ABSTRACT

GRAVER, BRANDON MICHAEL. Measurement and Evaluation of Passenger Locomotive Fuel Use and Emissions Using a Portable Emissions Measurement System. (Under the direction of H. Christopher Frey).

Diesel engines, such as those used in locomotives, produce exhaust emissions that affect human health and contribute to climate change. They emit nitrogen oxides (NO_x), comprised of nitric oxide (NO) and nitrogen dioxide (NO_2), which are precursors to tropospheric ozone, as well as particulate matter (PM).

In a diesel locomotive, the prime mover engine (PME) generates direct current power for propulsion. The PME operates at eight discrete throttle notch positions and Idle. One way of slowing the locomotive is through dynamic braking, where the traction motors act as generators and electricity is dissipated as heat through an electric resistance grid. A head-end power engine (HEP) is used to generate alternating current power for “hotel services” in the passenger cars of the train.

The U.S. Environmental Protection Agency promulgated locomotive emission standards, with a primary focus on NO_x and PM. Steady-state, Federal Reference Method (FRM) dynamometer emissions measurements are used to certify PMEs. However, there are few U.S. locomotive facilities for FRM measurements; thus, these measurements can be costly, time-consuming, and logistically challenging. Moreover, the dynamometer-measured emission rates could differ from emission rates during real-world locomotive operation. The PME may perform differently under steady-state conditions than in the real-world, leading to different emission concentrations. Steady-state measurements do not take into account emissions during transitions between notch positions during in-use operation.

A methodology was developed to measure and evaluate PME activity, ultra-low sulfur diesel (ULSD) fuel use, and emission rates on a dynamometer, during rail yard (RY) static load testing, and over-the-rail (OTR) during passenger rail service for the seven locomotives in the North Carolina Department of Transportation (NCDOT) fleet. A portable emissions measurement system (PEMS) measured exhaust concentrations of NO, PM, carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbons (HC). A PEMS methodology was also developed to measure and evaluate HEP emissions during RY measurements.

In general, RY PME measurements produced similar engine output-based emission rates to dynamometer measurements. Overall, RY testing is a suitable substitute for dynamometer testing for developing emission factors as a basis for emissions comparisons at different stages of the life of a PME. RY and OTR measurements produce statistically different notch average fuel use and emission rates. Therefore, RY measurements are not representative of emissions produced during real-world PME operation. The HEP is a small, but significant, contributor to emissions, representing up to 20 percent of total emissions depending on pollutant and locomotive.

The methodologies developed have practical applications of interest to locomotive operators, such as comparing emission rates for locomotives operating on biodiesel rather than ULSD. RY and OTR measurements were conducted on three PMEs using ULSD and various biodiesel blends. For the NCDOT fleet, the expected average reduction in time-based cycle average emission rates of switching to B20 biodiesel from ULSD is 11 percent for CO_2, 23 percent for PM, 42 percent for CO, and 62 percent for HC based on OTR measurements. There was not a statistically significant difference in NO_x OTR emission rates.

Another methodology application is comparing passenger rail and highway vehicle emissions. Per passenger-kilometer locomotive emissions for an average one-way trip between Raleigh and Charlotte were estimated based on OTR emission rates and duty cycles. Motor Vehicle Emission Simulator (MOVES) software was used to estimate fleet average light-duty gasoline vehicle (LDGV) emission rates. Passenger rail emits 44 and 94 percent less CO_2 and CO, respectively, compared to a single occupant LDGV. However, higher NO_x, HC, and PM emission rates are observed for passenger rail. Rail ridership would have to increase, or newer locomotives brought into service, in order for NO_x, HC, and PM emission rates to be comparable to LDGVs.

Measurement and Evaluation of Passenger Locomotive Fuel Use and Emissions Using a Portable Emissions Measurement System

by
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DEDICATION

To my father,

Varick P. Graver

(August 22, 1948 – August 12, 2013)

A man devoted

To his nation,

To his community,

To his family

The man I strive to be.

“My father gave me the greatest gift anyone could give another person, he believed in me.”

--- Jim Valvano

BIOGRAPHY

Brandon Michael Graver was born in the picturesque Hudson Valley of New York in April 1986. He received his Bachelor of Science in Environmental Engineering and Science, Technology & Society from the oldest technological university in the English-speaking world – Rensselaer Polytechnic Institute – in May 2008. He joined the Department of Civil, Construction and Environmental Engineering at North Carolina State University in August 2008 to pursue a Master of Science degree. His research focused on the estimation and measurement of energy use and emissions from a plug-in hybrid electric vehicle. He received his Master of Science degree in Environmental Engineering in May 2011, and elected to remain at North Carolina State University to pursue a Doctor of Philosophy degree in Civil Engineering. His research focused on the estimation and measurement of energy use and emissions from passenger rail.

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CHAPTER 1

INTRODUCTION

This chapter provides background information and a review of the published methodologies, studies, and data with respect to the measurement and evaluation of passenger locomotive fuel use and emissions. Also included are discussions on the key method and data gaps from prior studies, key research questions to be answered, and an overview of the dissertation organization.

BACKGROUND

Background information includes a discussion of passenger rail in the United States, the emissions created by locomotive operation, and a review of available literature on the measurement of locomotive emissions, the use of biodiesel in locomotives, and the comparison of locomotive emission rates to other modes of transportation.

U.S. Passenger Rail

In 2013, Amtrak and their state partners used over 400 locomotives to move nearly 31 million people on 21,000 miles of track in 46 states, 3 Canadian provinces, and the District of Columbia [Amtrak, 2013]. One of Amtrak's partners is North Carolina, where the state Department of Transportation (NCDOT) owns a fleet of F59PH and F59PHI locomotives for the Piedmont passenger rail service between Raleigh and Charlotte, NC. Over 80 percent of locomotives deployed for Amtrak service use diesel prime mover engines (PMEs) for propulsion [Amtrak, 2012]. That includes about 100 F59PH and F59PHI locomotives, which are used by passenger rail operators in California, the Pacific Northwest, and the Chicago and Dallas-Ft. Worth metropolitan areas, in addition to North Carolina. Amtrak consumed 67 million gallons of petroleum diesel (petrodiesel) fuel that year [Davis et al., 2015].

Locomotive Emissions

Diesel engines, such as those used in locomotives, produce exhaust emissions that affect human health and contribute to climate change [WHO, 2015]. They emit nitrogen oxides (NO_x), comprised of nitric oxide (NO) and nitrogen dioxide (NO_2), which are precursors to tropospheric ozone (O_3) formation [Cooper and Alley, 2011]. Transportation sources account for nearly 58 percent of all NO_x emissions in the United States, with off-highway vehicles accounting for nearly 22 percent [Davis et al., 2015]. NO_2 and O_3 are both criteria pollutants regulated by the U.S. Environmental Protection Agency (EPA) under the National Ambient Air Quality Standards (NAAQS) because of their impact on human health [CFR, 2013a]. Inhalation of ground level ozone can cause health problems such as damage to lung tissue, reduction of lung function, and sensitization of the lungs to other irritants [EPA, 2013]. Another criteria pollutant produced in significant amounts by diesel engines is particulate matter (PM). Inhalation of PM can cause cardiovascular disease and premature mortality in humans [EPA, 2009a].

To combat the environmental and health effects of these pollutants, the EPA promulgated locomotive emission standards in 1998, with a primary focus on NO_x and PM [EPA, 1998].

The applicability of the standards depends on the date by which a locomotive is manufactured or remanufactured. The emission standards were updated in 2008 to include more stringent emission levels for future and remanufactured locomotives [EPA, 2009b]. Available data regarding locomotive emissions are typically from engine dynamometer measurements [EPA, 1998a]. Certification tests require adherence to Federal Reference Method (FRM) measurement methods in accordance with Part 1033 of the Code of Federal Regulations (CFR) Title 40 [CFR, 2013c]. The FRM measures emissions of NO_x, PM, carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbons (HC) in the engine exhaust at each throttle position. Engine load in FRM tests is imposed by a dynamometer or alternator/generator configuration that must control torque and speed. Fuel consumption is measured continuously on either a weight or volume basis. Cycle average emission rates are estimated based on the pollutant emission rates at each notch position, weighted by one of the EPA duty cycles. FRM methods provide the greatest degree of sensitivity, precision, and accuracy.

