,2,3,4	5	0.034	[0.033, 0.034]	0.000079	0.81
	Final Model		0.036	[0.036, 0.036]	0.000081	0.81
CO_2 Emission Rate	2,3,4,5	1	0.120	[0.119, 0.121]	0.00034	0.81
	1,3,4,5	2	0.116	[0.115, 0.116]	0.00023	0.83
	1,2,4,5	3	0.113	[0.112, 0.114]	0.00036	0.78
	1,2,3,5	4	0.118	[0.117, 0.119]	0.00027	0.83
	1,2,3,4	5	0.111	[0.110, 0.112]	0.00025	0.84
	Final Model		0.116	[0.115, 0.116]	0.00029	0.82
CO Emission Rate	2,3,4,5	1	0.00017	[0.00016, 0.00017]	0.00000093	0.52
	1,3,4,5	2	0.00014	[0.00014, 0.00014]	0.00000085	0.45
	1,2,4,5	3	0.00017	[0.00017, 0.00018]	0.00000098	0.50
	1,2,3,5	4	0.00014	[0.00014, 0.00015]	0.00000096	0.39
	1,2,3,4	5	0.00015	[0.00014, 0.00015]	0.00000095	0.43
	Final Model		0.00015	[0.00015, 0.00016]	0.00000093	0.46

Table F-16 Continued on next page.

Table F-16 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5	1	0.00014	[0.00013, 0.00016]	0.0000034	0.06
	1,3,4,5	2	0.00009	[0.00008, 0.00010]	0.0000035	0.04
	1,2,4,5	3	0.00016	[0.00015, 0.00017]	0.0000037	0.07
	1,2,3,5	4	0.00009	[0.00008, 0.00010]	0.0000039	0.03
	1,2,3,4	5	0.00015	[0.00014, 0.00016]	0.0000036	0.06
	Final Model		0.00013	[0.00011, 0.00014]	0.0000034	0.05
NO_x Emission Rate	2,3,4,5	1	0.0026	[0.0025, 0.0026]	0.0000097	0.70
	1,3,4,5	2	0.0024	[0.0024, 0.0025]	0.0000085	0.69
	1,2,4,5	3	0.0026	[0.0026, 0.0026]	0.0000094	0.69
	1,2,3,5	4	0.0026	[0.0026, 0.0027]	0.0000098	0.72
	1,2,3,4	5	0.0025	[0.0024, 0.0025]	0.0000099	0.69
	Final Model		0.0025	[0.0025, 0.0026]	0.0000095	0.70
PM Emission Rate	2,3,4,5	1	0.000031	[0.000031, 0.000032]	0.00000025	0.52
	1,3,4,5	2	0.000032	[0.000031, 0.000032]	0.00000017	0.56
	1,2,4,5	3	0.000032	[0.000031, 0.000033]	0.00000024	0.55
	1,2,3,5	4	0.000033	[0.000032, 0.000033]	0.00000026	0.54
	1,2,3,4	5	0.000031	[0.000031, 0.000032]	0.00000018	0.67
	Final Model		0.000032	[0.000031, 0.000032]	0.00000019	0.57

TABLE F-17. Calibrated Locomotive Power Demand Model Parameters without Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1810 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.032	[0.031, 0.032]	0.000075	0.77
	1,3,4,5,6	2	0.032	[0.031, 0.032]	0.000087	0.76
	1,2,4,5,6	3	0.031	[0.030, 0.031]	0.000084	0.78
	1,2,3,5,6	4	0.030	[0.030, 0.031]	0.000086	0.76
	1,2,3,4,6	5	0.030	[0.030, 0.031]	0.000086	0.74
	1,2,3,4,5	6	0.031	[0.030, 0.031]	0.000084	0.75
	Final Model		0.031	[0.030, 0.031]	0.000083	0.76
CO_2 Emission Rate	2,3,4,5,6	1	0.095	[0.093, 0.097]	0.00220	0.69
	1,3,4,5,6	2	0.099	[0.097, 0.102]	0.00214	0.76
	1,2,4,5,6	3	0.093	[0.091, 0.096]	0.00210	0.75
	1,2,3,5,6	4	0.102	[0.099, 0.104]	0.00218	0.75
	1,2,3,4,6	5	0.098	[0.096, 0.100]	0.00210	0.70
	1,2,3,4,5	6	0.098	[0.097, 0.100]	0.00109	0.70
	Final Model		0.098	[0.096, 0.100]	0.00197	0.78
CO Emission Rate	2,3,4,5,6	1	0.00031	[0.00031, 0.00032]	0.0000024	0.48
	1,3,4,5,6	2	0.00029	[0.00028, 0.00030]	0.0000028	0.45
	1,2,4,5,6	3	0.00032	[0.00031, 0.00033]	0.0000025	0.46
	1,2,3,5,6	4	0.00028	[0.00027, 0.00028]	0.0000027	0.45
	1,2,3,4,6	5	0.00032	[0.00031, 0.00032]	0.0000023	0.48
	1,2,3,4,5	6	0.00028	[0.00028, 0.00029]	0.0000025	0.45
	Final Model		0.00030	[0.00029, 0.00031]	0.0000023	0.46

Table F-17 Continued on next page

Table F-17 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.00027	[0.00026, 0.00028]	0.0000024	0.26
	1,3,4,5,6	2	0.00021	[0.00020, 0.00022]	0.0000026	0.20
	1,2,4,5,6	3	0.00025	[0.00024, 0.00025]	0.0000028	0.25
	1,2,3,5,6	4	0.00022	[0.00021, 0.00023]	0.0000025	0.23
	1,2,3,4,6	5	0.00028	[0.00027, 0.00029]	0.0000037	0.24
	1,2,3,4,5	6	0.00021	[0.00020, 0.00021]	0.0000024	0.18
	Final Model		0.00024	[0.00023, 0.00025]	0.0000026	0.23
NO_x Emission Rate	2,3,4,5,6	1	0.0012	[0.0012, 0.0012]	0.0000033	0.78
	1,3,4,5,6	2	0.0012	[0.0011, 0.0012]	0.0000035	0.79
	1,2,4,5,6	3	0.0012	[0.0011, 0.0012]	0.0000038	0.79
	1,2,3,5,6	4	0.0012	[0.0012, 0.0012]	0.0000038	0.78
	1,2,3,4,6	5	0.0012	[0.0012, 0.0012]	0.0000034	0.76
	1,2,3,4,5	6	0.0012	[0.0012, 0.0012]	0.0000033	0.79
	Final Model		0.0012	[0.0012, 0.0012]	0.0000035	0.78
PM Emission Rate	2,3,4,5,6	1	0.000073	[0.000072, 0.000074]	0.00000033	0.61
	1,3,4,5,6	2	0.000073	[0.000072, 0.000074]	0.00000035	0.57
	1,2,4,5,6	3	0.000073	[0.000072, 0.000074]	0.00000037	0.60
	1,2,3,5,6	4	0.000071	[0.000070, 0.000072]	0.00000039	0.61
	1,2,3,4,6	5	0.000074	[0.000072, 0.000075]	0.00000035	0.60
	1,2,3,4,5	6	0.000070	[0.000069, 0.000071]	0.00000033	0.59
	Final Model		0.000072	[0.000071, 0.000073]	0.00000033	0.60

TABLE F-18. Calibrated Locomotive Power Demand Model Parameters without Lagged Error Terms for the Tandem-Locomotive Consist with Locomotive NC 1859 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5	1	0.029	[0.028, 0.029]	0.000083	0.75
	1,3,4,5	2	0.029	[0.029, 0.029]	0.000088	0.78
	1,2,4,5	3	0.029	[0.029, 0.030]	0.000085	0.77
	1,2,3,5	4	0.028	[0.028, 0.029]	0.000084	0.79
	1,2,3,4	5	0.029	[0.029, 0.030]	0.000076	0.79
	Final Model		0.029	[0.029, 0.029]	0.000087	0.77
CO_2 Emission Rate	2,3,4,5	1	0.091	[0.090, 0.092]	0.00039	0.75
	1,3,4,5	2	0.089	[0.088, 0.090]	0.00034	0.75
	1,2,4,5	3	0.092	[0.091, 0.093]	0.00026	0.80
	1,2,3,5	4	0.089	[0.088, 0.090]	0.00024	0.81
	1,2,3,4	5	0.094	[0.093, 0.095]	0.00026	0.81
	Final Model		0.091	[0.090, 0.092]	0.00025	0.78
CO Emission Rate	2,3,4,5	1	0.00011	[0.00011, 0.00011]	0.00000064	0.49
	1,3,4,5	2	0.00011	[0.00011, 0.00012]	0.00000066	0.52
	1,2,4,5	3	0.00010	[0.00010, 0.00011]	0.00000068	0.47
	1,2,3,5	4	0.00011	[0.00011, 0.00011]	0.00000074	0.49
	1,2,3,4	5	0.00010	[0.00010, 0.00011]	0.00000063	0.48
	Final Model		0.00011	[0.00011, 0.00011]	0.00000066	0.49

Table F-18 Continued on next page.

Table F-18 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5	1	0.000024	[0.000021, 0.000027]	0.0000015	0.07
	1,3,4,5	2	0.000035	[0.000034, 0.000036]	0.0000004	0.09
	1,2,4,5	3	0.000037	[0.000036, 0.000038]	0.0000003	0.10
	1,2,3,5	4	0.000038	[0.000035, 0.000041]	0.0000017	0.09
	1,2,3,4	5	0.000037	[0.000033, 0.000041]	0.0000018	0.08
	Final Model		0.000034	[0.000032, 0.000037]	0.0000011	0.09
NO_x Emission Rate	2,3,4,5	1	0.0014	[0.0014, 0.0015]	0.0000054	0.73
	1,3,4,5	2	0.0014	[0.0014, 0.0014]	0.0000055	0.75
	1,2,4,5	3	0.0015	[0.0015, 0.0016]	0.0000048	0.78
	1,2,3,5	4	0.0015	[0.0015, 0.0016]	0.0000049	0.76
	1,2,3,4	5	0.0015	[0.0015, 0.0015]	0.0000046	0.77
	Final Model		0.0015	[0.0015, 0.0015]	0.0000047	0.76
PM Emission Rate	2,3,4,5	1	0.000039	[0.000038, 0.000039]	0.00000013	0.74
	1,3,4,5	2	0.000041	[0.000040, 0.000041]	0.00000015	0.73
	1,2,4,5	3	0.000042	[0.000042, 0.000043]	0.00000013	0.72
	1,2,3,5	4	0.000041	[0.000041, 0.000042]	0.00000018	0.70
	1,2,3,4	5	0.000041	[0.000041, 0.000042]	0.00000016	0.77
	Final Model		0.000041	[0.000040, 0.000041]	0.00000014	0.73

TABLE F-19. Calibrated Locomotive Power Demand Model Parameters without Lagged Error Terms for the Single-Locomotive Consist with Locomotive NC 1893 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.029	[0.029, 0.030]	0.000063	0.80
	1,3,4,5,6	2	0.027	[0.026, 0.027]	0.000067	0.77
	1,2,4,5,6	3	0.028	[0.028, 0.028]	0.000075	0.82
	1,2,3,5,6	4	0.027	[0.027, 0.027]	0.000063	0.82
	1,2,3,4,6	5	0.028	[0.027, 0.028]	0.000077	0.78
	1,2,3,4,5	6	0.026	[0.026, 0.026]	0.000069	0.79
	Final Model		0.027	[0.027, 0.028]	0.000066	0.80
CO_2 Emission Rate	2,3,4,5,6	1	0.094	[0.093, 0.094]	0.00020	0.87
	1,3,4,5,6	2	0.084	[0.084, 0.084]	0.00022	0.83
	1,2,4,5,6	3	0.094	[0.094, 0.094]	0.00020	0.83
	1,2,3,5,6	4	0.089	[0.088, 0.089]	0.00019	0.83
	1,2,3,4,6	5	0.082	[0.081, 0.082]	0.00021	0.83
	1,2,3,4,5	6	0.085	[0.085, 0.086]	0.00022	0.81
	Final Model		0.088	[0.088, 0.089]	0.00021	0.83
CO Emission Rate	2,3,4,5,6	1	0.000075	[0.000066, 0.000084]	0.0000043	0.58
	1,3,4,5,6	2	0.000077	[0.000064, 0.000090]	0.0000063	0.56
	1,2,4,5,6	3	0.000074	[0.000063, 0.000085]	0.0000055	0.59
	1,2,3,5,6	4	0.000073	[0.000060, 0.000086]	0.0000066	0.57
	1,2,3,4,6	5	0.000075	[0.000062, 0.000088]	0.0000066	0.56
	1,2,3,4,5	6	0.000087	[0.000077, 0.000097]	0.0000049	0.63
	Final Model		0.000077	[0.000065, 0.000088]	0.0000060	0.58

Table F-19 Continued on next page.

Table F-19 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.000023	[0.000020, 0.000026]	0.0000014	0.08
	1,3,4,5,6	2	0.000037	[0.000031, 0.000043]	0.0000030	0.10
	1,2,4,5,6	3	0.000025	[0.000021, 0.000029]	0.0000021	0.09
	1,2,3,5,6	4	0.000028	[0.000025, 0.000031]	0.0000014	0.07
	1,2,3,4,6	5	0.000024	[0.000021, 0.000027]	0.0000013	0.09
	1,2,3,4,5	6	0.000017	[0.000014, 0.000020]	0.0000014	0.01
	Final Model		0.000026	[0.000022, 0.000029]	0.0000020	0.07
NO_x Emission Rate	2,3,4,5,6	1	0.0014	[0.0014, 0.0014]	0.0000034	0.79
	1,3,4,5,6	2	0.0014	[0.0014, 0.0014]	0.0000038	0.78
	1,2,4,5,6	3	0.0014	[0.0014, 0.0014]	0.0000035	0.80
	1,2,3,5,6	4	0.0014	[0.0014, 0.0014]	0.0000037	0.78
	1,2,3,4,6	5	0.0014	[0.0014, 0.0014]	0.0000035	0.78
	1,2,3,4,5	6	0.0013	[0.0013, 0.0013]	0.0000034	0.78
	Final Model		0.0014	[0.0014, 0.0014]	0.0000035	0.79

TABLE F-20. Calibrated Locomotive Power Demand Model Parameters without Lagged Error Terms for Double-Powered Consist with Locomotive NC 1871 operated on Ultra-low Sulfur Diesel based on Jan-Feb 2019 Measurements.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.029	[0.029, 0.030]	0.00013	0.75
	2,6	4	0.030	[0.029, 0.031]	0.00014	0.75
	2,4	6	0.029	[0.029, 0.030]	0.00017	0.72
	Final Model		0.030	[0.029, 0.030]	0.00015	0.74
CO_2 Emission Rate	4,6	2	0.091	[0.089, 0.093]	0.00044	0.74
	2,6	4	0.089	[0.088, 0.091]	0.00043	0.73
	2,4	6	0.094	[0.092, 0.095]	0.00046	0.75
	Final Model		0.091	[0.090, 0.093]	0.00044	0.74
CO Emission Rate	4,6	2	0.00010	[0.00009, 0.00011]	0.0000024	0.15
	2,6	4	0.00010	[0.00009, 0.00011]	0.0000026	0.15
	2,4	6	0.00010	[0.00009, 0.00011]	0.0000024	0.14
	Final Model		0.00010	[0.00009, 0.00011]	0.0000025	0.15
HC Emission Rate	4,6	2	0.000026	[0.000024, 0.000028]	0.0000016	0.11
	2,6	4	0.000028	[0.000025, 0.000030]	0.0000015	0.13
	2,4	6	0.000027	[0.000024, 0.000030]	0.0000015	0.12
	Final Model		0.000027	[0.000024, 0.000029]	0.0000015	0.12
NO_x Emission Rate	4,6	2	0.0028	[0.0028, 0.0029]	0.000014	0.71
	2,6	4	0.0027	[0.0027, 0.0028]	0.000014	0.71
	2,4	6	0.0027	[0.0027, 0.0028]	0.000014	0.71
	Final Model		0.0028	[0.0027, 0.0028]	0.000014	0.71
PM Emission Rate	4,6	2	0.000041	[0.000041, 0.000042]	0.00000024	0.63
	2,6	4	0.000041	[0.000041, 0.000042]	0.00000027	0.63
	2,4	6	0.000040	[0.000040, 0.000041]	0.00000015	0.60
	Final Model		0.000041	[0.000040, 0.000042]	0.00000026	0.62

TABLE F-21. Calibrated Locomotive Power Demand Model Parameters without Lagged Error Terms for the Single-Powered Consist with Locomotive NC 1871 operated on Ultra-low Sulfur Diesel based on Jan-Feb 2019 Measurements.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.035	[0.035, 0.036]	0.00026	0.71
	2,6	4	0.034	[0.034, 0.035]	0.00023	0.68
	2,4	6	0.035	[0.034, 0.035]	0.00025	0.71
	Final Model		0.035	[0.034, 0.035]	0.00024	0.70
CO_2 Emission Rate	4,6	2	0.109	[0.107, 0.111]	0.00056	0.68
	2,6	4	0.112	[0.110, 0.114]	0.00054	0.70
	2,4	6	0.108	[0.106, 0.110]	0.00056	0.69
	Final Model		0.110	[0.108, 0.112]	0.00054	0.69
CO Emission Rate	4,6	2	0.00021	[0.00020, 0.00022]	0.0000024	0.32
	2,6	4	0.00022	[0.00021, 0.00023]	0.0000026	0.34
	2,4	6	0.00022	[0.00021, 0.00022]	0.0000024	0.32
	Final Model		0.00021	[0.00021, 0.00022]	0.0000025	0.33
HC Emission Rate	4,6	2	0.0000074	[0.0000067, 0.0000081]	0.00000037	0.01
	2,6	4	0.0000074	[0.0000066, 0.0000082]	0.00000042	0.01
	2,4	6	0.0000065	[0.0000054, 0.0000076]	0.00000054	0.01
	Final Model		0.0000071	[0.0000062, 0.0000080]	0.00000040	0.01
NO_x Emission Rate	4,6	2	0.0033	[0.0032, 0.0034]	0.000015	0.71
	2,6	4	0.0032	[0.0031, 0.0032]	0.000016	0.71
	2,4	6	0.0032	[0.0032, 0.0033]	0.000015	0.69
	Final Model		0.0032	[0.0032, 0.0033]	0.000015	0.70
PM Emission Rate	4,6	2	0.000050	[0.000049, 0.000050]	0.00000025	0.62
	2,6	4	0.000050	[0.000049, 0.000050]	0.00000017	0.65
	2,4	6	0.000047	[0.000047, 0.000048]	0.00000024	0.61
	Final Model		0.000049	[0.000048, 0.000049]	0.00000026	0.63

TABLE F-22. Calibrated Locomotive Power Demand Model Parameters without Lagged Error Terms for Double-Powered Consist with Locomotive NC 1984 operated on Ultra-low Sulfur Diesel based on June 2019.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.020	[0.020, 0.021]	0.00014	0.62
	2,6	4	0.020	[0.019, 0.020]	0.00016	0.60
	2,4	6	0.020	[0.020, 0.021]	0.00018	0.61
	Final Model		0.020	[0.020, 0.021]	0.00016	0.61
CO_2 Emission Rate	4,6	2	0.066	[0.064, 0.068]	0.00048	0.62
	2,6	4	0.064	[0.062, 0.065]	0.00045	0.64
	2,4	6	0.065	[0.064, 0.067]	0.00046	0.64
	Final Model		0.065	[0.063, 0.067]	0.00045	0.63
CO Emission Rate	4,6	2	0.00031	[0.00029, 0.00033]	0.0000050	0.24
	2,6	4	0.00030	[0.00028, 0.00032]	0.0000057	0.25
	2,4	6	0.00030	[0.00028, 0.00032]	0.0000054	0.24
	Final Model		0.00030	[0.00028, 0.00032]	0.0000053	0.24
HC Emission Rate	4,6	2	0.000060	[0.000041, 0.000079]	0.0000044	0.01
	2,6	4	0.000060	[0.000040, 0.000079]	0.0000046	0.01
	2,4	6	0.000057	[0.000037, 0.000077]	0.0000055	0.01
	Final Model		0.000059	[0.000040, 0.000078]	0.0000054	0.01
NO_x Emission Rate	4,6	2	0.0015	[0.0014, 0.0015]	0.000010	0.63
	2,6	4	0.0015	[0.0015, 0.0015]	0.000010	0.62
	2,4	6	0.0015	[0.0015, 0.0015]	0.000009	0.65
	Final Model		0.0015	[0.0015, 0.0015]	0.000010	0.63
PM Emission Rate	4,6	2	0.000039	[0.000037, 0.000041]	0.00000054	0.59
	2,6	4	0.000041	[0.000039, 0.000043]	0.00000056	0.56
	2,4	6	0.000040	[0.000038, 0.000041]	0.00000044	0.56
	Final Model		0.000040	[0.000038, 0.000042]	0.00000056	0.57

TABLE F-23. Calibrated Locomotive Power Demand Model Parameters without Lagged Error Terms for Single-Powered Consist with Locomotive NC 1984 operated on Ultra-low Sulfur Diesel based on June 2019.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.030	[0.029, 0.031]	0.00014	0.69
	2,6	4	0.030	[0.030, 0.031]	0.00017	0.70
	2,4	6	0.031	[0.029, 0.031]	0.00015	0.69
	Final Model		0.030	[0.030, 0.031]	0.00014	0.70
CO_2 Emission Rate	4,6	2	0.091	[0.090, 0.093]	0.00045	0.72
	2,6	4	0.095	[0.093, 0.097]	0.00047	0.72
	2,4	6	0.094	[0.092, 0.096]	0.00045	0.70
	Final Model		0.093	[0.092, 0.095]	0.00044	0.71
CO Emission Rate	4,6	2	0.00046	[0.00045, 0.00048]	0.0000044	0.43
	2,6	4	0.00045	[0.00043, 0.00046]	0.0000046	0.45
	2,4	6	0.00045	[0.00044, 0.00047]	0.0000045	0.44
	Final Model		0.00046	[0.00044, 0.00047]	0.0000045	0.44
HC Emission Rate	4,6	2	0.000181	[0.000150, 0.000211]	0.00000854	0.03
	2,6	4	0.000172	[0.000140, 0.000204]	0.00000858	0.03
	2,4	6	0.000177	[0.000145, 0.000209]	0.00000853	0.03
	Final Model		0.000176	[0.000145, 0.000208]	0.00000854	0.03
NO_x Emission Rate	4,6	2	0.0021	[0.0020, 0.0021]	0.0000094	0.72
	2,6	4	0.0020	[0.0020, 0.0021]	0.0000097	0.72
	2,4	6	0.0020	[0.0020, 0.0021]	0.0000095	0.70
	Final Model		0.0020	[0.0020, 0.0021]	0.0000096	0.71
PM Emission Rate	4,6	2	0.000045	[0.000043, 0.000047]	0.00000055	0.64
	2,6	4	0.000044	[0.000042, 0.000046]	0.00000053	0.64
	2,4	6	0.000046	[0.000044, 0.000048]	0.00000058	0.64
	Final Model		0.000045	[0.000043, 0.000047]	0.00000055	0.64

TABLE F-24. Calibrated Locomotive Power Demand Model Parameters without Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1810 operated on B20 Biodiesel Blend.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.038	[0.037, 0.038]	0.000084	0.83
	1,3,4,5,6	2	0.039	[0.039, 0.040]	0.000088	0.82
	1,2,4,5,6	3	0.039	[0.039, 0.039]	0.000095	0.83
	1,2,3,5,6	4	0.038	[0.037, 0.038]	0.000084	0.82
	1,2,3,4,6	5	0.040	[0.039, 0.041]	0.000097	0.81
	1,2,3,4,5	6	0.041	[0.040, 0.041]	0.000085	0.84
	Final Model		0.039	[0.039, 0.039]	0.000084	0.82
CO_2 Emission Rate	2,3,4,5,6	1	0.116	[0.115, 0.116]	0.000265	0.87
	1,3,4,5,6	2	0.117	[0.116, 0.117]	0.000264	0.84
	1,2,4,5,6	3	0.122	[0.121, 0.122]	0.000266	0.85
	1,2,3,5,6	4	0.112	[0.112, 0.113]	0.000267	0.83
	1,2,3,4,6	5	0.125	[0.124, 0.125]	0.000264	0.85
	1,2,3,4,5	6	0.126	[0.125, 0.126]	0.000243	0.85
	Final Model		0.120	[0.119, 0.120]	0.000265	0.85
CO Emission Rate	2,3,4,5,6	1	0.000035	[0.000031, 0.000039]	0.0000019	0.23
	1,3,4,5,6	2	0.000034	[0.000030, 0.000038]	0.0000018	0.25
	1,2,4,5,6	3	0.000036	[0.000032, 0.000040]	0.0000019	0.27
	1,2,3,5,6	4	0.000039	[0.000033, 0.000045]	0.0000030	0.25
	1,2,3,4,6	5	0.000044	[0.000039, 0.000049]	0.0000027	0.27
	1,2,3,4,5	6	0.000036	[0.000032, 0.000040]	0.0000019	0.25
	Final Model		0.000037	[0.000033, 0.000042]	0.0000020	0.26

Table F-24 Continued on next page.

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Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.000034	[0.000030, 0.000038]	0.0000019	0.06
	1,3,4,5,6	2	0.000033	[0.000026, 0.000040]	0.0000033	0.06
	1,2,4,5,6	3	0.000037	[0.000033, 0.000041]	0.0000020	0.06
	1,2,3,5,6	4	0.000039	[0.000032, 0.000046]	0.0000034	0.04
	1,2,3,4,6	5	0.000044	[0.000039, 0.000049]	0.0000025	0.08
	1,2,3,4,5	6	0.000036	[0.000029, 0.000043]	0.0000033	0.04
	Final Model		0.000037	[0.000032, 0.000043]	0.0000029	0.06
NO_x Emission Rate	2,3,4,5,6	1	0.0011	[0.0011, 0.0011]	0.0000035	0.79
	1,3,4,5,6	2	0.0011	[0.0011, 0.0011]	0.0000036	0.76
	1,2,4,5,6	3	0.0011	[0.0010, 0.0011]	0.0000038	0.77
	1,2,3,5,6	4	0.0011	[0.0011, 0.0011]	0.0000036	0.76
	1,2,3,4,6	5	0.0011	[0.0011, 0.0011]	0.0000035	0.77
	1,2,3,4,5	6	0.0011	[0.0011, 0.0011]	0.0000034	0.79
	Final Model		0.0011	[0.0011, 0.0011]	0.0000036	0.77
PM Emission Rate	2,3,4,5,6	1	0.000055	[0.000054, 0.000056]	0.00000024	0.66
	1,3,4,5,6	2	0.000049	[0.000048, 0.000049]	0.00000028	0.67
	1,2,4,5,6	3	0.000050	[0.000049, 0.000050]	0.00000025	0.65
	1,2,3,5,6	4	0.000058	[0.000057, 0.000059]	0.00000027	0.67
	1,2,3,4,6	5	0.000057	[0.000056, 0.000058]	0.00000024	0.66
	1,2,3,4,5	6	0.000057	[0.000056, 0.000058]	0.00000026	0.63
	Final Model		0.000054	[0.000054, 0.000055]	0.00000025	0.65

TABLE F-25. Calibrated Locomotive Power Demand Model Parameters without Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1797 operated on B20 Biodiesel Blend.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.032	[0.032, 0.032]	0.000083	0.78
	1,3,4,5,6	2	0.030	[0.030, 0.031]	0.000086	0.77
	1,2,4,5,6	3	0.031	[0.031, 0.031]	0.000084	0.83
	1,2,3,5,6	4	0.028	[0.027, 0.028]	0.000086	0.80
	1,2,3,4,6	5	0.029	[0.028, 0.029]	0.000084	0.79
	1,2,3,4,5	6	0.030	[0.030, 0.030]	0.000083	0.79
	Final Model		0.030	[0.029, 0.030]	0.000082	0.79
CO_2 Emission Rate	2,3,4,5,6	1	0.100	[0.0996, 0.1001]	0.000253	0.77
	1,3,4,5,6	2	0.091	[0.0904, 0.0909]	0.000255	0.80
	1,2,4,5,6	3	0.101	[0.1008, 0.1012]	0.000237	0.80
	1,2,3,5,6	4	0.088	[0.0878, 0.0882]	0.000256	0.76
	1,2,3,4,6	5	0.090	[0.0894, 0.0899]	0.000268	0.75
	1,2,3,4,5	6	0.091	[0.0908, 0.0913]	0.000258	0.77
	Final Model		0.093	[0.0931, 0.0936]	0.000253	0.78
CO Emission Rate	2,3,4,5,6	1	0.000034	[0.000027, 0.000041]	0.0000033	0.24
	1,3,4,5,6	2	0.000037	[0.000032, 0.000042]	0.0000024	0.26
	1,2,4,5,6	3	0.000044	[0.000039, 0.000049]	0.0000026	0.27
	1,2,3,5,6	4	0.000036	[0.000032, 0.000040]	0.0000021	0.24
	1,2,3,4,6	5	0.000048	[0.000040, 0.000056]	0.0000039	0.27
	1,2,3,4,5	6	0.000039	[0.000035, 0.000043]	0.0000020	0.25
	Final Model		0.000040	[0.000034, 0.000045]	0.0000030	0.26

Table F-25 Continued on next page.