However, there are few locomotive FRM facilities in the United States; thus, dynamometer testing can be costly, time-consuming, and logistically challenging.

Locomotive Operation

In a diesel locomotive, the PME shaft turns an electric generator/alternator. Electricity produced is used to drive traction motors, which rotate the locomotive wheels. The PME operates at eight discrete throttle notch positions and Idle. One way of slowing the

locomotive is through dynamic braking, where the traction motors act as generators and electricity is dissipated as heat through the electric resistance grid [EPA, 1998].
The percent of time spent in Idle, Dynamic Brake, and each of the eight notch positions during locomotive operation is the locomotive duty cycle. Two distinct duty cycles have been identified by EPA for freight locomotives: (1) line-haul, or the movement of freight over a relatively long distance; and (2) switching, or the movement of locomotives in a relatively small area to assemble or dissemble trains [CFR, 2013b]. Based on data provided by Amtrak, the average passenger locomotive duty cycle reported by EPA is similar to the average line-haul duty cycle, with the exception of the amount of time spent in Idle [EPA, 1998].

Biodiesel

Besides emission standards compliance, there are other reasons why locomotive operators are interested in knowing what are the emission rates from their fleet. They apply for Federal funding for upgrades to existing track and rolling stock. A requirement of such funding is to demonstrate improvement of air quality. Governmental agencies often target NO_x control from transportation sources to reach air quality goals. Operators want to be able to evaluate the efficacy of alternative fuels and technologies in combatting NO_x emissions.

Biodiesel is a naturally oxygenated drop-in diesel replacement fuel made from natural, renewable sources, such as new and used vegetable oils or animal fats, that can be used without engine modifications [EPA, 2002]. Fuel use and exhaust emission rates of a diesel engine are influenced by fuel properties, such as cetane number and oxygen content. Soy-based biodiesel is typically higher in oxygen content and cetane number than ultra-low sulfur diesel (ULSD) [EPA, 2002]. The slightly higher observed NO_x emission rate for soy-based B20 versus ULSD rate is typically attributed to higher cetane number [EPA, 2002; EPA, 2003; EPA, 2010a]. Increases in oxygen content and cetane number appear to be associated with reductions in PM emission rate [Akasaka et al., 1997; McCormick et al., 1997; McCormick et al., 2001; Yanowitz et al., 2000]. Any significant increase in NO_x emission from fuel switching can affect future implementation.

A key motivation for considering biodiesel blends is that they could lead to lower fuel cycle greenhouse gas emissions. The CO_2 exhaust emission rate is expected to be slightly higher on a per energy content basis, by less than 2 percent for soy-based B100 than for petrodiesel, taking into account differences in fuel heating value and carbon content, and assuming no difference in how much fuel energy is consumed by the engine [Frey and Kim, 2006]. However, biodiesel provides a reduction in net CO_2 emissions when considering the entire fuel cycle [Sheehan et al., 1998]. For example, based on typical production methods (e.g., diesel tractors for farming), the fossil energy embodied in biodiesel is reduced by 9 percent for B20 and 42 percent for B100 compared to petrodiesel [Pang et al., 2009]. The uncertainty in assessing differences in net CO_2 emissions between biodiesel and petrodiesel was found to be greatest with respect to diesel refining, as it contributes approximately 16 percent to the total petrodiesel life cycle energy consumption [Pang et al., 2009].

There are few comparisons of real-world locomotive engine emissions for biodiesel versus petrodiesel [Frey and Graver, 2012; Fritz, 2004; McKenna et al., 2008; Osborne et al., 2011]. Data from three studies suggest that for B20 versus ULSD, there is an average increase in both fuel consumption and emission rates of all pollutants. Fuel use rate increased by 1 percent and emission rates of HC, NO_x, and PM increased by 2, 4, and 6 percent, respectively [Frey and Graver, 2012; Fritz, 2004; McKenna et al., 2008]. The average difference for CO was negligible. However, there is substantial engine-to-engine and test-to-test variability. The range of differences in NO_x biodiesel emission rates compared to ULSD were 0.8 to 6.4 percent, 0 to 6.8 percent for HC, -16.8 to 21.5 percent for CO, and 4.3 to 8.0 percent for PM. In addition, these studies were static load tests conducted on either a dynamometer or in a rail yard.

While emission reductions are the goal, a concern locomotive operators have regarding the use of biodiesel is possible accelerated engine wear. Advanced engine wear caused by fuel switching can affect future implementation. There are differences in the lubricity of biodiesel versus petrodiesel, and also differences in the solvent properties of the two fuels. Biofuels tend to be better solvents than petrodiesel, and thus can dissolve residues in the fuel tank and fuel line. These dissolved residues can cause fuel filter clogging [Tyson, 2001]. Previous studies suggest no significant difference in performance or engine wear in a diesel engine caused by the use of biodiesel compared to petrodiesel [Agarwal et al., 2003; Fazal et al., 2011; Xue et al., 2011]. None of these studies were conducted on a locomotive engine, however.

Between 2010 and 2011, Amtrak operated one General Electric P32-8 locomotive on animal fat-based B20 on the Heartland Flyer service in Oklahoma. According to Amtrak, the results indicated lower HC, CO, NO_x, and PM exhaust emissions compared to the EPA Tier 0 emission standard for the locomotive. In addition, engine wear did not increase and locomotive performance and reliability did not decrease with B20 compared to conventional diesel fuel [Amtrak, 2011]. Norfolk Southern has used B11 to fuel selected locomotives in the Midwestern U.S. and in 2012 fueled selected locomotives on B100. No engine modifications were necessary to use B100 in the locomotives [NS, 2013].

Comparison with Highway Travel

Many locomotive operators depend on governmental funding for operation, such as state Departments of Transportation, as is the case with the Piedmont service, or the Federal government, like Amtrak. Funding of passenger rail may not only depend on ridership and revenue figures, but also demonstration of air quality improvements compared to other transportation modes. There are multiple motorized passenger transportation modes, including trains and automobiles. Each mode involves different technologies, fuels, travel distance and time, and the number of passengers that can be transported.

There have been many analyses that compare avoided emissions, from shifting freight from one transport mode to another [Barth and Tadi, 1996; Facanha and Horvath, 2006; Facanha and Horvath, 2007; Kim and Van Wee, 2009; Kolb and Wacker, 1995; Komor, 1995; Matei and Nes, 2012; You et al., 2010]. Freight locomotives are designed differently from passenger locomotives, having larger engines with more horsepower [EPA, 1998].

A few analyses compare passenger rail to other means of transport. One extensive study compares emission rates from numerous alternative land-based transportation modes and fuels, with passenger rail emission rates estimated from published emissions data [Delucchi, 1996]. However, the analysis is not based on measured real-world locomotive emission rates and there is no direct comparison of emission rates from highway and rail travel. Two studies focus on high-speed rail powered by electricity from renewable sources, which are not currently in operation in the United States, but hypothesized to be in operation in future decades [Chester and Horvath, 2010; Chester and Horvath, 2012]. One study compared emissions from commuter rail, using real-world duty cycles and notch-based emission factors from laboratory measurements of the same locomotive model, to automobile travel, using an automobile emissions model, and found that commuter rail emitted more NO_x and PM, but less HC and CO [Barth et al., 1996]. Tang *et al.* [2015] measured black carbon emissions from passing passenger locomotives and estimated mass per passenger-kilometer emission factors for black carbon and CO_2. Locomotive exhaust was measured using a sampling line hung above a track, rather than directly from the engine. CO_2 emission factors were based on estimated fuel economies, not actual measurements. Measured locomotive black carbon emissions were estimated to be ten times higher than for a light-duty vehicle. No studies were found that estimate trip-based per passenger emission factors from exhaust emissions measured directly from the locomotive engine during operation.

From 2003 to 2013, Amtrak's revenue passenger-kilometers increased 1.8 percent, while the energy intensity decreased by 2.8 percent to approximately 1,400 kilojoules per passenger-kilometer (kJ/pkm) [Davis et al., 2015]. This is approximately 57 and 67 percent lower than the energy intensity of passenger cars and passenger trucks, respectively [Davis et al., 2015]. The latter include pickup trucks, minivans, and sport utility vehicles. A decrease in energy intensity correlates with a reduction in emissions.

The National Cooperative Rail Research Program (NCRRP) of the Transportation Research Board commissioned a model to compare energy consumption and greenhouse gas emissions from passenger rail to that of highway and air travel [NCRRP, 2015]. The resulting Multi-Modal Passenger Simulation model (MMPASSIM) allows users to specify rail equipment and route parameters to estimate energy and greenhouse gas (GHG) emission intensities per passenger-distance. The model did not include criteria air contaminants, such as NO_x, CO, HC, and PM. MMPASSIM simulates rail energy intensity using a traditional train energy and resistance methodology, and estimates GHG emission intensity using EPA-published GHG emission rates by fuel type. The model accounts for energy consumption and greenhouse gas emissions associated with operation of the transport vehicle, as well as for the fuel cycle for gasoline, diesel, or electricity.

The actual duty cycles observed during normal passenger rail service may differ from those used by the EPA in regulatory analyses and affect estimations of the total fuel use and emissions associated with a one-way trip. Numerous factors can lead to variations in observed duty cycles and travel time, including: (1) differences in operating behavior among engineers; (2) longer than scheduled periods at the rail station to load and unload passengers; (3) slow orders because of weather or track repair; and (4) allowing other rail traffic to pass by changing tracks or stopping on a siding. Stopping in the siding or remaining at a station longer than scheduled increases trip duration and the duration and percentage of time spent in idle. Delays in rail travel time could lead to a less favorable comparison of the train versus avoided highway emissions. No studies were found that quantify the effects of rail delays on real-world locomotive emission factors.

Conversely, delays in highway travel time could lead to a more favorable comparison of the train versus highway emissions. Highway vehicle emission rates are affected by vehicle type, time of day, travel time, and trip average speed [Frey et al., 2008d; Unal et al., 2003]. Passenger trucks, on average, have higher energy intensities than passenger cars, which lead to higher emissions [Davis et al., 2015]. The time of day can have an effect on roadway congestion, such as during rush hour commutes to and from work. Idling in highway congestion decreases trip average speed and increases travel time. In one study, decreased congestion, during non-rush hours, approximately doubled trip average speed and decreased NO_x, CO, and HC emission rates by up to 60 percent [Unal et al., 2003]. CO_2 emission rates typically increase as trip average speed decreases [Liu and Frey, 2015].

RESEARCH NEEDS

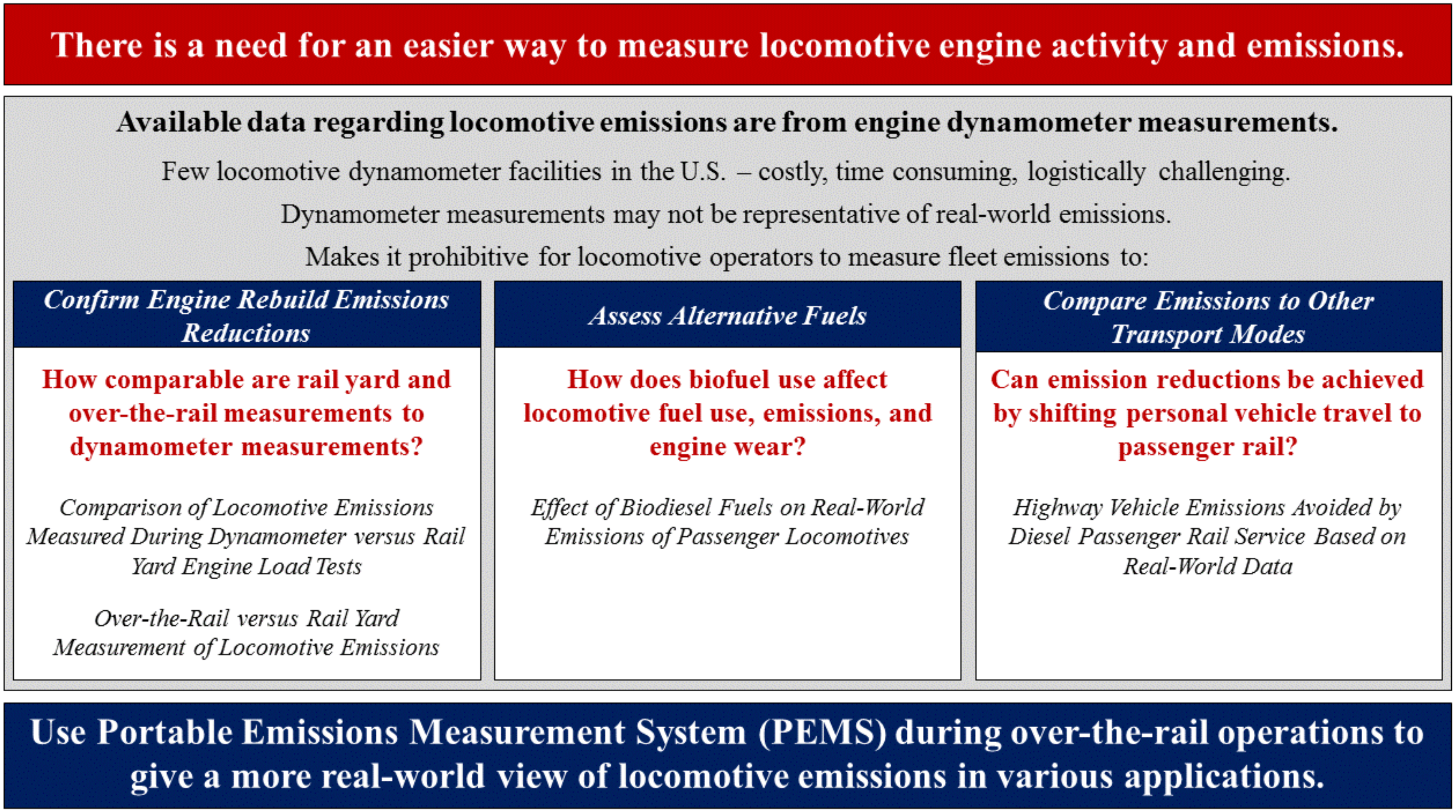
There are some data gaps in the existing literature that will be addressed by this research with respect to emissions measurement methodologies, the use of biodiesel in locomotives, and the comparison of locomotive and highway vehicle emission factors. Figure 1-1 graphically depicts the motivation of the dissertation, the research opportunities created, and what research needs to be completed. The following three subsections discuss the key research needs for the measurement of locomotive emissions, assessing biodiesel use in locomotives, and comparing emissions from locomotives and highway vehicles.

Emissions Measurement

The work is motivated by the need for an easier way of measuring locomotive engine activity and emissions. This makes it prohibitive for locomotive operators to measure their fleet emissions to confirm efficacy of engine rebuilds in reducing fuel use and emission rates. It also limits research on alternative fuels and technologies that may reduce locomotive exhaust emissions and the comparison of locomotive emissions to other modes of transportation.

Biodiesel

There is a data gap with respect to real-world engine and emissions data from switching fuels in locomotives from ULSD to biodisel. Additional testing on the effect of biodiesel on engine wear and locomotive performance and reliability are warranted. Previous studies are limited in the number of locomotives and the variety of biodiesel fuel blends analyzed. The



There is a need for an easier way to measure locomotive engine activity and emissions.