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Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.00013	[0.00012, 0.00014]	0.000007	0.12
	1,3,4,5,6	2	0.00012	[0.00012, 0.00013]	0.000007	0.12
	1,2,4,5,6	3	0.00015	[0.00014, 0.00016]	0.000012	0.14
	1,2,3,5,6	4	0.00013	[0.00012, 0.00014]	0.000008	0.11
	1,2,3,4,6	5	0.00016	[0.00015, 0.00016]	0.000010	0.16
	1,2,3,4,5	6	0.00013	[0.00012, 0.00014]	0.000012	0.13
	Final Model		0.00014	[0.00013, 0.00014]	0.000009	0.13
NO_x Emission Rate	2,3,4,5,6	1	0.0024	[0.0024, 0.0025]	0.00014	0.66
	1,3,4,5,6	2	0.0024	[0.0023, 0.0024]	0.00013	0.68
	1,2,4,5,6	3	0.0022	[0.0022, 0.0022]	0.00020	0.67
	1,2,3,5,6	4	0.0022	[0.0022, 0.0022]	0.00017	0.65
	1,2,3,4,6	5	0.0024	[0.0024, 0.0024]	0.00016	0.69
	1,2,3,4,5	6	0.0022	[0.0022, 0.0023]	0.00015	0.65
	Final Model		0.0023	[0.0023, 0.0023]	0.00016	0.67
PM Emission Rate	2,3,4,5,6	1	0.000031	[0.000031, 0.000032]	0.0000019	0.74
	1,3,4,5,6	2	0.000030	[0.000030, 0.000031]	0.0000021	0.71
	1,2,4,5,6	3	0.000028	[0.000028, 0.000029]	0.0000027	0.73
	1,2,3,5,6	4	0.000030	[0.000029, 0.000030]	0.0000016	0.69
	1,2,3,4,6	5	0.000136	[0.000128, 0.000145]	0.0000105	0.13
	1,2,3,4,5	6	0.000111	[0.000105, 0.000118]	0.0000070	0.12
	Final Model		0.000061	[0.000058, 0.000064]	0.0000040	0.52

TABLE F-26. Calibrated Locomotive Power Demand Model Parameters without Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1859 operated on B20 Biodiesel Blend.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
Fuel Use Rate	2-15	1	0.045	[0.044, 0.045]	0.00014	0.62
	1, 3-15	2	0.045	[0.045, 0.046]	0.00013	0.62
	1-2, 4-15	3	0.044	[0.044, 0.045]	0.00012	0.65
	1-3, 5-15	4	0.043	[0.043, 0.043]	0.00014	0.65
	1-4, 6-15	5	0.043	[0.043, 0.044]	0.00013	0.65
	1-5, 7-15	6	0.043	[0.043, 0.043]	0.00014	0.61
	1-6, 8-15	7	0.044	[0.044, 0.044]	0.00015	0.65
	1-7, 9-15	8	0.044	[0.044, 0.045]	0.00016	0.62
	1-8, 10-15	9	0.046	[0.045, 0.046]	0.00014	0.63
	1-9, 11-15	10	0.046	[0.045, 0.046]	0.00013	0.66
	1-10, 12-15	11	0.045	[0.045, 0.045]	0.00014	0.62
	1 -11, 13-15	12	0.045	[0.044, 0.045]	0.00013	0.64
	1-12, 14-15	13	0.045	[0.044, 0.045]	0.00014	0.65
	1-13, 15	14	0.046	[0.046, 0.047]	0.00014	0.64
	1-14	15	0.045	[0.045, 0.046]	0.00013	0.63
	Final Model		0.045	[0.044, 0.045]	0.00013	0.63
CO_2 Emission Rate	2-15	1	0.138	[0.137, 0.139]	0.000344	0.62
	1, 3-15	2	0.134	[0.133, 0.136]	0.000357	0.65
	1-2, 4-15	3	0.140	[0.138, 0.141]	0.000365	0.65
	1-3, 5-15	4	0.136	[0.135, 0.137]	0.000343	0.63
	1-4, 6-15	5	0.140	[0.138, 0.141]	0.000335	0.63
	1-5, 7-15	6	0.138	[0.137, 0.139]	0.000358	0.63
	1-6, 8-15	7	0.138	[0.137, 0.139]	0.000346	0.63
	1-7, 9-15	8	0.134	[0.133, 0.136]	0.000335	0.61
	1-8, 10-15	9	0.142	[0.141, 0.143]	0.000343	0.65
	1-9, 11-15	10	0.137	[0.135, 0.138]	0.000345	0.66
	1-10, 12-15	11	0.138	[0.137, 0.139]	0.000347	0.61
	1 -11, 13-15	12	0.142	[0.141, 0.143]	0.000348	0.62
	1-12, 14-15	13	0.136	[0.134, 0.137]	0.000335	0.63
	1-13, 15	14	0.140	[0.139, 0.141]	0.000357	0.64
	1-14	15	0.141	[0.139, 0.142]	0.000349	0.62
	Final Model		0.138	[0.137, 0.139]	0.000340	0.63

Table F-26 Continued on next page.

Table F-26 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
CO Emission Rate	2-15	1	0.00010	[0.00009, 0.00011]	0.0000059	0.10
	1, 3-15	2	0.00010	[0.00009, 0.00011]	0.0000052	0.10
	1-2, 4-15	3	0.00009	[0.00008, 0.00010]	0.0000047	0.10
	1-3, 5-15	4	0.00008	[0.00007, 0.00009]	0.0000043	0.12
	1-4, 6-15	5	0.00010	[0.00009, 0.00011]	0.0000051	0.10
	1-5, 7-15	6	0.00011	[0.00009, 0.00013]	0.0000096	0.12
	1-6, 8-15	7	0.00011	[0.00009, 0.00013]	0.0000085	0.11
	1-7, 9-15	8	0.00011	[0.00010, 0.00012]	0.0000056	0.11
	1-8, 10-15	9	0.00011	[0.00010, 0.00012]	0.0000060	0.12
	1-9, 11-15	10	0.00011	[0.00009, 0.00013]	0.0000077	0.10
	1-10, 12-15	11	0.00010	[0.00009, 0.00011]	0.0000058	0.10
	1 -11, 13-15	12	0.00011	[0.00009, 0.00013]	0.0000091	0.11
	1-12, 14-15	13	0.00009	[0.00008, 0.00010]	0.0000050	0.10
	1-13, 15	14	0.00011	[0.00009, 0.00013]	0.0000088	0.12
	1-14	15	0.00010	[0.00009, 0.00011]	0.0000075	0.11
	Final Model		0.00010	[0.00009, 0.00012]	0.0000100	0.11
HC Emission Rate	2-15	1	0.00021	[0.00019, 0.00023]	0.000011	0.12
	1, 3-15	2	0.00020	[0.00016, 0.00024]	0.000018	0.10
	1-2, 4-15	3	0.00019	[0.00016, 0.00022]	0.000014	0.11
	1-3, 5-15	4	0.00017	[0.00015, 0.00019]	0.000010	0.10
	1-4, 6-15	5	0.00020	[0.00017, 0.00023]	0.000017	0.10
	1-5, 7-15	6	0.00023	[0.00021, 0.00025]	0.000012	0.13
	1-6, 8-15	7	0.00021	[0.00018, 0.00024]	0.000015	0.11
	1-7, 9-15	8	0.00021	[0.00018, 0.00024]	0.000014	0.12
	1-8, 10-15	9	0.00022	[0.00019, 0.00025]	0.000014	0.12
	1-9, 11-15	10	0.00023	[0.00019, 0.00027]	0.000018	0.14
	1-10, 12-15	11	0.00018	[0.00016, 0.00020]	0.000010	0.09
	1 -11, 13-15	12	0.00022	[0.0002, 0.000240]	0.000012	0.13
	1-12, 14-15	13	0.00018	[0.00016, 0.00020]	0.000010	0.09
	1-13, 15	14	0.00021	[0.00018, 0.00024]	0.000017	0.13
	1-14	15	0.00018	[0.00015, 0.00021]	0.000016	0.10
	Final Model		0.00020	[0.00016, 0.00022]	0.000010	0.11

Table F-26 Continued on next page.

Table F-26 Continued from previous page.

Species	Calibration Trips	Validation Trip	Proportionality Constant (g/kW)	95 % Confidence Interval (g/kW)	Standard Error in Proportionality Constant (g/kW)	Goodness of Fit (R^2)
NO_x Emission Rate	2-15	1	0.0021	[0.0021, 0.0021]	0.0000042	0.66
	1, 3-15	2	0.0022	[0.0022, 0.0022]	0.0000045	0.65
	1-2, 4-15	3	0.0022	[0.0022, 0.0022]	0.0000043	0.65
	1-3, 5-15	4	0.0022	[0.0022, 0.0022]	0.0000043	0.66
	1-4, 6-15	5	0.0022	[0.0022, 0.0022]	0.0000043	0.65
	1-5, 7-15	6	0.0021	[0.0021, 0.0021]	0.0000044	0.66
	1-6, 8-15	7	0.0021	[0.0021, 0.0021]	0.0000044	0.65
	1-7, 9-15	8	0.0021	[0.0021, 0.0021]	0.0000044	0.67
	1-8, 10-15	9	0.0022	[0.0022, 0.0022]	0.0000043	0.66
	1-9, 11-15	10	0.0022	[0.0022, 0.0022]	0.0000045	0.65
	1-10, 12-15	11	0.0021	[0.0021, 0.0021]	0.0000044	0.66
	1 -11, 13-15	12	0.0022	[0.0022, 0.0022]	0.0000043	0.66
	1-12, 14-15	13	0.0022	[0.0022, 0.0022]	0.0000043	0.66
	1-13, 15	14	0.0022	[0.0022, 0.0022]	0.0000042	0.70
	1-14	15	0.0021	[0.0021, 0.0021]	0.0000044	0.66
	Final Model		0.0022	[0.0020, 0.0022]	0.0000044	0.66
PM Emission Rate	2-15	1	0.000047	[0.000046, 0.000047]	0.00000018	0.51
	1, 3-15	2	0.000050	[0.000049, 0.000051]	0.00000018	0.51
	1-2, 4-15	3	0.000048	[0.000047, 0.000049]	0.00000019	0.49
	1-3, 5-15	4	0.000049	[0.000048, 0.000050]	0.00000018	0.51
	1-4, 6-15	5	0.000048	[0.000047, 0.000048]	0.00000018	0.52
	1-5, 7-15	6	0.000046	[0.000045, 0.000047]	0.00000018	0.50
	1-6, 8-15	7	0.000049	[0.000048, 0.000049]	0.00000018	0.52
	1-7, 9-15	8	0.000050	[0.000050, 0.000051]	0.00000018	0.51
	1-8, 10-15	9	0.000049	[0.000048, 0.000051]	0.00000018	0.52
	1-9, 11-15	10	0.000049	[0.000048, 0.000050]	0.00000019	0.51
	1-10, 12-15	11	0.000050	[0.000049, 0.000051]	0.00000019	0.50
	1 -11, 13-15	12	0.000047	[0.000046, 0.000048]	0.00000018	0.53
	1-12, 14-15	13	0.000047	[0.000046, 0.000047]	0.00000018	0.51
	1-13, 15	14	0.000046	[0.000046, 0.000047]	0.00000019	0.53
	1-14	15	0.000044	[0.000043, 0.000045]	0.00000018	0.51
	Final Model		0.000048	[0.000047, 0.000049]	0.00000018	0.51

TABLE F-27. Validation Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1859 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	1.07	[1.04, 1.10]	0.06	0.81
	1,3,4,5,6	2	0.99	[0.97, 1.00]	0.03	0.83
	1,2,4,5,6	3	1.00	[0.96, 1.03]	0.07	0.92
	1,2,3,5,6	4	0.85	[0.83, 0.87]	0.04	0.90
	1,2,3,4,6	5	0.97	[0.95, 0.99]	0.04	0.82
	1,2,3,4,5	6	0.85	[0.84, 0.87]	0.03	0.87
	Average		0.96	[0.93, 1.00]	0.07	0.86
CO_2 Emission Rate	2,3,4,5,6	1	1.08	[1.06, 1.09]	0.03	0.83
	1,3,4,5,6	2	1.00	[0.98, 1.02]	0.04	0.82
	1,2,4,5,6	3	0.99	[0.95, 1.03]	0.08	0.94
	1,2,3,5,6	4	0.83	[0.85, 0.86]	0.01	0.88
	1,2,3,4,6	5	0.96	[0.96, 0.99]	0.03	0.83
	1,2,3,4,5	6	0.83	[0.85, 0.85]	0.00	0.88
	Average		0.95	[0.96, 1.05]	0.03	0.86
CO Emission Rate	2,3,4,5,6	1	1.18	[1.08, 1.23]	0.15	0.44
	1,3,4,5,6	2	0.73	[0.69, 0.79]	0.10	0.42
	1,2,4,5,6	3	0.81	[0.78, 0.86]	0.08	0.41
	1,2,3,5,6	4	1.11	[1.08, 1.15]	0.07	0.56
	1,2,3,4,6	5	0.77	[0.74, 0.87]	0.13	0.43
	1,2,3,4,5	6	1.16	[1.11, 1.26]	0.15	0.39
	Average		0.96	[0.92, 1.03]	0.11	0.44

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Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.98	[0.84, 1.09]	0.25	0.06
	1,3,4,5,6	2	0.55	[0.42, 0.68]	0.26	0.05
	1,2,4,5,6	3	0.92	[0.72, 1.08]	0.36	0.06
	1,2,3,5,6	4	1.43	[1.25, 1.52]	0.27	0.06
	1,2,3,4,6	5	0.59	[0.41, 0.69]	0.28	0.05
	1,2,3,4,5	6	1.27	[1.16, 1.35]	0.19	0.04
	Average		0.96	[0.80, 1.07]	0.27	0.05
NO_x Emission Rate	2,3,4,5,6	1	0.97	[0.94, 0.99]	0.05	0.84
	1,3,4,5,6	2	1.07	[1.01, 1.13]	0.12	0.86
	1,2,4,5,6	3	1.06	[1.04, 1.13]	0.09	0.79
	1,2,3,5,6	4	0.91	[0.81, 0.98]	0.17	0.81
	1,2,3,4,6	5	1.01	[0.98, 1.04]	0.06	0.79
	1,2,3,4,5	6	1.10	[1.04, 1.20]	0.16	0.77
	Average		1.02	[0.97, 1.08]	0.11	0.81
PM Emission Rate	2,3,4,5,6	1	1.07	[1.03, 1.16]	0.13	0.54
	1,3,4,5,6	2	1.05	[1.03, 1.11]	0.08	0.56
	1,2,4,5,6	3	1.14	[1.11, 1.19]	0.08	0.58
	1,2,3,5,6	4	0.92	[0.85, 0.95]	0.10	0.59
	1,2,3,4,6	5	1.11	[1.10, 1.15]	0.05	0.52
	1,2,3,4,5	6	0.92	[0.90, 0.94]	0.04	0.54
	Average		1.03	[1.00, 1.08]	0.08	0.56

TABLE F-28. Validation Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1797 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5	1	1.10	[1.03, 1.12]	0.012	0.90
	1,3,4,5	2	1.11	[1.02, 1.11]	0.007	0.86
	1,2,4,5	3	0.86	[0.85, 0.89]	0.016	0.83
	1,2,3,5	4	1.08	[1.05, 1.08]	0.008	0.81
	1,2,3,4	5	0.93	[0.93, 1.00]	0.015	0.92
	Average		1.02	[0.95, 1.04]	0.011	0.86
CO_2 Emission Rate	2,3,4,5	1	1.02	[1.00, 1.07]	0.026	0.85
	1,3,4,5	2	0.94	[0.89, 0.99]	0.009	0.81
	1,2,4,5	3	0.93	[0.91, 1.02]	0.023	0.79
	1,2,3,5	4	0.89	[0.87, 0.93]	0.006	0.87
	1,2,3,4	5	1.06	[1.01, 1.12]	0.011	0.86
	Average		0.97	[0.94, 1.03]	0.015	0.84
CO Emission Rate	2,3,4,5	1	0.98	[0.94, 1.00]	0.046	0.55
	1,3,4,5	2	0.73	[0.68, 0.82]	0.031	0.51
	1,2,4,5	3	0.79	[0.76, 0.89]	0.037	0.52
	1,2,3,5	4	0.78	[0.68, 0.83]	0.039	0.44
	1,2,3,4	5	1.01	[0.94, 1.07]	0.050	0.50
	Average		0.86	[0.80, 0.92]	0.041	0.51

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Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5	1	1.44	[1.33, 1.58]	0.092	0.07
	1,3,4,5	2	0.59	[0.53, 0.70]	0.031	0.04
	1,2,4,5	3	0.80	[0.80, 0.90]	0.044	0.08
	1,2,3,5	4	0.56	[0.55, 0.68]	0.031	0.03
	1,2,3,4	5	0.63	[0.61, 0.78]	0.038	0.07
	Average		0.80	[0.76, 0.93]	0.047	0.06
NO_x Emission Rate	2,3,4,5	1	0.87	[0.85, 0.92]	0.020	0.69
	1,3,4,5	2	0.97	[0.96, 1.00]	0.014	0.67
	1,2,4,5	3	1.03	[0.99, 1.05]	0.013	0.69
	1,2,3,5	4	1.05	[0.99, 1.12]	0.014	0.79
	1,2,3,4	5	0.88	[0.82, 0.88]	0.019	0.74
	Average		0.96	[0.92, 1.00]	0.016	0.72
PM Emission Rate	2,3,4,5	1	0.86	[0.77, 0.94]	0.019	0.53
	1,3,4,5	2	1.10	[1.05, 1.19]	0.019	0.56
	1,2,4,5	3	1.14	[1.08, 1.19]	0.009	0.59
	1,2,3,5	4	1.00	[0.91, 1.05]	0.024	0.56
	1,2,3,4	5	0.93	[0.92, 0.95]	0.023	0.68
	Average		1.01	[0.95, 1.07]	0.019	0.58

TABLE F-29. Validation Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1810 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.90	[0.88, 0.96]	0.008	0.78
	1,3,4,5,6	2	0.98	[0.97, 1.06]	0.017	0.76
	1,2,4,5,6	3	1.10	[1.08, 1.18]	0.019	0.76
	1,2,3,5,6	4	0.93	[0.84, 1.01]	0.012	0.82
	1,2,3,4,6	5	0.96	[0.93, 1.01]	0.009	0.84
	1,2,3,4,5	6	0.93	[0.87, 1.01]	0.017	0.78
	Average		0.97	[0.93, 1.04]	0.013	0.79
CO_2 Emission Rate	2,3,4,5,6	1	0.86	[0.78, 0.94]	0.009	0.89
	1,3,4,5,6	2	0.98	[0.89, 1.01]	0.011	0.78
	1,2,4,5,6	3	0.97	[0.92, 1.04]	0.013	0.82
	1,2,3,5,6	4	1.11	[1.03, 1.19]	0.020	0.77
	1,2,3,4,6	5	1.08	[1.05, 1.08]	0.013	0.81
	1,2,3,4,5	6	1.13	[1.09, 1.22]	0.012	0.84
	Average		1.02	[0.96, 1.08]	0.013	0.82
CO Emission Rate	2,3,4,5,6	1	0.98	[0.89, 1.02]	0.044	0.51
	1,3,4,5,6	2	1.06	[1.04, 1.13]	0.038	0.49
	1,2,4,5,6	3	0.77	[0.68, 0.79]	0.038	0.54
	1,2,3,5,6	4	1.20	[1.18, 1.23]	0.036	0.50
	1,2,3,4,6	5	1.27	[1.23, 1.29]	0.037	0.47
	1,2,3,4,5	6	0.93	[0.83, 0.99]	0.025	0.53
	Average		1.03	[0.98, 1.08]	0.036	0.50

Table F-29 Continued on next page.

Table F-29 Continued from previous page.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	1.10	[0.93, 1.18]	0.049	0.31
	1,3,4,5,6	2	0.69	[0.61, 0.88]	0.036	0.21
	1,2,4,5,6	3	0.96	[0.76, 1.10]	0.051	0.28
	1,2,3,5,6	4	0.88	[0.69, 1.08]	0.054	0.25
	1,2,3,4,6	5	0.71	[0.62, 0.88]	0.032	0.24
	1,2,3,4,5	6	1.29	[1.14, 1.40]	0.071	0.20
	Average		0.94	[0.79, 1.09]	0.049	0.25
NO_x Emission Rate	2,3,4,5,6	1	1.07	[1.04, 1.10]	0.007	0.84
	1,3,4,5,6	2	0.99	[0.92, 1.06]	0.025	0.80
	1,2,4,5,6	3	0.93	[0.91, 0.98]	0.008	0.84
	1,2,3,5,6	4	1.03	[1.01, 1.06]	0.023	0.78
	1,2,3,4,6	5	0.97	[0.95, 1.01]	0.021	0.86
	1,2,3,4,5	6	0.92	[0.83, 0.94]	0.007	0.82
	Average		0.99	[0.94, 1.02]	0.015	0.82
PM Emission Rate	2,3,4,5,6	1	1.03	[0.98, 1.11]	0.008	0.72
	1,3,4,5,6	2	1.06	[1.04, 1.13]	0.026	0.64
	1,2,4,5,6	3	0.90	[0.88, 0.95]	0.019	0.71
	1,2,3,5,6	4	1.08	[1.06, 1.09]	0.027	0.64
	1,2,3,4,6	5	1.12	[1.07, 1.13]	0.019	0.63
	1,2,3,4,5	6	0.97	[0.90, 1.03]	0.013	0.66
	Average		1.03	[0.99, 1.07]	0.019	0.66

TABLE F-30. Validation Locomotive Power Demand Model Parameters with Lagged Error Terms for Tandem-Locomotive Consist with Locomotive NC 1859 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5	1	0.98	[0.96, 1.01]	0.008	0.83
	1,3,4,5	2	1.02	[0.97, 1.08]	0.005	0.79
	1,2,4,5	3	1.00	[0.99, 1.05]	0.018	0.78
	1,2,3,5	4	0.87	[0.85, 0.88]	0.009	0.85
	1,2,3,4	5	0.89	[0.79, 0.94]	0.004	0.90
	Average		0.95	[0.91, 0.99]	0.009	0.83
CO_2 Emission Rate	2,3,4,5	1	1.05	[1.02, 1.07]	0.020	0.75
	1,3,4,5	2	1.07	[1.01, 1.17]	0.016	0.86
	1,2,4,5	3	0.95	[0.85, 1.01]	0.008	0.84
	1,2,3,5	4	1.06	[0.98, 1.16]	0.019	0.81
	1,2,3,4	5	1.11	[1.02, 1.14]	0.008	0.81
	Average		1.05	[0.98, 1.11]	0.014	0.81
CO Emission Rate	2,3,4,5	1	0.93	[0.89, 0.97]	0.046	0.50
	1,3,4,5	2	0.80	[0.77, 0.88]	0.021	0.60
	1,2,4,5	3	1.12	[1.05, 1.20]	0.040	0.53
	1,2,3,5	4	1.34	[1.33, 1.38]	0.059	0.49
	1,2,3,4	5	0.92	[0.89, 0.95]	0.034	0.48
	Average		1.02	[0.98, 1.08]	0.040	0.52

Table F-30 Continued on next page.

Table F-30 Continued from previous page.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5	1	0.99	[0.83, 1.09]	0.052	0.08
	1,3,4,5	2	0.65	[0.60, 0.76]	0.042	0.10
	1,2,4,5	3	0.90	[0.84, 1.02]	0.055	0.11
	1,2,3,5	4	1.26	[1.20, 1.39]	0.062	0.10
	1,2,3,4	5	1.19	[1.13, 1.31]	0.054	0.09
	Average		1.00	[0.92, 1.12]	0.053	0.10
NO_x Emission Rate	2,3,4,5	1	0.86	[0.78, 0.90]	0.008	0.75
	1,3,4,5	2	1.06	[1.05, 1.10]	0.020	0.76
	1,2,4,5	3	0.91	[0.83, 0.92]	0.005	0.87
	1,2,3,5	4	1.02	[0.97, 1.02]	0.008	0.85
	1,2,3,4	5	0.86	[0.81, 0.95]	0.005	0.80
	Average		0.94	[0.89, 0.98]	0.009	0.81
PM Emission Rate	2,3,4,5	1	0.97	[0.92, 1.01]	0.009	0.78
	1,3,4,5	2	0.97	[0.91, 0.99]	0.022	0.82
	1,2,4,5	3	0.96	[0.89, 0.98]	0.023	0.81
	1,2,3,5	4	1.02	[1.01, 1.10]	0.007	0.81
	1,2,3,4	5	1.10	[1.04, 1.13]	0.013	0.75
	Average		1.00	[0.96, 1.04]	0.015	0.79

TABLE F-31. Validation Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1893 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	1.13	[1.04, 1.19]	0.015	0.78
	1,3,4,5,6	2	1.10	[1.09, 1.18]	0.023	0.76
	1,2,4,5,6	3	1.07	[1.04, 1.15]	0.006	0.79
	1,2,3,5,6	4	0.92	[0.85, 0.97]	0.013	0.81
	1,2,3,4,6	5	0.86	[0.81, 0.95]	0.015	0.76
	1,2,3,4,5	6	1.02	[1.09, 1.09]	0.014	0.75
	Average		1.02	[1.09, 1.09]	0.014	0.78
CO_2 Emission Rate	2,3,4,5,6	1	1.12	[1.03, 1.18]	0.015	0.80
	1,3,4,5,6	2	1.11	[1.11, 1.18]	0.023	0.77
	1,2,4,5,6	3	1.07	[1.03, 1.14]	0.006	0.81
	1,2,3,5,6	4	0.91	[0.84, 0.97]	0.013	0.82
	1,2,3,4,6	5	0.88	[0.80, 0.94]	0.015	0.74
	1,2,3,4,5	6	1.01	[1.07, 1.08]	0.014	0.76
	Average		1.02	[0.96, 1.05]	0.014	0.78
CO Emission Rate	2,3,4,5,6	1	1.17	[1.15, 1.26]	0.036	0.41
	1,3,4,5,6	2	1.19	[1.10, 1.23]	0.056	0.44
	1,2,4,5,6	3	1.01	[0.95, 1.05]	0.053	0.52
	1,2,3,5,6	4	1.13	[1.04, 1.19]	0.015	0.46
	1,2,3,4,6	5	1.10	[1.09, 1.18]	0.023	0.47
	1,2,3,4,5	6	1.07	[1.04, 1.15]	0.006	0.44
	Average		1.08	[1.02, 1.14]	0.044	0.46

Table F-31 Continued on next page.

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Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.59	[0.43, 0.75]	0.031	0.05
	1,3,4,5,6	2	0.90	[0.81, 1.04]	0.055	0.06
	1,2,4,5,6	3	1.27	[1.17, 1.39]	0.057	0.10
	1,2,3,5,6	4	1.34	[1.30, 1.52]	0.080	0.06
	1,2,3,4,6	5	0.72	[0.63, 0.81]	0.043	0.09
	1,2,3,4,5	6	0.96	[0.87, 1.10]	0.053	0.10
	Average		0.96	[0.87, 1.10]	0.053	0.08
NO_x Emission Rate	2,3,4,5,6	1	1.04	[0.97, 1.07]	0.006	0.71
	1,3,4,5,6	2	0.98	[0.93, 1.03]	0.024	0.73
	1,2,4,5,6	3	1.06	[0.99, 1.14]	0.026	0.73
	1,2,3,5,6	4	1.06	[1.04, 1.07]	0.024	0.69
	1,2,3,4,6	5	0.59	[0.43, 0.75]	0.031	0.76
	1,2,3,4,5	6	0.90	[0.81, 1.04]	0.055	0.75
	Average		1.04	[0.97, 1.08]	0.021	0.73

TABLE F-32. Validation Locomotive Power Demand Model Parameters with Lagged Error Terms for Double-Powered Consist with Locomotive NC 1871 operated on Ultra-low Sulfur Diesel based on Jan-Feb 2019 Measurements.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.90	[0.85, 0.99]	0.022	0.87
	2,6	4	0.90	[0.87, 0.90]	0.013	0.86
	2,4	6	1.10	[1.03, 1.14]	0.027	0.89
	Average		1.00	[0.98, 1.04]	0.016	0.85
CO_2 Emission Rate	4,6	2	0.89	[0.83, 0.98]	0.022	0.89
	2,6	4	0.88	[0.89, 0.89]	0.013	0.88
	2,4	6	1.11	[1.03, 1.14]	0.027	0.89
	Average		0.96	[0.92, 1.00]	0.021	0.88
CO Emission Rate	4,6	2	0.90	[0.77, 0.93]	0.009	0.86
	2,6	4	1.10	[1.09, 1.18]	0.010	0.88
	2,4	6	1.10	[1.11, 1.16]	0.006	0.88
	Average		0.80	[0.77, 0.88]	0.029	0.27
HC Emission Rate	4,6	2	1.30	[1.12, 1.35]	0.065	0.15
	2,6	4	1.20	[1.14, 1.32]	0.068	0.13
	2,4	6	1.40	[1.33, 1.56]	0.083	0.16
	Average		1.20	[1.08, 1.31]	0.068	0.14
NO_x Emission Rate	4,6	2	1.20	[1.12, 1.35]	0.074	0.16
	2,6	4	1.20	[1.08, 1.31]	0.068	0.14
	2,4	6	0.90	[0.84, 0.91]	0.007	0.72
	Average		1.00	[0.93, 1.03]	0.012	0.73
PM Emission Rate	4,6	2	1.10	[1.03, 1.14]	0.005	0.75
	2,6	4	0.90	[0.84, 0.97]	0.021	0.72
	2,4	6	1.10	[1.04, 1.09]	0.018	0.71
	Average		1.00	[0.95, 1.06]	0.019	0.76