Available data regarding locomotive emissions are from engine dynamometer measurements.

Few locomotive dynamometer facilities in the U.S. – costly, time consuming, logistically challenging.

Dynamometer measurements may not be representative of real-world emissions.

Makes it prohibitive for locomotive operators to measure fleet emissions to:

Confirm Engine Rebuild Emissions Reductions

How comparable are rail yard and over-the-rail measurements to dynamometer measurements?

Comparison of Locomotive Emissions Measured During Dynamometer versus Rail Yard Engine Load Tests

Over-the-Rail versus Rail Yard Measurement of Locomotive Emissions

Assess Alternative Fuels

How does biofuel use affect locomotive fuel use, emissions, and engine wear?

Effect of Biodiesel Fuels on Real-World Emissions of Passenger Locomotives

Compare Emissions to Other Transport Modes

Can emission reductions be achieved by shifting personal vehicle travel to passenger rail?

Highway Vehicle Emissions Avoided by Diesel Passenger Rail Service Based on Real-World Data

Use Portable Emissions Measurement System (PEMS) during over-the-rail operations to give a more real-world view of locomotive emissions in various applications.

Figure 1-1: Research Motivation Concept Map

measurement methodology allows for the analysis of the effect of biodiesel fuels on real-world emissions of passenger locomotives.

Comparison with Highway Travel

There are data gaps with respect to comparing passenger rail and highway emissions based on real-world locomotive emission measurements. The measurement methodology allows for the analysis of the highway vehicle emissions avoided by diesel passenger rail service based on real-world data. It also provides a means of estimating the effect of rail and highway delays on the comparison of the emission rates from the competing travel modes.

RESEARCH QUESTIONS

Using PEMS during over-the-rail operations could give a more real-world view of estimating emissions on locomotives, which can be used to assess the efficacy of emission control strategies and to compare emission rates to those of other transportation modes. This dissertation aims to answer the following research questions with the use of a PEMS: (1) How comparable are rail yard and over-the-rail measurements to dynamometer measurements? (2) How does biofuel use affect locomotive fuel use, emissions, and engine wear? and (3) Can emission reductions be achieved by shifting personal vehicle travel to passenger rail?

ORGANIZATION

This dissertation consists of six chapters, as well as appendices containing supporting information.

Chapter 1, which is this part, describes general information regarding locomotive fuel use and emissions, the literature available and the research needs that this dissertation addresses, the research questions that will be answered, and the organization of this dissertation.

Chapter 2 addresses Research Question 1, and compares locomotive emissions measured during dynamometer and rail yard engine load tests. The objectives of this chapter are to: (1) demonstrate an approach for quantifying locomotive emission rates using a PEMS during dynamometer and rail yard engine load tests; (2) compare the emissions measured in dynamometer versus rail yard load tests; and (3) assess the relative change in fuel use and emissions from engine rebuild.

Chapter 3 also addresses Research Question 1, and compares over-the-rail versus rail yard measurement of locomotive emissions. The objectives of this chapter are to determine: (1) if rail yard emission measurements are representative of emissions produced during real-world locomotive operation; (2) if the regulatory duty cycle differs from duty cycles measured during passenger rail service, and whether duty cycles affect trip total emission estimates; and (3) if prime mover engine transient operation affects trip total emission estimates.

Chapter 4 addresses Research Question 2, and compares emissions measurements of passenger locomotive engines operating on diesel and biodiesel fuels. The objectives of this chapter are to determine if, compared to ultra-low sulfur diesel: (1) biodiesel use significantly affects fuel use and emissions of locomotive prime mover engines; and (2) biodiesel use affects the performance of the prime mover engine.

Chapter 5 addresses Research Question 3, and estimates highway vehicle emissions avoided by passenger rail service in North Carolina. The objectives of this chapter are to determine if: (1) rail travel has lower per passenger-kilometer emission factors compared to travel with a highway vehicle; (2) rail travel emission factors are sensitive to where on the route a rider boards the train; (3) rail travel delays significantly increase per passenger-kilometer emission factors; and (4) highway travel delays significantly increase per passenger-kilometer emission factors.

Finally, the conclusions and recommendations from this research are presented in Chapter 6.

Ten appendices are included in this dissertation. The contents of each appendix are detailed in the Table of Contents.

CHAPTER 2

COMPARISION OF LOCOMOTIVE EMISSIONS MEASURED DURING DYNAMOMETER VERSUS RAIL YARD ENGINE LOAD TESTS

The objectives in this chapter are to: (1) demonstrate an approach for quantifying locomotive emission rates using a PEMS during dynamometer and RY engine load tests; (2) compare the emissions measured in dynamometer versus RY load tests; and (3) assess the relative change in fuel use and emissions from engine rebuild.

METHODS

A PEMS is used to quantify fuel use and emission rates of three locomotive prime mover engines during dynamometer and RY measurements.

Field Study Design

Three locomotive prime mover engines, one from a GP40 and two from F59PHs were tested on both a water brake dynamometer and in the rail yard. Dynamometer measurements occurred at American Motive Power, Inc. (AMP) in Dansville, NY, where the locomotives were undergoing rebuild. RY static load testing occurred at the NCDOT Capital Yard Maintenance Facility in Raleigh, NC. RY measurements for the GP40 locomotive, numbered NC 1792, were conducted both before and after rebuild. For the two F59PHs, numbered NC 1859 and NC 1869, RY measurements occurred after rebuild. Technical specification for all of the locomotives are included in Appendix A.

Instruments

Instruments used for data collection include a PEMS with engine sensor array, a dynamometer facility, and a locomotive activity data recorder.

Portable Emissions Measurement System

The PEMS used here are the OEM-2100 Montana and the OEM-2100AX Axion systems, both manufactured by Clean Air Technologies International, Inc. (now GlobalMRV). These PEMS are comprised of two parallel five-gas analyzers, a laser light scattering PM detection system, an engine sensor array, and an on-board computer [CATI, 2003; CATI, 2008]. Emission concentrations and engine activity data are recorded on a second-by-second basis.

Similar to the FRM, nondispersive infrared (NDIR) detection is used for CO_2 and CO. The accuracy for CO and CO_2 are excellent. These PEMS use NDIR for the detection of HC, instead of heated flame ionization detection (FID) used in the FRM. FID requires the use of hydrogen as a “fuel” to burn the HC sample without contributing carbon to the sample. However, transporting a hydrogen gas mixture onboard the locomotive is prohibited. The accuracy of the HC measurement depends on the type of fuel used [Andros, 2007; Vojtisek-Lom and Allsop, 2001]. The PEMS has a detection limit of 0.008 volume percent and 13 parts per million for CO and HC, respectively. For measurement of nitric oxide (NO), electrochemical sensing is used, whereas the FRM method is chemiluminescence. Nitrogen oxides (NO_x) is typically comprised of approximately 95 volume percent NO; therefore, NO emissions converted to an equivalent NO_2 mass basis (using the molecular weight of NO_2)

are a good indicator of total NO_x emissions. NO_x emissions are typically reported as equivalent NO_2. Also similar to the FRM, light scattering is used to measured opacity.

Prior to each set of measurements, the PEMS was calibrated with a California Bureau of Automotive Repair (BAR) certified calibration gas (BAR-97 Low). Each PEMS gas analyzer was re-calibrated using ambient air to “zero” values every 15 minutes on a staggered schedule, so that typically at least one gas analyzer was measuring while the other was “zeroing.” More information regarding the calibration of the PEMS is included in Appendix B.

The precision of this PEMS is ±25 ppm, ±4 ppm, ±0.02 vol-%, and ±0.3 vol-% for NO, HC, CO and CO_2, respectively [Zhang, 2006]. Comparison of the PEMS with a dynamometer laboratory shows that the Montana system has good precision and accuracy [Myers et al., 2003; Vojtisek-Lom and Allsop, 2001]. For example, the Montana system has been evaluated in the Environmental Technology Verification (ETV) program of the U.S. EPA. In an independent study by Battelle, 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 for exceeded 0.86 for all pollutants, indicating good precision. The slopes of the parity plots for CO, CO_2 and NO ranged from 0.92 to 1.05, indicating good accuracy. 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 types of S-3 compounds, such as aromatics [Singer et al., 1998; Stephens et al., 1996a,b].