TABLE F-33. Validation Locomotive Power Demand Model Parameters with Lagged Error Terms for the Single-Powered Consist with Locomotive NC 1871 operated on Ultra-low Sulfur Diesel based on Jan-Feb 2019 Measurements.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.87	[0.85, 0.87]	0.019	0.72
	2,6	4	0.87	[0.85, 0.88]	0.020	0.73
	2,4	6	1.12	[1.09, 1.15]	0.024	0.70
	Average		0.95	[0.93, 0.97]	0.021	0.72
CO_2 Emission Rate	4,6	2	1.09	[1.03, 1.16]	0.010	0.69
	2,6	4	0.93	[0.84, 0.98]	0.015	0.69
	2,4	6	1.05	[0.97, 1.12]	0.015	0.74
	Average		1.03	[0.95, 1.09]	0.013	0.71
CO Emission Rate	4,6	2	0.97	[0.95, 1.03]	0.036	0.32
	2,6	4	0.76	[0.67, 0.85]	0.020	0.36
	2,4	6	1.34	[1.26, 1.40]	0.070	0.37
	Average		1.02	[0.96, 1.09]	0.042	0.35
HC Emission Rate	4,6	2	0.48	[0.39, 0.66]	0.031	0.00
	2,6	4	1.05	[0.87, 1.16]	0.055	0.01
	2,4	6	0.75	[0.64, 0.91]	0.035	0.01
	Average		0.76	[0.64, 0.91]	0.040	0.01
NO_x Emission Rate	4,6	2	1.12	[1.06, 1.13]	0.021	0.73
	2,6	4	1.15	[1.08, 1.17]	0.006	0.68
	2,4	6	0.90	[0.89, 0.96]	0.010	0.69
	Average		1.06	[1.01, 1.09]	0.012	0.70
PM Emission Rate	4,6	2	1.07	[1.05, 1.14]	0.027	0.66
	2,6	4	1.00	[0.96, 1.07]	0.022	0.67
	2,4	6	0.94	[0.85, 1.03]	0.008	0.67
	Average		1.00	[0.95, 1.08]	0.019	0.67

TABLE F-34. Validation Locomotive Power Demand Model Parameters with Lagged Error Terms for Double-Powered Consist with Locomotive NC 1984 operated on Ultra-low Sulfur Diesel based on June 2019.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.86	[0.84, 0.86]	0.011	0.68
	2,6	4	1.09	[1.08, 1.11]	0.025	0.67
	2,4	6	0.93	[0.85, 1.03]	0.013	0.69
	Average		0.96	[0.94, 1.00]	0.016	0.68
CO_2 Emission Rate	4,6	2	0.98	[0.96, 1.04]	0.009	0.61
	2,6	4	0.93	[0.85, 0.99]	0.016	0.60
	2,4	6	1.07	[1.06, 1.09]	0.005	0.61
	Average		0.99	[0.96, 1.04]	0.010	0.61
CO Emission Rate	4,6	2	1.26	[1.17, 1.28]	0.051	0.26
	2,6	4	1.29	[1.25, 1.36]	0.055	0.25
	2,4	6	1.32	[1.23, 1.36]	0.062	0.24
	Average		1.29	[1.22, 1.33]	0.056	0.25
HC Emission Rate	4,6	2	0.86	[0.72, 0.94]	0.056	0.01
	2,6	4	0.59	[0.42, 0.77]	0.032	0.01
	2,4	6	1.26	[1.16, 1.34]	0.058	0.01
	Average		0.90	[0.76, 1.02]	0.049	0.01
NO_x Emission Rate	4,6	2	0.86	[0.83, 0.93]	0.019	0.68
	2,6	4	1.02	[1.00, 1.04]	0.020	0.62
	2,4	6	1.05	[0.99, 1.08]	0.009	0.65
	Average		0.98	[0.94, 1.02]	0.016	0.65
PM Emission Rate	4,6	2	1.07	[0.98, 1.15]	0.010	0.62
	2,6	4	1.00	[0.96, 1.06]	0.014	0.62
	2,4	6	0.89	[0.83, 0.95]	0.005	0.62
	Average		0.99	[0.93, 1.05]	0.010	0.62

TABLE F-35. Validation Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Powered Consist with Locomotive NC 1984 operated on Ultra-low Sulfur Diesel based on June 2019.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	1.08	[0.99, 1.11]	0.008	0.73
	2,6	4	1.12	[1.08, 1.20]	0.020	0.70
	2,4	6	1.09	[1.01, 1.09]	0.016	0.77
	Average		1.10	[1.09, 1.13]	0.015	0.73
CO_2 Emission Rate	4,6	2	1.02	[0.96, 1.06]	0.013	0.80
	2,6	4	1.03	[0.99, 1.07]	0.026	0.75
	2,4	6	1.06	[1.04, 1.13]	0.017	0.72
	Average		1.03	[0.99, 1.09]	0.019	0.76
CO Emission Rate	4,6	2	1.02	[0.99, 1.04]	0.030	0.48
	2,6	4	1.23	[1.21, 1.25]	0.055	0.45
	2,4	6	0.96	[0.92, 0.98]	0.039	0.43
	Average		1.07	[1.04, 1.09]	0.041	0.45
HC Emission Rate	4,6	2	0.58	[0.46, 0.77]	0.035	0.03
	2,6	4	0.51	[0.41, 0.60]	0.030	0.03
	2,4	6	0.92	[0.80, 1.09]	0.054	0.03
	Average		0.67	[0.56, 0.82]	0.040	0.03
NO_x Emission Rate	4,6	2	1.11	[1.02, 1.19]	0.025	0.77
	2,6	4	0.90	[0.82, 0.93]	0.008	0.73
	2,4	6	1.06	[0.99, 1.10]	0.023	0.75
	Average		1.02	[0.94, 1.07]	0.019	0.75
PM Emission Rate	4,6	2	1.05	[0.96, 1.08]	0.025	0.67
	2,6	4	1.07	[0.99, 1.09]	0.021	0.63
	2,4	6	1.04	[0.97, 1.08]	0.007	0.65
	Average		1.05	[0.97, 1.09]	0.018	0.65

TABLE F-36. Validation Locomotive Power Demand Model Parameters with Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1810 operated on B20 Biodiesel Blend.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.88	[0.81, 0.98]	0.022	0.79
	1,3,4,5,6	2	0.86	[0.79, 0.91]	0.015	0.89
	1,2,4,5,6	3	0.86	[0.82, 0.87]	0.012	0.81
	1,2,3,5,6	4	1.08	[1.04, 1.15]	0.025	0.82
	1,2,3,4,6	5	1.11	[1.01, 1.14]	0.006	0.92
	1,2,3,4,5	6	1.00	[0.91, 1.02]	0.012	0.87
	Average		0.97	[0.95, 1.01]	0.015	0.85
CO_2 Emission Rate	2,3,4,5,6	1	1.02	[0.95, 1.03]	0.015	0.82
	1,3,4,5,6	2	1.05	[0.96, 1.07]	0.021	0.90
	1,2,4,5,6	3	1.12	[1.06, 1.17]	0.006	0.82
	1,2,3,5,6	4	0.90	[0.88, 0.90]	0.021	0.87
	1,2,3,4,6	5	1.13	[1.04, 1.18]	0.024	0.85
	1,2,3,4,5	6	0.95	[0.89, 0.95]	0.014	0.90
	Average		1.03	[0.96, 1.05]	0.017	0.86
CO Emission Rate	2,3,4,5,6	1	0.84	[0.76, 0.86]	0.034	0.37
	1,3,4,5,6	2	0.93	[0.86, 0.98]	0.047	0.39
	1,2,4,5,6	3	1.06	[1.03, 1.08]	0.042	0.40
	1,2,3,5,6	4	0.78	[0.72, 0.80]	0.043	0.37
	1,2,3,4,6	5	0.79	[0.73, 0.85]	0.034	0.45
	1,2,3,4,5	6	0.72	[0.67, 0.79]	0.036	0.36
	Average		0.85	[0.79, 0.89]	0.039	0.39

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Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.79	[0.68, 0.93]	0.050	0.06
	1,3,4,5,6	2	0.93	[0.83, 1.02]	0.042	0.06
	1,2,4,5,6	3	1.25	[1.15, 1.36]	0.074	0.07
	1,2,3,5,6	4	1.40	[1.23, 1.50]	0.064	0.04
	1,2,3,4,6	5	1.43	[1.24, 1.55]	0.087	0.08
	1,2,3,4,5	6	1.05	[0.92, 1.17]	0.055	0.05
	Average		1.14	[1.01, 1.25]	0.062	0.06
NO_x Emission Rate	2,3,4,5,6	1	1.08	[1.00, 1.13]	0.008	0.81
	1,3,4,5,6	2	0.90	[0.81, 0.99]	0.007	0.77
	1,2,4,5,6	3	0.98	[0.90, 1.07]	0.009	0.83
	1,2,3,5,6	4	1.02	[0.96, 1.03]	0.013	0.80
	1,2,3,4,6	5	1.07	[1.02, 1.07]	0.005	0.78
	1,2,3,4,5	6	0.97	[0.95, 0.99]	0.014	0.77
	Average		1.00	[0.94, 1.05]	0.009	0.79
PM Emission Rate	2,3,4,5,6	1	1.07	[1.00, 1.08]	0.018	0.63
	1,3,4,5,6	2	1.07	[0.98, 1.13]	0.025	0.72
	1,2,4,5,6	3	1.01	[0.98, 1.03]	0.014	0.71
	1,2,3,5,6	4	0.90	[0.86, 0.92]	0.023	0.72
	1,2,3,4,6	5	1.10	[1.01, 1.11]	0.025	0.71
	1,2,3,4,5	6	1.10	[1.07, 1.19]	0.024	0.68
	Average		1.04	[0.98, 1.08]	0.021	0.69

TABLE F-37. Validation Locomotive Power Demand Model Parameters with Lagged Error Terms for the Single-Locomotive Consist with Locomotive NC 1797 operated on B20 Biodiesel Blend.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	1.14	[1.10, 1.17]	0.009	0.79
	1,3,4,5,6	2	0.96	[0.93, 0.97]	0.022	0.82
	1,2,4,5,6	3	0.89	[0.85, 0.97]	0.007	0.90
	1,2,3,5,6	4	1.11	[1.02, 1.15]	0.018	0.82
	1,2,3,4,6	5	1.04	[1.02, 1.08]	0.009	0.88
	1,2,3,4,5	6	1.03	[1.07, 1.07]	0.013	0.84
	Average		1.03	[1.07, 1.07]	0.013	0.84
CO_2 Emission Rate	2,3,4,5,6	1	1.09	[1.03, 1.11]	0.007	0.88
	1,3,4,5,6	2	1.15	[1.13, 1.16]	0.017	0.88
	1,2,4,5,6	3	1.15	[1.08, 1.24]	0.022	0.82
	1,2,3,5,6	4	1.00	[0.97, 1.10]	0.020	0.83
	1,2,3,4,6	5	1.09	[1.05, 1.14]	0.015	0.85
	1,2,3,4,5	6	0.73	[0.64, 0.81]	0.018	0.28
	Average		1.09	[1.05, 1.14]	0.015	0.85
CO Emission Rate	2,3,4,5,6	1	0.88	[0.81, 0.92]	0.030	0.28
	1,3,4,5,6	2	1.20	[1.11, 1.24]	0.040	0.27
	1,2,4,5,6	3	1.15	[1.13, 1.20]	0.046	0.30
	1,2,3,5,6	4	1.04	[0.98, 1.09]	0.038	0.28
	1,2,3,4,6	5	1.14	[1.10, 1.17]	0.009	0.79
	1,2,3,4,5	6	0.96	[0.93, 0.97]	0.022	0.82
	Average		1.04	[0.98, 1.09]	0.038	0.28

Table F-37 Continued on next page.

Table F-37 Continued from previous page.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	1.32	[1.18, 1.45]	0.080	0.14
	1,3,4,5,6	2	0.66	[0.65, 0.78]	0.042	0.13
	1,2,4,5,6	3	1.39	[1.37, 1.50]	0.067	0.17
	1,2,3,5,6	4	1.11	[1.09, 1.30]	0.053	0.13
	1,2,3,4,6	5	1.40	[1.35, 1.49]	0.063	0.17
	1,2,3,4,5	6	1.17	[1.13, 1.30]	0.061	0.15
	Average		1.17	[1.13, 1.30]	0.061	0.15
NO_x Emission Rate	2,3,4,5,6	1	0.98	[0.95, 0.99]	0.016	0.67
	1,3,4,5,6	2	0.90	[0.81, 0.90]	0.008	0.75
	1,2,4,5,6	3	0.93	[0.88, 1.00]	0.015	0.65
	1,2,3,5,6	4	1.02	[0.93, 1.04]	0.007	0.64
	1,2,3,4,6	5	0.97	[0.92, 1.01]	0.012	0.69
	1,2,3,4,5	6	0.86	[0.85, 0.92]	0.018	0.75
	Average		0.97	[0.92, 1.01]	0.012	0.69
PM Emission Rate	2,3,4,5,6	1	0.98	[0.91, 0.99]	0.008	0.73
	1,3,4,5,6	2	1.13	[1.10, 1.21]	0.007	0.72
	1,2,4,5,6	3	1.05	[0.97, 1.07]	0.011	0.80
	1,2,3,5,6	4	1.32	[1.18, 1.45]	0.080	0.77
	1,2,3,4,6	5	0.66	[0.65, 0.78]	0.042	0.72
	1,2,3,4,5	6	1.39	[1.37, 1.50]	0.067	0.71
	Average		1.01	[0.96, 1.04]	0.012	0.74

TABLE F-38. Validation Locomotive Power Demand Model Parameters with Lagged Error Terms for the Single-Locomotive Consist with Locomotive NC 1859 operated on B20 Biodiesel Blend.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2-15	1	0.90	[0.85, 0.96]	0.023	0.65
	1, 3-15	2	0.97	[0.91, 0.99]	0.014	0.64
	1-2, 4-15	3	0.90	[0.85, 0.96]	0.023	0.63
	1-3, 5-15	4	1.00	[0.92, 1.01]	0.015	0.68
	1-4, 6-15	5	0.88	[0.83, 0.93]	0.004	0.67
	1-5, 7-15	6	0.95	[0.93, 1.01]	0.025	0.64
	1-6, 8-15	7	1.15	[1.07, 1.22]	0.036	0.63
	1-7, 9-15	8	1.07	[1.00, 1.14]	0.027	0.66
	1-8, 10-15	9	0.96	[0.88, 1.06]	0.015	0.67
	1-9, 11-15	10	1.04	[0.94, 1.12]	0.014	0.63
	1-10, 12-15	11	1.09	[1.05, 1.17]	0.023	0.62
	1 -11, 13-15	12	0.90	[0.89, 0.99]	0.024	0.63
	1-12, 14-15	13	0.97	[0.91, 1.05]	0.025	0.67
	1-13, 15	14	0.88	[0.84, 0.96]	0.024	0.67
	1-14	15	1.10	[1.02, 1.14]	0.015	0.67
	Average		0.98	[0.05, 1.05]	0.014	0.65
CO_2 Emission Rate	2-15	1	0.95	[0.92, 1.00]	0.024	0.70
	1, 3-15	2	0.96	[0.89, 0.96]	0.025	0.68
	1-2, 4-15	3	0.94	[0.87, 1.04]	0.024	0.66
	1-3, 5-15	4	1.00	[0.96, 1.00]	0.023	0.67
	1-4, 6-15	5	1.15	[1.10, 1.24]	0.033	0.70
	1-5, 7-15	6	1.10	[1.07, 1.11]	0.024	0.64
	1-6, 8-15	7	0.94	[0.87, 0.99]	0.025	0.63
	1-7, 9-15	8	1.09	[1.06, 1.13]	0.026	0.70
	1-8, 10-15	9	0.91	[0.83, 0.96]	0.014	0.69
	1-9, 11-15	10	1.07	[1.02, 1.12]	0.013	0.63
	1-10, 12-15	11	1.05	[1.01, 1.12]	0.012	0.68
	1 -11, 13-15	12	0.86	[0.85, 0.88]	0.023	0.67
	1-12, 14-15	13	1.05	[1.01, 1.12]	0.024	0.68
	1-13, 15	14	1.15	[1.08, 1.22]	0.025	0.66
	1-14	15	1.15	[1.05, 1.18]	0.023	0.65
	Average		1.02	[0.97, 1.06]	0.024	0.67

Table F-38 Continued on next page.