Correction factors are used to adjust for biases associated with the PEMS emissions measurement methods. As noted earlier, NO_x is typically comprised of 90 to 95 percent NO by volume. A correction factor of 1.053 (1/0.95) is used to approximate for total NO_x, based on 95 percent NO in $NO_{x.}$ If the actual share of NO in NO_x is slightly lower (e.g., by 5 percent), the estimate of total NO_x will be slightly low (e.g. by approximately 5 percent). The overall response to NDIR to a mixture of hydrocarbons in engine exhaust is approximately 23 to 68 percent of the actual total HC [Stephens et al., 1996a]. A correction factor of 2.5 is used to approximate for total HC. An evaluation of the laser light scattering technique for measuring PM showed as much as an 80 percent difference in the emission measurement relative to the FRM [Durbin et al., 2007]. Thus, the PM emission rates are based on a correction factor of 5 to approximate total PM.

A sensor array is used to measure manifold absolute pressure (MAP), intake air temperature (IAT), and engine speed (RPM) of the PME. To measure MAP, a pressure sensor is attached to a barb fitting installed on an engine cylinder cover. The IAT sensor is a thermistor installed in the intake air flow path of the engine. The RPM optical sensor is used in combination with reflective tape to measure the time interval of revolutions of the flywheel, which rotates at the same speed as the engine crankshaft. Real-time notch and RPM data are displayed on a digital display in the locomotive cab. During every RY measurement, comparisons between the RPM reported on the digital display and the RPM reported on the PEMS were made at each notch position. The RPM values were identical during all measurements.

Dynamometer Facility

Engine fuel use and horsepower output needed for the calculation of engine output-based emission rates are obtained from the dynamometer control system. Fuel consumption rate is measured by the weight differential of a fuel tank on top of a scale. Engine horsepower (hp) output is derived from the dynamometer torque meter.

Other engine variables are collected by the dynamometer control system, including: engine RPM, air box pressure and temperature, intake air temperature, and barometric pressure. These data are useful for characterizing engine operation and for comparison to values measured by the PEMS.

Locomotive Activity Data

Each locomotive has a locomotive activity data recorder, installed. Real-time locomotive activity data are provided on a digital display, including notch position, engine RPM, and horsepower output. The data are archived on the data recorder and can be downloaded and saved on a personal laptop. These data are used to synchronize real-time locomotive activity data and emissions data during over-the-rail measurements.

Data Collection Procedure

Field data collection includes: (1) installation; (2) test schedule; and (3) data collection.

Installation

The time to instrument a prime mover engine was approximately one to four hours, excluding the time associated with fabricating parts to allow for sampling of engine parameters and of exhaust gases. Additional efforts included fabricating a replaceable fitting with a sampling port that could be installed on the exhaust duct of the engine. Figures 2-1 through 2-9 depict the installation of the PEMS for PME RY measurements.

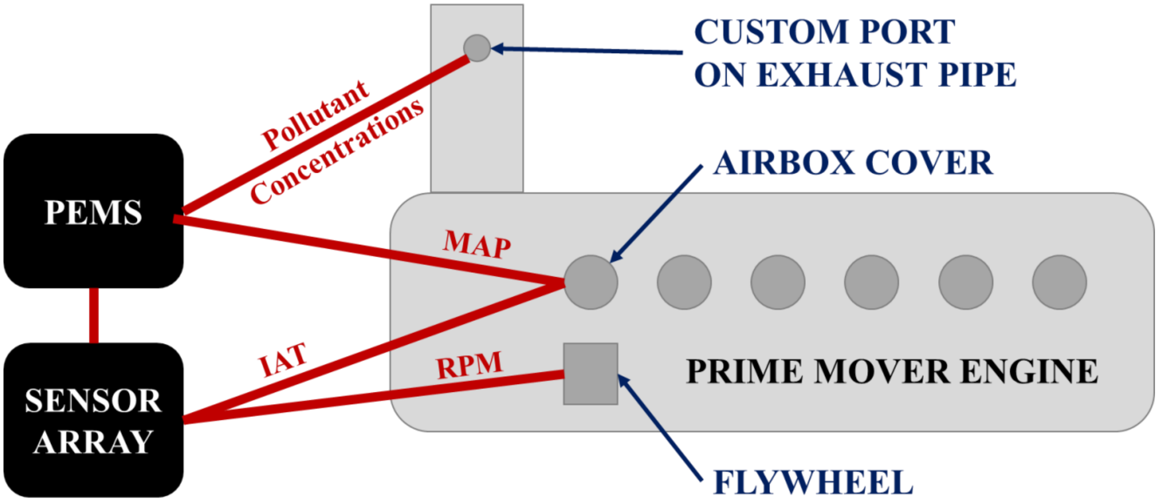


Figure 2-1: Diagram of PEMS Setup on Locomotive Prime Mover Engine

Figure 2-2: PEMS Placement for F59PH Locomotive Prime Mover Engine Measurement

(a) inside of the locomotive cab; (b) inside an air conditioned vehicle during extreme heat

Figure 2-3: Installation of Sensors on an F59PH Locomotive Prime Mover Engine

(a) exhaust sampling port and metal tubes; (b) manifold absolute pressure (MAP) sensor; (c) RPM sensor

Figure 2-4: Prime Mover Engine Activity Digital Display in F59PH Locomotive Cab

Figure 2-5: Installation of PEMS on an F59PHI Locomotive Prime Mover Engine
(a) PEMS main unit (front-view); (b) exhaust sampling port and metal tubes; (c) sensor array box

Figure 2-6: Installation of Sensors on an F59PHI Locomotive Prime Mover Engine
(a) RPM sensor; (b) manifold absolute pressure (MAP) sensor; (c) intake air temperature (IAT) sensor

Figure 2-7: Installation of PEMS Exhaust Sample Lines in an F59PHI Locomotive
(a) routing sampling hoses and cables; (b) routing sampling hoses through a side door, secured with ties (rear-view); (c) side-view of F59PHI locomotive

Figure 2-8: Installation of PEMS on a GP40 Locomotive Prime Mover Engine
(a) PEMS main unit (front-view); (b) exhaust sampling port and metal tubes; (c) sensor array box

Figure 2-9: Installation of Sensors on a GP40 Locomotive Prime Mover Engine
(a) RPM sensor; (b) manifold absolute pressure (MAP) sensor; (c) side-view of locomotive

Test Schedule

A test schedule is the order and duration of each prime mover engine throttle (notch) position. Each locomotive has one or two idle and eight non-idle notch positions. The test schedules for dynamometer and RY measurements are shown in Table 2-1. Prior to measurements, the PEMS and the engine were warmed up for at least 45 minutes to ensure consistency [CATI, 2003; CATI, 2008].

During dynamometer measurements, the engine was operated at each notch position for approximately 5 minutes, starting at Notch 8. The shaft power produced by the engine was dissipated by the water-cooled dynamometer via a series of heat exchangers in the cooling water loop. Emissions and engine operation data were collected once the engine reached a steady state at each notch and the PEMS recorded data. Typically, the engine reaches steady state within 30 seconds of engaging in a new notch. Five-second average engine operation data were logged by the dynamometer control system approximately every 30 seconds. There was a direct transition from one notch to the next. Time needed to transition the engine to steady state operation at the next notch was excluded from data analysis. Three measurement replicates were run for each engine.

Table 2-1: Test Schedule for Dynamometer and Rail Yard Load Tests of Locomotive Prime Mover Engines

Notch Position	Engine Speed (RPM)[a]	Manifold Absolute Pressure (kPa)[a]	Time (min)	
			Dynamometer	Rail Yard[b]
Idle for Warm Up	N/A	N/A	45	45
Notch 8	895-912	225-272	5	3-5
Idle for Cooling[c]	N/A	N/A	0	5
Notch 7	822-830	183-224	5	3-5
Idle for Cooling	N/A	N/A	0	5
Notch 6	722-731	159-167	5	3-5
Idle for Cooling	N/A	N/A	0	5
Notch 5	649-653	144-151	5	3-5
Notch 4	560-570	131-137	5	3-5
Notch 3	488-494	121-127	5	3-5
Notch 2	326-350	108-113	5	3-5
Notch 1	258-350	103-112	5	3-5
Idle	191-350	102-104	5	3-5

[a] Engine speed and manifold absolute pressure measured by PEMS. The test is controlled by selecting notch position. The engine RPM and Manifold Absolute Pressure are observed values. Ranges of values represent variability among locomotives and between test method (dynamometer and rail yard).

[b] Prime mover engine of GP40 was tested for three minutes at each notch position. Prime mover engines of F59PHs were tested for five minutes at each notch position.

[c] Prime mover engine lowered to idle after Notches 8 through 6 during rail yard measurements to prevent overheating of the dynamic braking grids at high engine load.

During rail yard measurements, electrical current generated by the engine-connected generator was dissipated as heat by the on-board dynamic braking grid. The engine was run at Notch 8 for a period of 3 to 5 minutes. The PEMS recorded emissions and engine operation data continuously. During analysis, data during notch position transitions were excluded. Unlike during dynamometer measurements, after each high load notch position, the engine was returned to idle to prevent overheating of the dynamic braking grid. In consultation with the NCDOT mechanical staff, five minutes of idle was selected. Returning the engine to idle does not have a significant influence on emission measurements of the following notch position. It took approximately 15 seconds for the engines to reach idle from Notch 8, and the data collected during this transition was excluded from analyses. Testing occurred sequentially for Notches 1 through 5 without any intermediate idling.

Data Collection

Data collection occurred between March 2008 and August 2011. One dynamometer, one pre-rebuild RY, and one post-rebuild RY measurement were performed on the 3,000 hp EMD16-645 engine of the GP40. Three dynamometer and two post-rebuild RY measurements were conducted on NC 1859. Three dynamometer and one post-rebuild RY measurement were conducted on NC 1869. The F59PH prime movers are both 3,000 hp EMD12-710 engines.

Data Quality Assurance

For quality assurance purposes, the combined PEMS and engine parameter data for each test was screened to check for errors. The types of errors typically encountered include gas analyzer errors and negative emission values. If errors were identified, they were either corrected or the affected data were not used.

Emission concentrations from each of the two gas analyzers are compared to evaluate their consistency. If the difference in concentrations reported between the analyzers does not exceed a maximum allowable difference (MAD) threshold, then the measurements are averaged. However, if the inter-analyzer discrepancy exceeds the MAD, the data are either not used for analysis, or data from a preferred analyzer are used if the other analyzer is suspected of producing invalid measurements.

Because of random inherent measurement errors associated with the PEMS, some measured concentrations will occasionally appear as negative values, which are statistically equivalent to zero. This situation is frequently encountered when measuring HC and CO due to their low concentrations in diesel engines [Cooper and Alley, 2011]. Negative values for these pollutants that were within the precision of the instrument were assumed to be zero.

Additional details on data processing and quality assurance procedures are given elsewhere [Choi and Frey, 2010; Frey et al., 2003; Frey et al., 2008a,b].

Fuel Use and Emission Rate Estimation

The method for calculation of fuel use and emission rates differs between dynamometer and RY tests. For both types of measurements, emission rates are calculated as time-based (g/s), fuel-based (g/gal), and engine output-based (g/bhp-hr).

Dynamometer Measurement

Engine fuel use and horsepower output needed for the calculation emission rates are obtained from the dynamometer control system. Specific fuel consumption rates are estimated by the weight differential of a fuel tank on top of a scale as:

$$SFC = \frac{\Delta w_{fuel}}{(HP)\left(\frac{\Delta t}{3600}\right)} \tag{2.1}$$

Where SFC = specific fuel consumption (lb/hp-hr); Δw_{fuel} = change in fuel tank weight during each notch position (lb); HP = average engine horsepower output during each notch position, derived from the dynamometer torque meter; and Δt = notch position duration (sec)

Fuel-based emission rates are estimated based on exhaust gas and fuel compositions, independent of fuel flow rate data. The key concept of these emission factors is that the exhaust composition accounts for all of the carbon contained in the fuel, which is emitted as CO_2, CO, and HC. From the mole fractions of these three exhaust components, the fraction of carbon in the fuel emitted as CO_2 is estimated as:

$$f_C = \frac{y_{CO_2}}{y_{CO_2} + y_{CO} + 3\, y_{HC}} \tag{2.2}$$

Where f_c = fraction of carbon as CO_2 in exhaust (gmol C as CO_2/total gmol C) and y_i = mole fraction of specie *i* (gmol of specie *i*/gmol of all species)

Since the PEMS gas analyzer is calibrated based on propane as an indicator of HC, propane is used as the basis for characterizing the properties of the hydrocarbons. Since propane has 3 moles of carbon atoms per mole of molecules, the HC mole fraction is multiplied by 3 to estimate the amount of carbon contained in the HC.

The carbon density of fuel is estimated based on the weight percent of carbon in the fuel and the fuel density:

$$\rho_C = \rho_f \, p_C \tag{2.3}$$

Where p_C = weight proportion of carbon in fuel (g C/g fuel); ρ_C = carbon density of fuel (g C/gallon of fuel); and ρ_f = density of fuel (g fuel/gallon of fuel)

The conversion of carbon in the fuel to CO_2 can be estimated per gallon of fuel consumed, since the weight percent of carbon in the fuel is known:

$$EF^f_{CO_2} = MW_{CO_2}(f_C)\left(\frac{\rho_f \times p_C}{MW_C}\right) \tag{2.4}$$

Where $EF^f_{CO_2}$ = fuel-based CO_2 emission factor (g CO_2/gal fuel); MW_C = molecular weight of carbon (12 g/mol); MW_{CO_2} = molecular weight of CO_2 (44 g/mol); p_C = weight proportion of carbon in fuel (g C/g fuel); and ρ_f = density of fuel (g fuel/gal fuel)

Molar ratios of NO, CO, and HC to CO_2 are used to estimate the amount of each pollutant emitted per gallon of fuel consumed:

$$EF_i^f = \left(\frac{y_i}{y_{CO_2}}\right)\left(\frac{MW_i}{MW_{CO_2}}\right)EF_{CO_2}^f \tag{2.5}$$

Where EF^f_i = fuel-based emission factor for specie i (g/gal fuel)

Engine output-based emission rates are estimated by multiplying the fuel-based emission factors and the fuel use rate:

$$EF_i^w = \frac{EF_i^f\left(\frac{3600\, m_f}{\rho_f}\right)}{W_s} \tag{2.6}$$

Where EF^w_i = engine output-based emission factor for specie i (g/bhp-hr); m_f = fuel use rate (g fuel/s); and W_s = engine shaft output (bhp)

Fuel use rate is directly measured on a mass per time basis. Engine output is directly measured by the dynamometer. Therefore, engine output-specific fuel use rate (gal/bhp-hr) is known.

For particulate matter, the gas analyzer reports a mass per volume concentration in units of mg/m^3 on a dry basis. Therefore, an estimate is needed of the exhaust flow in dry m^3 per gallon of fuel consumed in order to calculate an emission rate of PM in units of mass per gallon of fuel consumed. The fuel-based PM emission rate is calculated based on the air-to-fuel ratio that is calculated based on fuel properties and the observed mole fraction of CO_2 in the exhaust.