Table F-38 Continued from previous page.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
CO Emission Rate	2-15	1	0.89	[0.84, 0.96]	0.043	0.10
	1, 3-15	2	0.88	[0.86, 0.96]	0.045	0.10
	1-2, 4-15	3	1.05	[0.99, 1.15]	0.044	0.11
	1-3, 5-15	4	1.06	[0.96, 1.15]	0.045	0.14
	1-4, 6-15	5	0.66	[0.57, 0.75]	0.023	0.11
	1-5, 7-15	6	0.65	[0.64, 0.72]	0.033	0.12
	1-6, 8-15	7	1.30	[1.28, 1.38]	0.045	0.12
	1-7, 9-15	8	0.89	[0.86, 0.90]	0.057	0.13
	1-8, 10-15	9	1.24	[1.15, 1.27]	0.038	0.12
	1-9, 11-15	10	0.95	[0.92, 1.02]	0.055	0.12
	1-10, 12-15	11	0.92	[0.87, 1.02]	0.024	0.11
	1 -11, 13-15	12	0.82	[0.75, 0.89]	0.046	0.11
	1-12, 14-15	13	0.99	[0.96, 1.05]	0.055	0.10
	1-13, 15	14	0.90	[0.84, 0.94]	0.054	0.12
	1-14	15	1.25	[1.16, 1.34]	0.055	0.12
	Average		0.96	[0.81, 0.95]	0.046	0.12
HC Emission Rate	2-15	1	0.75	[0.64, 0.84]	0.054	0.12
	1, 3-15	2	0.70	[0.59, 0.88]	0.043	0.12
	1-2, 4-15	3	0.71	[0.58, 0.91]	0.045	0.12
	1-3, 5-15	4	1.15	[1.03, 1.27]	0.067	0.11
	1-4, 6-15	5	0.95	[0.77, 1.12]	0.059	0.12
	1-5, 7-15	6	1.25	[1.12, 1.45]	0.067	0.13
	1-6, 8-15	7	1.44	[1.35, 1.56]	0.076	0.14
	1-7, 9-15	8	1.21	[1.02, 1.40]	0.074	0.15
	1-8, 10-15	9	0.57	[0.47, 0.74]	0.033	0.13
	1-9, 11-15	10	0.91	[0.74, 1.10]	0.064	0.15
	1-10, 12-15	11	1.12	[0.94, 1.25]	0.075	0.11
	1 -11, 13-15	12	0.62	[0.42, 0.76]	0.036	0.13
	1-12, 14-15	13	1.25	[1.15, 1.40]	0.068	0.10
	1-13, 15	14	0.58	[0.38, 0.71]	0.035	0.13
	1-14	15	0.67	[0.58, 0.85]	0.036	0.12
	Average		0.92	[0.79, 1.08]	0.053	0.13

Table F-38 Continued on next page.

Table F-38 Continued from previous page.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
NO_x Emission Rate	2-15	1	0.94	[0.91, 0.99]	0.013	0.75
	1, 3-15	2	0.98	[0.97, 0.99]	0.015	0.75
	1-2, 4-15	3	0.92	[0.87, 1.02]	0.028	0.66
	1-3, 5-15	4	0.94	[0.89, 1.02]	0.016	0.69
	1-4, 6-15	5	0.85	[0.80, 0.91]	0.025	0.74
	1-5, 7-15	6	1.05	[1.04, 1.12]	0.014	0.73
	1-6, 8-15	7	1.12	[1.04, 1.14]	0.033	0.66
	1-7, 9-15	8	0.95	[0.85, 0.97]	0.024	0.67
	1-8, 10-15	9	1.05	[0.97, 1.11]	0.026	0.74
	1-9, 11-15	10	0.86	[0.78, 0.95]	0.018	0.70
	1-10, 12-15	11	0.96	[0.87, 0.98]	0.029	0.67
	1 -11, 13-15	12	0.88	[0.86, 0.97]	0.020	0.67
	1-12, 14-15	13	1.14	[1.08, 1.18]	0.028	0.75
	1-13, 15	14	0.95	[0.88, 1.01]	0.025	0.77
	1-14	15	0.87	[0.84, 0.88]	0.014	0.69
	Average		0.96	[0.91, 1.01]	0.024	0.71
PM Emission Rate	2-15	1	0.97	[0.90, 0.98]	0.024	0.55
	1, 3-15	2	1.12	[1.08, 1.21]	0.025	0.56
	1-2, 4-15	3	1.11	[1.01, 1.12]	0.014	0.51
	1-3, 5-15	4	1.02	[0.97, 1.12]	0.013	0.55
	1-4, 6-15	5	1.03	[1.01, 1.06]	0.025	0.50
	1-5, 7-15	6	1.12	[1.08, 1.13]	0.016	0.53
	1-6, 8-15	7	1.09	[1.02, 1.11]	0.037	0.54
	1-7, 9-15	8	0.92	[0.84, 1.00]	0.015	0.51
	1-8, 10-15	9	1.14	[1.08, 1.15]	0.024	0.52
	1-9, 11-15	10	0.86	[0.86, 0.94]	0.013	0.54
	1-10, 12-15	11	1.07	[1.00, 1.12]	0.013	0.57
	1 -11, 13-15	12	0.86	[0.79, 0.91]	0.015	0.51
	1-12, 14-15	13	1.09	[1.07, 1.13]	0.037	0.51
	1-13, 15	14	1.01	[0.94, 1.02]	0.016	0.56
	1-14	15	0.95	[0.90, 0.98]	0.017	0.50
	Average		1.02	[1.01, 1.10]	0.016	0.53

TABLE F-39. Validation Locomotive Power Demand Model Parameters without Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1797 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5	1	1.16	[1.06, 1.25]	0.013	0.83
	1,3,4,5	2	1.17	[1.07, 1.26]	0.007	0.81
	1,2,4,5	3	0.95	[0.90, 0.99]	0.017	0.75
	1,2,3,5	4	1.14	[1.11, 1.18]	0.009	0.77
	1,2,3,4	5	1.00	[0.93, 1.08]	0.016	0.87
	Average		1.08	[1.02, 1.15]	0.012	0.81
CO_2 Emission Rate	2,3,4,5	1	1.15	[1.06, 1.25]	0.013	0.84
	1,3,4,5	2	1.16	[1.07, 1.26]	0.007	0.77
	1,2,4,5	3	0.92	[0.88, 0.96]	0.017	0.76
	1,2,3,5	4	1.20	[1.17, 1.23]	0.008	0.75
	1,2,3,4	5	0.97	[0.89, 1.04]	0.016	0.87
	Average		1.08	[1.01, 1.15]	0.012	0.80
CO Emission Rate	2,3,4,5	1	1.06	[0.99, 1.13]	0.051	0.51
	1,3,4,5	2	0.83	[0.68, 0.98]	0.036	0.46
	1,2,4,5	3	0.85	[0.71, 0.99]	0.040	0.48
	1,2,3,5	4	0.87	[0.69, 1.04]	0.043	0.39
	1,2,3,4	5	1.08	[0.94, 1.22]	0.056	0.45
	Average		0.94	[0.80, 1.07]	0.045	0.46

Table F-39 Continued on next page.

Table F-39 Continued from previous page.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5	1	1.64	[1.35, 1.93]	0.105	0.07
	1,3,4,5	2	0.70	[0.49, 0.90]	0.036	0.03
	1,2,4,5	3	0.84	[0.73, 0.95]	0.052	0.07
	1,2,3,5	4	0.64	[0.49, 0.79]	0.036	0.03
	1,2,3,4	5	0.67	[0.49, 0.86]	0.042	0.06
	Average		0.90	[0.71, 1.09]	0.054	0.05
NO_x Emission Rate	2,3,4,5	1	0.95	[0.87, 1.02]	0.021	0.64
	1,3,4,5	2	1.04	[0.99, 1.08]	0.015	0.62
	1,2,4,5	3	1.09	[1.03, 1.16]	0.014	0.64
	1,2,3,5	4	1.10	[0.96, 1.24]	0.015	0.73
	1,2,3,4	5	0.92	[0.86, 0.99]	0.020	0.69
	Average		1.02	[0.94, 1.10]	0.017	0.66
PM Emission Rate	2,3,4,5	1	0.91	[0.73, 1.10]	0.021	0.49
	1,3,4,5	2	1.23	[1.09, 1.38]	0.021	0.53
	1,2,4,5	3	1.27	[1.15, 1.38]	0.010	0.56
	1,2,3,5	4	1.05	[0.90, 1.20]	0.027	0.52
	1,2,3,4	5	0.98	[0.94, 1.01]	0.025	0.63
	Average		1.09	[0.96, 1.21]	0.021	0.55

TABLE F-40. Validation Locomotive Power Demand Model Parameters without Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1810 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.99	[0.97, 1.01]	0.009	0.73
	1,3,4,5,6	2	0.95	[0.91, 0.99]	0.018	0.71
	1,2,4,5,6	3	0.92	[0.88, 0.96]	0.020	0.71
	1,2,3,5,6	4	1.03	[1.00, 1.06]	0.013	0.75
	1,2,3,4,6	5	1.02	[1.00, 1.04]	0.010	0.76
	1,2,3,4,5	6	0.93	[0.89, 0.97]	0.019	0.72
	Average		0.97	[0.94, 1.01]	0.015	0.73
CO_2 Emission Rate	2,3,4,5,6	1	0.99	[0.97, 1.01]	0.009	0.72
	1,3,4,5,6	2	0.95	[0.91, 0.99]	0.019	0.70
	1,2,4,5,6	3	0.92	[0.88, 0.96]	0.020	0.72
	1,2,3,5,6	4	1.03	[1.00, 1.06]	0.013	0.73
	1,2,3,4,6	5	1.02	[1.00, 1.04]	0.010	0.74
	1,2,3,4,5	6	0.93	[0.89, 0.97]	0.019	0.72
	Average		0.97	[0.94, 1.01]	0.015	0.72
CO Emission Rate	2,3,4,5,6	1	1.08	[0.93, 1.22]	0.048	0.44
	1,3,4,5,6	2	1.19	[1.08, 1.29]	0.042	0.44
	1,2,4,5,6	3	0.86	[0.74, 0.98]	0.043	0.47
	1,2,3,5,6	4	1.30	[1.24, 1.35]	0.041	0.46
	1,2,3,4,6	5	1.36	[1.29, 1.42]	0.042	0.43
	1,2,3,4,5	6	1.07	[0.90, 1.24]	0.028	0.48
	Average		1.14	[1.03, 1.25]	0.041	0.45

Table F-40 Continued on next page.

Table F-40 Continued from previous page.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	1.32	[1.05, 1.60]	0.058	0.26
	1,3,4,5,6	2	0.76	[0.48, 1.04]	0.038	0.18
	1,2,4,5,6	3	1.13	[0.75, 1.51]	0.055	0.25
	1,2,3,5,6	4	1.01	[0.59, 1.43]	0.058	0.20
	1,2,3,4,6	5	0.78	[0.50, 1.07]	0.038	0.19
	1,2,3,4,5	6	1.46	[1.15, 1.76]	0.075	0.17
	Average		1.08	[0.75, 1.40]	0.054	0.21
NO_x Emission Rate	2,3,4,5,6	1	1.13	[1.07, 1.20]	0.007	0.76
	1,3,4,5,6	2	1.07	[0.92, 1.22]	0.027	0.73
	1,2,4,5,6	3	1.01	[0.94, 1.09]	0.008	0.76
	1,2,3,5,6	4	1.08	[1.03, 1.13]	0.024	0.72
	1,2,3,4,6	5	1.02	[0.96, 1.08]	0.023	0.78
	1,2,3,4,5	6	1.01	[0.89, 1.13]	0.008	0.75
	Average		1.05	[0.97, 1.14]	0.016	0.75
PM Emission Rate	2,3,4,5,6	1	1.12	[0.98, 1.26]	0.009	0.65
	1,3,4,5,6	2	1.11	[1.01, 1.21]	0.029	0.58
	1,2,4,5,6	3	0.98	[0.91, 1.06]	0.021	0.65
	1,2,3,5,6	4	1.17	[1.13, 1.20]	0.029	0.60
	1,2,3,4,6	5	1.20	[1.14, 1.26]	0.021	0.59
	1,2,3,4,5	6	1.05	[0.91, 1.19]	0.014	0.60
	Average		1.10	[1.01, 1.20]	0.020	0.61

TABLE F-41. Validation Locomotive Power Demand Model Parameters without Lagged Error Terms for Tandem-Locomotive Consist with Locomotive NC 1859 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5	1	1.08	[1.03, 1.13]	0.009	0.76
	1,3,4,5	2	1.10	[0.98, 1.22]	0.005	0.75
	1,2,4,5	3	1.08	[1.01, 1.15]	0.020	0.72
	1,2,3,5	4	0.93	[0.90, 0.96]	0.010	0.77
	1,2,3,4	5	0.94	[0.78, 1.11]	0.004	0.83
	Average		1.03	[0.94, 1.11]	0.010	0.76
CO_2 Emission Rate	2,3,4,5	1	1.11	[1.06, 1.17]	0.021	0.69
	1,3,4,5	2	1.12	[0.95, 1.30]	0.017	0.81
	1,2,4,5	3	1.00	[0.82, 1.17]	0.008	0.76
	1,2,3,5	4	1.11	[0.92, 1.31]	0.020	0.74
	1,2,3,4	5	1.21	[1.08, 1.34]	0.009	0.75
	Average		1.11	[0.97, 1.26]	0.015	0.75
CO Emission Rate	2,3,4,5	1	1.01	[0.92, 1.11]	0.050	0.45
	1,3,4,5	2	0.86	[0.73, 0.98]	0.024	0.51
	1,2,4,5	3	1.25	[1.09, 1.42]	0.043	0.47
	1,2,3,5	4	1.43	[1.38, 1.49]	0.063	0.45
	1,2,3,4	5	1.01	[0.95, 1.08]	0.038	0.41
	Average		1.11	[1.01, 1.21]	0.044	0.46

Table F-41 Continued on next page.