Complete combustion of fuel with excess air is represented as the following mass balance:

$$CH_yO_z + a\,O_2 + 3.76\,a\,N_2 \rightarrow b\,CO_2 + c\,H_2O + d\,N_2 + e\,O_2 \qquad (2.7)$$

From the fuel properties, the values of *y* (gmol H/gmol C) and *z* (gmol O/gmol C) are known. From the exhaust measurements, the mole fraction of CO_2, on a dry basis, is known. Thus, the unknowns are *a* (inlet gmol O_2/gmol C), *b* (gmol CO_2/gmol C), *c* (gmol H_2O/gmol C), *d* (gmol N_2/gmol C), and *e* (exhaust gmol O_2/gmol C). These can be calculated using a system of equations based on elemental mass balances and the observed mole fraction of CO_2:

Description	**Equation**	**Re-arranged Equation**
Atom balance for C	$1 = b$	$b = 1$
Atom balance for H	$y = 2c$	$c = y/2$
Atom balance for O	$2a + z = 2b + c + 2e$	$a = b + c/2 + e - z/2$
Atom balance for N	$3.76(2)a = 2d$	$d = 3.76a$
Mole Fraction of CO_2, dry basis	$y_{CO_2} = \frac{b}{b+d+e}$	$e = b\left(\frac{1 - y_{CO_2}}{y_{CO_2}}\right) - d$

Substituting into the equation for *a* (inlet gmol O_2/gmol C):

$$a = \left(\frac{1}{4.76}\right)\left\{b\left[1 + \left(\frac{1 - y_{CO_2}}{y_{CO_2}}\right)\right] + \frac{y}{4} - \frac{z}{2}\right\} \qquad (2.8)$$

Hence, *a* can be solved by knowing values for *y* and *z* from the fuel properties and based on the observed mole fraction (dry basis) for CO_2.

The air-to-fuel ratio (g air/g fuel) is estimated as:

$$\left(\frac{m_a}{m_f}\right) = \frac{32a + 28\,(3.76)a}{MW_f} = 137.28\,\frac{a}{MW_f} \qquad (2.9)$$

Specific fuel consumption is reported as lb/hp-hr. Therefore, the fuel flow rate (g/sec) is estimated as:

$$m_f = \frac{454\, \dot{m}_f\, W_s}{3{,}600} \tag{2.10}$$

The air flow rate (g/sec) is:

$$m_a = m_f \left(\frac{m_a}{m_f}\right) \tag{2.11}$$

The exhaust flow (g/sec) is the sum of the flow of air and fuel:

$$m_e = m_f + m_a \tag{2.12}$$

While these equations characterize a mass balance for the engine, they include moisture. In order to calculate PM mass emission rate, the volume flow rate of exhaust on a dry basis is needed. The molar exhaust per mol of C in fuel consumed is equal to the sum of *b*, *d*, and *e* from Equation 2.7. Fuel flow is known from specific fuel consumption and can be estimated on a molar basis. The molar flow rate (gmol/sec) of the exhaust is estimated using the ideal gas law and conditions of standard temperature and pressure (STP).

$$M_{e,dry} = (b + d + e)\, \frac{m_f}{MW_f} \tag{2.13}$$

The volumetric dry exhaust flow rate (m^3/sec) is:

$$V_{e,dry} = M_{e,dry} \left(\frac{R\,T}{P}\right) \tag{2.14}$$

Where P = barometric pressure (assumption: 101,330 Pa); R = ideal gas constant (assumption: 8.3144 Pa-m^3/gmol-K); and T = ambient temperature (assumption: 298 K)

The PM mass emission rate (g/sec) is estimated as:

$$E_{PM}^{t} = C_{PM}^{dry} \, V_{e,dry} \tag{2.15}$$

The fuel-based PM emission rate (g/gal) is estimated as:

$$E_{PM}^{f} = \frac{E_{PM}^{t} \, \rho_f}{m_f} \tag{2.16}$$

Engine output-based emission factors are calculated by multiplying the fuel-based emission factors (g/gal) and the fuel use rate (gal/bhp-hr).

To calculate cycle average emission rates, the steady-state emission rate for each pollutant is multiplied by the percent time spent in each notch in the duty cycle, and summed over all notches. All measured emission rates are of the same magnitude as published emission rates for the same locomotive engine models.

Rail Yard Measurement

For RY measurements, fuel-based emission rates are calculated in the same manner as for dynamometer measurements. However, it is not feasible to accurately measure rail yard fuel use, since fuel is taken from an onboard tank of typically 900 to 1,500 gallons, and diesel engines return unspent fuel to the tank continuously. Instead, exhaust flow rate is estimated based on calculation of the mass air flow through the engine based on key engine parameters and inference of the air-to-fuel ratio from the measured exhaust composition.

Mass air flow is estimated based on the "speed density" method, which is based on the ideal gas law [Burgard et al., 2006; Vojtisek-Lom and Cobb, 1997]. Intake air molar flow rate is:

$$M_a = \frac{\left(P_M - \frac{P_B}{ER}\right) \times EV \times \left(\frac{ES}{30 \times EC}\right) \times VE}{R \times (T_{int} + 273.15)} \qquad (2.17)$$

Where *EC* = engine strokes per cycle (2); *ER* = engine compression ratio (typically 15 to 16); *ES* = engine speed (RPM); *EV* = engine displacement (L); M_a = intake air molar flow rate (mole/sec) (air: 21 vol-% O_2 and 79 vol-% N_2); P_B = barometric pressure (101 kPa); P_M = engine manifold absolute pressure (kPa); T_{int} = intake air temperature (°C); and *VE* = engine volumetric efficiency

Exhaust molar flow rate on a dry basis is estimated based on intake air molar flow rate and the air-to-fuel ratio inferred from the exhaust gas composition:

$$M_{e,t} = \frac{2 \times 0.21 \times M_{a,t}}{\left(2+\frac{x}{2}-z\right) y_{CO_2,t,dry} + \left(1+\frac{x}{2}-z\right) y_{CO,t,dry} + 2y_{O_2,t,dry} + y_{NO,t,dry} + (3x-7-6z)\, y_{C_6H_{14},t,dry}} \qquad (2.18)$$

Where $M_{e,t}$ = dry exhaust molar flow rate for time *t* (mole/s); $y_{i,t,dry}$ = mole fraction of pollutant species *i* on a dry basis for time *t* (gmol/gmol dry exhaust gases); and *x*,*z* = elemental composition of fuel CH_xO_z (gmol of H or O, respectively, per gmol of carbon in the fuel)

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

$$E_{i,t} = \left(y_{i,t,dry}\right)\left(M_{e,t}\right)(MW_i) \qquad (2.19)$$

Where $E_{i,t}$ = mass emission rate of pollutant species i (g/s) and MW_i = molecular weight of pollutant species i (g/mol)

It is possible to obtain VE if dynamometer measurements are conducted, which then allows the use of MAP in field measurements. Mass air flow is calibrated, by adjusting the value of VE in Equation 5, so that the fuel specific engine output (FSEO), in bhp-hr/gal, observed during rail yard measurements is equal to FSEO observed during dynamometer tests of the same engine and notch position. VE has been reported to range up to 1.90 for turbocharged 2-stroke diesel engines [Donaldson Filtration Solutions, 2012].

Engine output-based emission rates are estimated based on mass emission rate divided by engine output observed from the digital display in the locomotive cab.

RESULTS

The results include quality assurance, dynamometer and RY emission rates for each engine, and a comparison of the dynamometer and RY results.

Quality Assurance

Nearly 32,000 seconds of data were collected during dynamometer and RY measurements of the three engines. After the application of the quality assurance procedure, no dynamometer data and less than 2 percent of RY data were removed due to errors that could not be corrected, such as large discrepancies between PEMS gas analyzers. Negative HC concentrations observed during F59PH dynamometer measurements were corrected.