Table F-41 Continued from previous page.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5	1	1.17	[0.88, 1.46]	0.055	0.07
	1,3,4,5	2	0.72	[0.53, 0.91]	0.047	0.09
	1,2,4,5	3	1.01	[0.81, 1.21]	0.065	0.10
	1,2,3,5	4	1.36	[1.16, 1.56]	0.073	0.09
	1,2,3,4	5	1.27	[1.06, 1.48]	0.058	0.08
	Average		1.11	[0.89, 1.33]	0.060	0.09
NO_x Emission Rate	2,3,4,5	1	0.92	[0.79, 1.05]	0.009	0.68
	1,3,4,5	2	1.16	[1.10, 1.21]	0.022	0.68
	1,2,4,5	3	0.96	[0.87, 1.06]	0.005	0.81
	1,2,3,5	4	1.12	[1.07, 1.18]	0.009	0.78
	1,2,3,4	5	0.92	[0.77, 1.07]	0.005	0.73
	Average		1.02	[0.92, 1.11]	0.010	0.74
PM Emission Rate	2,3,4,5	1	1.04	[0.94, 1.13]	0.010	0.73
	1,3,4,5	2	1.09	[1.00, 1.17]	0.024	0.76
	1,2,4,5	3	1.05	[0.95, 1.14]	0.025	0.72
	1,2,3,5	4	1.14	[1.05, 1.24]	0.008	0.76
	1,2,3,4	5	1.16	[1.06, 1.25]	0.015	0.71
	Average		1.09	[1.00, 1.19]	0.016	0.74

TABLE F-42. Validation Locomotive Power Demand Model Parameters without Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1893 operated on Ultra-low Sulfur Diesel.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.92	[0.88, 0.96]	0.016	0.70
	1,3,4,5,6	2	0.88	[0.85, 0.92]	0.025	0.70
	1,2,4,5,6	3	0.96	[0.93, 0.99]	0.007	0.75
	1,2,3,5,6	4	0.98	[0.95, 1.02]	0.014	0.75
	1,2,3,4,6	5	0.90	[0.85, 0.95]	0.017	0.69
	1,2,3,4,5	6	0.87	[0.82, 0.90]	0.015	0.70
	Average		0.92	[0.88, 0.95]	0.016	0.71
CO_2 Emission Rate	2,3,4,5,6	1	0.92	[0.88, 0.96]	0.016	0.69
	1,3,4,5,6	2	0.88	[0.85, 0.92]	0.025	0.70
	1,2,4,5,6	3	0.96	[0.93, 0.99]	0.007	0.76
	1,2,3,5,6	4	0.98	[0.95, 1.02]	0.014	0.75
	1,2,3,4,6	5	0.90	[0.85, 0.95]	0.017	0.69
	1,2,3,4,5	6	0.87	[0.82, 0.90]	0.016	0.70
	Average		0.92	[0.88, 0.95]	0.016	0.72
CO Emission Rate	2,3,4,5,6	1	1.33	[1.22, 1.45]	0.041	0.38
	1,3,4,5,6	2	1.33	[1.19, 1.47]	0.060	0.40
	1,2,4,5,6	3	1.14	[1.03, 1.25]	0.057	0.44
	1,2,3,5,6	4	1.22	[1.05, 1.39]	0.017	0.40
	1,2,3,4,6	5	1.24	[1.14, 1.35]	0.025	0.40
	1,2,3,4,5	6	1.14	[1.02, 1.27]	0.007	0.39
	Average		1.24	[1.11, 1.36]	0.035	0.40

Table F-42 Continued on next page.

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Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.71	[0.35, 1.07]	0.037	0.04
	1,3,4,5,6	2	0.95	[0.69, 1.20]	0.058	0.05
	1,2,4,5,6	3	1.46	[1.21, 1.71]	0.066	0.08
	1,2,3,5,6	4	1.58	[1.34, 1.82]	0.095	0.05
	1,2,3,4,6	5	0.82	[0.62, 1.02]	0.049	0.07
	1,2,3,4,5	6	1.15	[0.90, 1.40]	0.059	0.09
	Average		1.11	[0.85, 1.37]	0.061	0.07
NO_x Emission Rate	2,3,4,5,6	1	1.12	[1.02, 1.23]	0.006	0.64
	1,3,4,5,6	2	1.05	[0.94, 1.16]	0.026	0.69
	1,2,4,5,6	3	1.17	[1.01, 1.33]	0.028	0.69
	1,2,3,5,6	4	1.14	[1.11, 1.18]	0.025	0.63
	1,2,3,4,6	5	0.63	[0.30, 0.97]	0.033	0.68
	1,2,3,4,5	6	0.99	[0.74, 1.24]	0.059	0.68
	Average		1.02	[0.85, 1.18]	0.030	0.67

TABLE F-43. Validation Locomotive Power Demand Model Parameters without Lagged Error Terms for Double-Powered Consist with Locomotive NC 1871 operated on Ultra-low Sulfur Diesel based on Jan-Feb 2019 Measurements.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.99	[0.84, 1.14]	0.023	0.83
	2,6	4	0.95	[0.91, 0.98]	0.014	0.82
	2,4	6	1.17	[1.05, 1.29]	0.030	0.81
	Average		1.03	[0.93, 1.14]	0.022	0.82
CO_2 Emission Rate	4,6	2	0.98	[0.83, 1.13]	0.023	0.82
	2,6	4	0.93	[0.89, 0.96]	0.014	0.82
	2,4	6	1.20	[1.08, 1.31]	0.029	0.83
	Average		1.04	[1.05, 1.16]	0.022	0.82
CO Emission Rate	4,6	2	1.03	[0.85, 1.20]	0.010	0.79
	2,6	4	1.19	[1.09, 1.29]	0.011	0.83
	2,4	6	1.21	[1.16, 1.27]	0.007	0.82
	Average		1.14	[1.03, 1.25]	0.009	0.81
HC Emission Rate	4,6	2	1.23	[1.14, 1.31]	0.068	0.14
	2,6	4	0.88	[0.68, 1.09]	0.072	0.12
	2,4	6	1.65	[1.41, 1.90]	0.090	0.15
	Average		1.25	[1.02, 1.50]	0.077	0.14
NO_x Emission Rate	4,6	2	1.05	[0.89, 1.21]	0.080	0.65
	2,6	4	0.93	[0.78, 1.08]	0.073	0.63
	2,4	6	0.99	[0.98, 1.00]	0.007	0.66
	Average		0.99	[0.88, 1.10]	0.054	0.63
PM Emission Rate	4,6	2	1.02	[1.01, 1.03]	0.005	0.68
	2,6	4	0.95	[0.91, 0.99]	0.022	0.65
	2,4	6	0.99	[0.95, 1.03]	0.020	0.65
	Average		0.99	[0.96, 1.02]	0.016	0.66

TABLE F-44. Validation Locomotive Power Demand Model Parameters without Lagged Error Terms for the Single-Powered Consist with Locomotive NC 1871 operated on Ultra-low Sulfur Diesel based on Jan-Feb 2019 Measurements.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.94	[0.92, 0.96]	0.020	0.66
	2,6	4	0.92	[0.89, 0.96]	0.021	0.69
	2,4	6	1.19	[1.12, 1.25]	0.025	0.67
	Average		1.02	[0.98, 1.06]	0.022	0.67
CO_2 Emission Rate	4,6	2	1.14	[1.01, 1.28]	0.011	0.63
	2,6	4	0.99	[0.84, 1.14]	0.016	0.63
	2,4	6	1.10	[0.94, 1.26]	0.016	0.67
	Average		1.08	[0.93, 1.23]	0.014	0.65
CO Emission Rate	4,6	2	1.08	[0.99, 1.16]	0.040	0.29
	2,6	4	0.81	[0.61, 1.01]	0.021	0.34
	2,4	6	1.53	[1.37, 1.69]	0.077	0.33
	Average		1.14	[0.99, 1.29]	0.046	0.32
HC Emission Rate	4,6	2	0.55	[0.24, 0.85]	0.034	0.00
	2,6	4	1.19	[0.87, 1.50]	0.058	0.01
	2,4	6	0.89	[0.58, 1.19]	0.038	0.01
	Average		0.87	[0.57, 1.18]	0.043	0.01
NO_x Emission Rate	4,6	2	1.03	[0.99, 1.07]	0.022	0.69
	2,6	4	0.91	[0.90, 0.92]	0.006	0.63
	2,4	6	0.99	[0.97, 1.01]	0.011	0.64
	Average		0.98	[0.95, 1.00]	0.013	0.66
PM Emission Rate	4,6	2	1.14	[1.05, 1.24]	0.029	0.05
	2,6	4	1.07	[0.95, 1.19]	0.023	0.07
	2,4	6	0.99	[0.79, 1.19]	0.009	0.07
	Average		1.07	[0.93, 1.20]	0.020	0.06

TABLE F-45. Validation Locomotive Power Demand Model Parameters without Lagged Error Terms for Double-Powered Consist with Locomotive NC 1984 operated on Ultra-low Sulfur Diesel based on June 2019.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	0.93	[0.91, 0.95]	0.012	0.63
	2,6	4	1.20	[1.17, 1.23]	0.027	0.63
	2,4	6	0.99	[0.79, 1.18]	0.014	0.63
	Average		1.04	[0.96, 1.12]	0.017	0.63
CO_2 Emission Rate	4,6	2	1.03	[0.94, 1.11]	0.010	0.57
	2,6	4	1.01	[0.87, 1.16]	0.017	0.56
	2,4	6	1.14	[1.11, 1.18]	0.005	0.57
	Average		1.06	[0.97, 1.15]	0.011	0.57
CO Emission Rate	4,6	2	1.36	[1.24, 1.48]	0.055	0.24
	2,6	4	1.38	[1.26, 1.50]	0.059	0.23
	2,4	6	1.45	[1.31, 1.59]	0.066	0.22
	Average		1.40	[1.27, 1.52]	0.060	0.23
HC Emission Rate	4,6	2	1.02	[0.79, 1.26]	0.060	0.01
	2,6	4	0.64	[0.25, 1.02]	0.035	0.01
	2,4	6	1.40	[1.20, 1.60]	0.064	0.01
	Average		1.02	[0.74, 1.30]	0.053	0.01
NO_x Emission Rate	4,6	2	0.95	[0.84, 1.05]	0.021	0.62
	2,6	4	1.09	[1.05, 1.13]	0.022	0.56
	2,4	6	1.11	[1.02, 1.21]	0.009	0.59
	Average		1.05	[0.97, 1.13]	0.017	0.59
PM Emission Rate	4,6	2	1.16	[0.97, 1.34]	0.011	0.62
	2,6	4	1.10	[1.00, 1.21]	0.015	0.62
	2,4	6	0.95	[0.82, 1.08]	0.005	0.62
	Average		1.07	[0.93, 1.21]	0.010	0.62

TABLE F-46. Validation Locomotive Power Demand Model Parameters without Lagged Error Terms for Single-Powered Consist with Locomotive NC 1984 operated on Ultra-low Sulfur Diesel based on June 2019.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	4,6	2	1.19	[1.06, 1.32]	0.009	0.66
	2,6	4	1.20	[1.07, 1.33]	0.021	0.64
	2,4	6	1.17	[1.08, 1.25]	0.017	0.73
	Average		1.18	[1.07, 1.30]	0.016	0.68
CO_2 Emission Rate	4,6	2	1.10	[0.99, 1.21]	0.014	0.73
	2,6	4	1.12	[1.04, 1.21]	0.028	0.71
	2,4	6	1.16	[1.06, 1.25]	0.018	0.66
	Average		1.13	[1.03, 1.22]	0.020	0.70
CO Emission Rate	4,6	2	1.11	[1.06, 1.17]	0.033	0.44
	2,6	4	1.38	[1.33, 1.42]	0.060	0.43
	2,4	6	1.08	[1.01, 1.14]	0.042	0.41
	Average		1.19	[1.13, 1.24]	0.045	0.42
HC Emission Rate	4,6	2	0.67	[0.33, 1.02]	0.037	0.03
	2,6	4	0.58	[0.38, 0.78]	0.032	0.03
	2,4	6	1.09	[0.78, 1.41]	0.058	0.03
	Average		0.78	[0.50, 1.07]	0.043	0.03
NO_x Emission Rate	4,6	2	0.89	[0.83, 0.95]	0.028	0.71
	2,6	4	0.93	[0.91, 0.95]	0.009	0.69
	2,4	6	1.04	[0.99, 1.09]	0.024	0.69
	Average		0.95	[0.91, 1.00]	0.020	0.69
PM Emission Rate	4,6	2	0.88	[0.83, 0.93]	0.027	0.63
	2,6	4	0.97	[0.92, 1.02]	0.023	0.59
	2,4	6	1.04	[1.02, 1.06]	0.008	0.59
	Average		0.96	[0.92, 1.00]	0.019	0.60

TABLE F-47. Validation Locomotive Power Demand Model Parameters without Lagged Error Terms for Single-Locomotive Consist with Locomotive NC 1810 operated on B20 Biodiesel Blend.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	0.96	[0.78, 1.14]	0.023	0.72
	1,3,4,5,6	2	0.93	[0.80, 1.06]	0.016	0.81
	1,2,4,5,6	3	0.94	[0.88, 0.99]	0.013	0.75
	1,2,3,5,6	4	1.13	[1.02, 1.25]	0.028	0.77
	1,2,3,4,6	5	1.22	[1.08, 1.36]	0.006	0.86
	1,2,3,4,5	6	1.09	[0.97, 1.21]	0.013	0.80
	Average		1.05	[0.92, 1.17]	0.017	0.78
CO_2 Emission Rate	2,3,4,5,6	1	0.94	[0.76, 1.12]	0.023	0.71
	1,3,4,5,6	2	0.95	[0.82, 1.08]	0.016	0.82
	1,2,4,5,6	3	0.93	[0.88, 0.98]	0.013	0.73
	1,2,3,5,6	4	1.16	[1.04, 1.28]	0.028	0.76
	1,2,3,4,6	5	1.21	[1.07, 1.35]	0.006	0.84
	1,2,3,4,5	6	1.10	[0.98, 1.22]	0.013	0.81
	Average		1.05	[0.92, 1.17]	0.017	0.78
CO Emission Rate	2,3,4,5,6	1	0.94	[0.83, 1.05]	0.038	0.34
	1,3,4,5,6	2	1.02	[0.89, 1.16]	0.052	0.35
	1,2,4,5,6	3	1.13	[1.08, 1.19]	0.047	0.36
	1,2,3,5,6	4	0.87	[0.78, 0.95]	0.048	0.31
	1,2,3,4,6	5	0.89	[0.76, 1.02]	0.039	0.41
	1,2,3,4,5	6	0.81	[0.67, 0.94]	0.041	0.32
	Average		0.94	[0.83, 1.05]	0.044	0.35

Table F-47 Continued on next page.

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Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	0.87	[0.57, 1.17]	0.053	0.05
	1,3,4,5,6	2	1.04	[0.82, 1.27]	0.045	0.06
	1,2,4,5,6	3	1.41	[1.18, 1.64]	0.078	0.06
	1,2,3,5,6	4	1.68	[1.36, 2.00]	0.072	0.03
	1,2,3,4,6	5	1.66	[1.31, 2.00]	0.104	0.07
	1,2,3,4,5	6	1.24	[0.95, 1.52]	0.062	0.04
	Average		1.32	[1.03, 1.60]	0.069	0.05
NO_x Emission Rate	2,3,4,5,6	1	1.13	[0.99, 1.28]	0.009	0.73
	1,3,4,5,6	2	0.97	[0.78, 1.16]	0.008	0.70
	1,2,4,5,6	3	1.08	[0.90, 1.26]	0.010	0.78
	1,2,3,5,6	4	1.12	[1.05, 1.20]	0.014	0.72
	1,2,3,4,6	5	1.14	[1.09, 1.20]	0.005	0.73
	1,2,3,4,5	6	1.06	[1.01, 1.10]	0.015	0.71
	Average		1.08	[0.97, 1.20]	0.010	0.73
PM Emission Rate	2,3,4,5,6	1	1.20	[1.11, 1.29]	0.020	0.58
	1,3,4,5,6	2	1.12	[0.96, 1.28]	0.028	0.66
	1,2,4,5,6	3	1.12	[1.07, 1.18]	0.016	0.67
	1,2,3,5,6	4	0.96	[0.90, 1.03]	0.025	0.66
	1,2,3,4,6	5	1.22	[1.11, 1.33]	0.027	0.63
	1,2,3,4,5	6	1.22	[1.10, 1.35]	0.025	0.62
	Average		1.14	[1.04, 1.24]	0.023	0.64

TABLE F-48. Validation Locomotive Power Demand Model Parameters without Lagged Error Terms for the Single-Locomotive Consist with Locomotive NC 1797 operated on B20 Biodiesel Blend.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2,3,4,5,6	1	1.22	[1.14, 1.30]	0.009	0.75
	1,3,4,5,6	2	1.01	[0.97, 1.05]	0.023	0.74
	1,2,4,5,6	3	0.95	[0.82, 1.08]	0.007	0.82
	1,2,3,5,6	4	1.17	[1.02, 1.31]	0.020	0.74
	1,2,3,4,6	5	1.14	[1.08, 1.21]	0.010	0.83
	1,2,3,4,5	6	1.13	[1.13, 1.13]	0.014	0.76
	Average		1.10	[1.03, 1.18]	0.014	0.77
CO_2 Emission Rate	2,3,4,5,6	1	1.20	[1.12, 1.27]	0.010	0.76
	1,3,4,5,6	2	1.00	[0.96, 1.04]	0.024	0.75
	1,2,4,5,6	3	0.97	[0.84, 1.10]	0.007	0.84
	1,2,3,5,6	4	1.17	[1.03, 1.30]	0.019	0.75
	1,2,3,4,6	5	1.17	[1.10, 1.23]	0.010	0.81
	1,2,3,4,5	6	1.14	[1.14, 1.14]	0.014	0.75
	Average		1.11	[1.03, 1.18]	0.014	0.78
CO Emission Rate	2,3,4,5,6	1	0.94	[0.82, 1.06]	0.033	0.25
	1,3,4,5,6	2	1.30	[1.15, 1.45]	0.045	0.23
	1,2,4,5,6	3	1.31	[1.23, 1.39]	0.049	0.28
	1,2,3,5,6	4	1.13	[1.01, 1.26]	0.043	0.26
	1,2,3,4,6	5	1.30	[1.22, 1.38]	0.010	0.72
	1,2,3,4,5	6	1.06	[1.01, 1.10]	0.024	0.70
	Average		1.17	[1.07, 1.27]	0.034	0.41

Table F-48 Continued on next page.

Table F-48 Continued from previous page.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
HC Emission Rate	2,3,4,5,6	1	1.48	[1.17, 1.79]	0.091	0.13
	1,3,4,5,6	2	0.77	[0.61, 0.92]	0.047	0.12
	1,2,4,5,6	3	1.46	[1.31, 1.61]	0.076	0.14
	1,2,3,5,6	4	1.23	[1.01, 1.45]	0.056	0.12
	1,2,3,4,6	5	1.51	[1.36, 1.66]	0.069	0.14
	1,2,3,4,5	6	1.28	[1.07, 1.48]	0.065	0.13
	Average		1.29	[1.09, 1.49]	0.067	0.13
NO_x Emission Rate	2,3,4,5,6	1	1.06	[1.02, 1.10]	0.017	0.63
	1,3,4,5,6	2	0.99	[0.89, 1.09]	0.009	0.68
	1,2,4,5,6	3	1.00	[0.88, 1.13]	0.016	0.61
	1,2,3,5,6	4	1.12	[1.00, 1.24]	0.007	0.59
	1,2,3,4,6	5	1.06	[0.96, 1.16]	0.013	0.65
	1,2,3,4,5	6	0.92	[0.84, 1.00]	0.019	0.71
	Average		1.03	[0.93, 1.12]	0.014	0.64
PM Emission Rate	2,3,4,5,6	1	1.07	[1.05, 1.09]	0.008	0.66
	1,3,4,5,6	2	0.87	[0.86, 0.88]	0.007	0.64
	1,2,4,5,6	3	1.13	[1.11, 1.15]	0.012	0.71
	1,2,3,5,6	4	0.99	[0.82, 1.16]	0.084	0.13
	1,2,3,4,6	5	0.92	[0.83, 1.01]	0.047	0.12
	1,2,3,4,5	6	0.95	[0.80, 1.10]	0.074	0.16
	Average		0.99	[0.91, 1.07]	0.039	0.40

TABLE F-49. Validation Locomotive Power Demand Model Parameters without Lagged Error Terms for the Single-Locomotive Consist with Locomotive NC 1859 operated on B20 Biodiesel Blend.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
Fuel Use Rate	2-15	1	0.99	[0.95, 1.05]	0.024	0.59
	1, 3-15	2	1.02	[0.93, 1.10]	0.016	0.60
	1-2, 4-15	3	0.97	[0.91, 1.02]	0.025	0.57
	1-3, 5-15	4	1.07	[0.97, 1.17]	0.014	0.65
	1-4, 6-15	5	0.93	[0.82, 1.04]	0.026	0.62
	1-5, 7-15	6	1.05	[0.96, 1.13]	0.027	0.60
	1-6, 8-15	7	0.93	[0.85, 0.94]	0.034	0.57
	1-7, 9-15	8	0.94	[0.86, 0.94]	0.025	0.61
	1-8, 10-15	9	1.01	[0.81, 1.21]	0.016	0.63
	1-9, 11-15	10	1.12	[0.93, 1.32]	0.014	0.59
	1-10, 12-15	11	0.95	[0.92, 0.98]	0.025	0.57
	1 -11, 13-15	12	0.99	[0.88, 1.10]	0.026	0.57
	1-12, 14-15	13	1.06	[0.90, 1.21]	0.027	0.61
	1-13, 15	14	0.95	[0.82, 1.08]	0.028	0.60
	1-14	15	0.97	[0.90, 1.05]	0.016	0.60
	Average		0.99	[0.93, 1.09]	0.027	0.60
CO_2 Emission Rate	2-15	1	0.99	[0.94, 1.05]	0.025	0.58
	1, 3-15	2	1.03	[0.93, 1.11]	0.014	0.60
	1-2, 4-15	3	0.97	[0.92, 1.05]	0.026	0.57
	1-3, 5-15	4	1.07	[0.97, 1.17]	0.014	0.65
	1-4, 6-15	5	0.93	[0.82, 1.04]	0.023	0.63
	1-5, 7-15	6	1.05	[0.96, 1.13]	0.025	0.60
	1-6, 8-15	7	0.92	[0.85, 0.96]	0.037	0.57
	1-7, 9-15	8	0.94	[0.86, 0.94]	0.028	0.63
	1-8, 10-15	9	1.01	[0.81, 1.21]	0.016	0.63
	1-9, 11-15	10	1.13	[0.93, 1.32]	0.016	0.59
	1-10, 12-15	11	0.95	[0.90, 0.99]	0.028	0.57
	1 -11, 13-15	12	0.99	[0.88, 1.10]	0.026	0.55
	1-12, 14-15	13	1.05	[0.90, 1.21]	0.024	0.61
	1-13, 15	14	0.95	[0.82, 1.08]	0.024	0.62
	1-14	15	0.97	[0.90, 1.05]	0.015	0.61
	Average		0.99	[0.93, 1.09]	0.026	0.61

Table F-49 Continued on next page.

Table F-49 Continued from previous page.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
CO Emission Rate	2-15	1	0.95	[0.83, 1.08]	0.044	0.09
	1, 3-15	2	0.99	[0.89, 1.10]	0.043	0.09
	1-2, 4-15	3	1.21	[1.03, 1.38]	0.043	0.09
	1-3, 5-15	4	1.21	[1.00, 1.41]	0.046	0.12
	1-4, 6-15	5	0.71	[0.51, 0.90]	0.021	0.09
	1-5, 7-15	6	0.70	[0.61, 0.78]	0.035	0.11
	1-6, 8-15	7	1.39	[1.28, 1.50]	0.044	0.11
	1-7, 9-15	8	0.97	[0.93, 1.01]	0.057	0.12
	1-8, 10-15	9	1.41	[1.28, 1.54]	0.034	0.10
	1-9, 11-15	10	1.05	[0.95, 1.16]	0.056	0.11
	1-10, 12-15	11	1.05	[0.89, 1.21]	0.022	0.10
	1 -11, 13-15	12	0.92	[0.76, 1.07]	0.044	0.09
	1-12, 14-15	13	1.07	[0.97, 1.16]	0.054	0.09
	1-13, 15	14	0.99	[0.89, 1.10]	0.058	0.11
	1-14	15	1.41	[1.22, 1.61]	0.056	0.11
	Average		1.07	[0.94, 1.20]	0.044	0.10
HC Emission Rate	2-15	1	0.81	[0.59, 1.03]	0.059	0.10
	1, 3-15	2	0.80	[0.49, 1.10]	0.047	0.11
	1-2, 4-15	3	0.84	[0.49, 1.20]	0.047	0.10
	1-3, 5-15	4	1.31	[1.05, 1.57]	0.072	0.10
	1-4, 6-15	5	1.13	[0.76, 1.50]	0.057	0.10
	1-5, 7-15	6	1.44	[1.07, 1.80]	0.071	0.11
	1-6, 8-15	7	1.67	[1.45, 1.89]	0.074	0.13
	1-7, 9-15	8	1.37	[0.96, 1.78]	0.076	0.14
	1-8, 10-15	9	0.67	[0.39, 0.96]	0.034	0.12
	1-9, 11-15	10	0.98	[0.60, 1.36]	0.065	0.13
	1-10, 12-15	11	1.24	[0.92, 1.57]	0.083	0.09
	1 -11, 13-15	12	0.70	[0.33, 1.07]	0.033	0.11
	1-12, 14-15	13	1.49	[1.22, 1.76]	0.067	0.08
	1-13, 15	14	0.67	[0.31, 1.03]	0.033	0.12
	1-14	15	0.75	[0.46, 1.04]	0.036	0.10
	Average		1.06	[0.74, 1.38]	0.057	0.11

Table F-49 Continued on next page.

Table F-49 Continued from previous page.

Species	Calibration Trips	Validation Trip	Slope	95 % Confidence Interval on Slope	Standard Error in Slope	Goodness of Fit (R^2)
NO_x Emission Rate	2-15	1	1.03	[0.95, 1.12]	0.011	0.69
	1, 3-15	2	1.06	[1.04, 1.08]	0.011	0.71
	1-2, 4-15	3	1.01	[0.85, 1.17]	0.021	0.59
	1-3, 5-15	4	1.01	[0.87, 1.14]	0.011	0.65
	1-4, 6-15	5	0.94	[0.82, 1.05]	0.021	0.70
	1-5, 7-15	6	1.14	[1.06, 1.23]	0.011	0.66
	1-6, 8-15	7	1.23	[1.12, 1.34]	0.033	0.63
	1-7, 9-15	8	1.04	[0.91, 1.16]	0.022	0.61
	1-8, 10-15	9	1.13	[0.98, 1.29]	0.022	0.69
	1-9, 11-15	10	0.91	[0.73, 1.10]	0.011	0.63
	1-10, 12-15	11	1.04	[0.92, 1.16]	0.021	0.62
	1 -11, 13-15	12	0.92	[0.81, 1.04]	0.021	0.62
	1-12, 14-15	13	1.22	[1.11, 1.32]	0.022	0.71
	1-13, 15	14	1.05	[0.91, 1.18]	0.021	0.71
	1-14	15	0.95	[0.91, 0.99]	0.011	0.63
	Average		1.05	[0.93, 1.16]	0.018	0.66
PM Emission Rate	2-15	1	1.04	[0.95, 1.12]	0.022	0.49
	1, 3-15	2	1.20	[1.06, 1.34]	0.022	0.50
	1-2, 4-15	3	1.24	[1.13, 1.36]	0.011	0.48
	1-3, 5-15	4	1.12	[0.96, 1.28]	0.011	0.48
	1-4, 6-15	5	0.93	[0.88, 0.98]	0.021	0.46
	1-5, 7-15	6	0.95	[0.91, 1.01]	0.011	0.47
	1-6, 8-15	7	1.18	[1.08, 1.27]	0.033	0.48
	1-7, 9-15	8	0.98	[0.81, 1.16]	0.011	0.47
	1-8, 10-15	9	0.94	[0.90, 0.98]	0.021	0.47
	1-9, 11-15	10	0.94	[0.85, 1.02]	0.011	0.49
	1-10, 12-15	11	1.18	[1.05, 1.31]	0.011	0.51
	1 -11, 13-15	12	0.90	[0.78, 1.03]	0.011	0.47
	1-12, 14-15	13	1.17	[1.10, 1.23]	0.033	0.47
	1-13, 15	14	1.12	[1.04, 1.21]	0.011	0.50
	1-14	15	1.05	[0.97, 1.14]	0.011	0.45
	Average		1.06	[1.01, 1.22]	0.017	0.48