Volumetric Efficiency Estimation

For each notch position, measurement replicate, and prime mover engine model, the estimated volumetric efficiency was plotted versus a multiplicative function of engine speed and manifold absolute pressure, since the product of these engine parameters are a good indicator of engine power demand, as shown in Figures 2-10 and 2-11 for the EMD 12-710G3B and EMD 16-645E3 engines, respectively. A trendline was fit to derive a model that would describe the relationship between VE, RPM, and MAP. The models used to describe the relationship between VE, RPM, and MAP for the datasets have an R^2 value that exceeds 0.95, indicating that the model explains the variation in data very well.

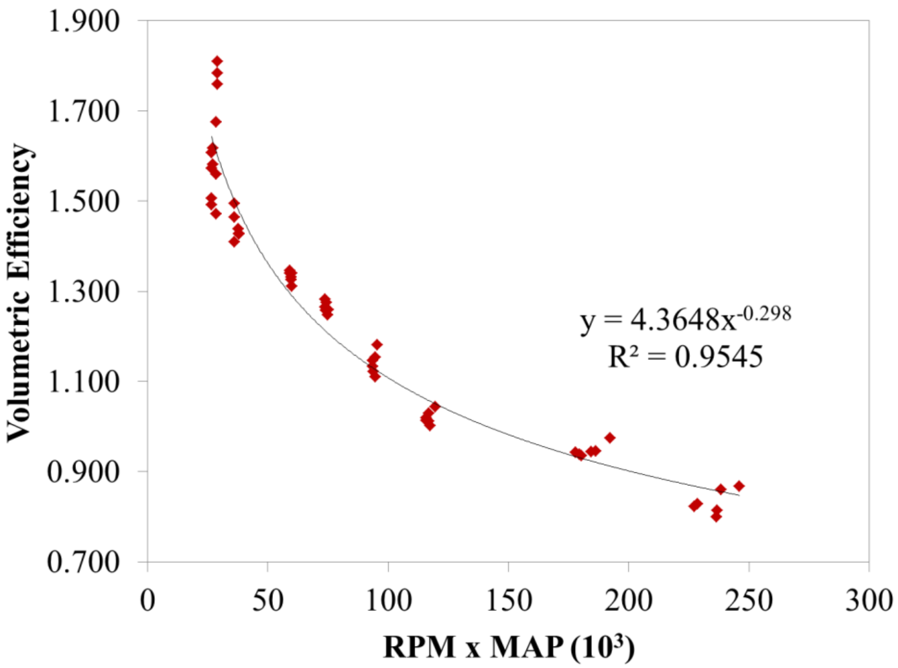


Figure 2-10: Volumetric Efficiency Model for Two EMD 12-710G3B Prime Mover Engines Measured on a Dynamometer

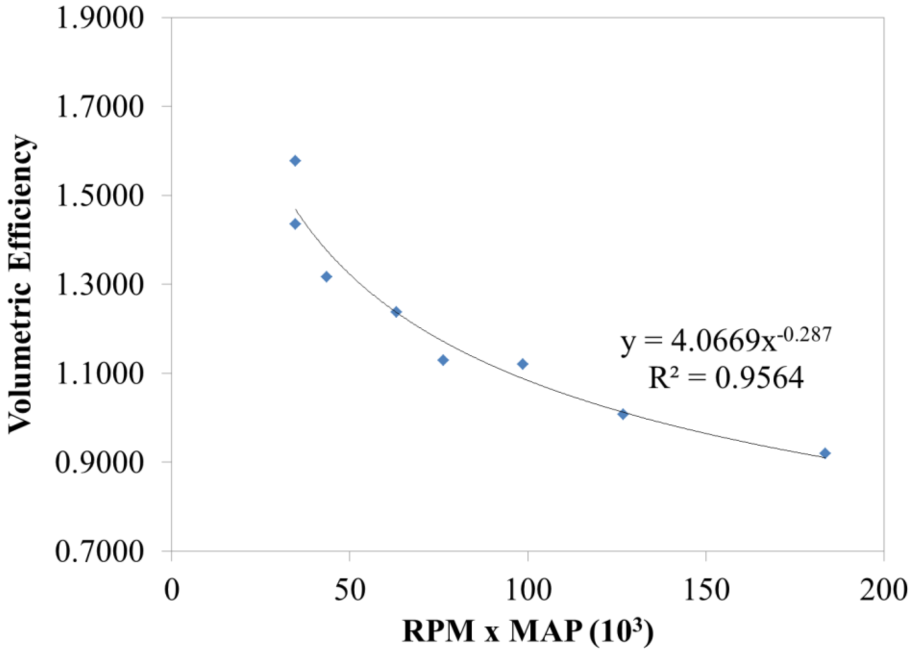


Figure 2-11: Volumetric Efficiency Model for One EMD 16-645E3 Prime Mover Engine Measured on a Dynamometer

Dynamometer Measurements

Fuel- and engine output-based average emission rates measured during dynamometer measurements for the three locomotives are shown in Tables 2-2 and 2-3, respectively. The 95-percent confidence intervals on the mean emission rates are typically ±2 percent or less for all notches and pollutants, except for a few of the very low CO emission rates measured for NC 1869.

While NC 1859 and NC 1869 are both F59PHs with the same model engine, there is inter-engine variability in emission rates. The fuel-based NO_x emission rates shown in Table 2 for NC 1859 are approximately constant at low loads from Idle to Notch 4, and then decrease by over 50 percent as engine load further increases. For NC 1869, NO_x emission rates increase by 18 percent from Idle to Notch 3, then decrease by 49 percent through Notch 8.
The fuel-based GP40 NO_x emission rates increase from by 58 percent from Idle to a peak of 220 g/gal at Notch 1. At high engine loads, the NO_x emissions vary within a relatively narrow range of 165 to 184 g/gallon. Engine output-based NO_x emission rates decrease 19 percent, on average, for each notch position increase for the F59PHs, as shown in Table 3. For the GP40, NO_x emission rates decrease from Idle to Notch 5, and then remain approximately constant with higher load.

Fuel-based HC emission rates decrease by 42 to 80 percent from Idle to Notch 1 among the three locomotives. At engine loads from Notches 5 to 8, the average emission rates are 63 to 8 percent lower than at Notch 1. However, the measured exhaust HC concentrations for all locomotives were below the PEMS detection limit of 13 parts per million, with the exception of Idle through Notch 5 for the GP40. Thus, the trends may not be significant. Engine output-based HC emission rates decrease as engine load increases from Idle to Notch 8 for the F59PHs, and from Idle to Notch 5 for the GP40.

The F59PH fuel-based CO emission rates increase with engine load, and are based on concentrations above the gas analyzer detection limit for Notches 6 through 8. For GP40, CO emission rates typically decrease with engine load, but only the CO concentration measured at Idle was above the detection limit. There is often a trade-off between NO_x and CO emissions. The F59PHs tend to have lower fuel-based NO_x emissions at high engine load, but higher fuel-based CO emissions, than the GP40. Engine output-based CO emission rates increase as engine load increases for the F59PHs, with the exception of Idle for NC 1859. Both CO and PM emission rates generally decrease as engine load increases for the GP40.

PM emission rates are not available for the F59PHs because of low flow through the PM sensor during measurements. Fuel-based PM emission rates for the GP40 are highest at Idle and tend to decrease with increasing engine load.

To enable comparison of the locomotives with emission rates previously published by EPA, Table 2-4 depicts the cycle average emission rates for NO_x, HC, CO, and PM based on the EPA line-haul freight duty cycle.

Table 2-2: Average Fuel-Based Prime Mover Engine Fuel Use and Emission Rates from Dynamometer Measurements[a]

Locomotive and Prime Mover	Notch Position	Engine Output (hp)	NO as NO_2[b] (g/gal)	HC[c,d] (g/gal)	CO[d] (g/gal)	Opacity-based PM[e,f] (g/gal)
NC 1859 F59PH 3,000 hp EMD 12-710	Idle	9	217	*81.5*	*0.00*	N/A
	1	184	205	*16.2*	*0.00*	
	2	422	207	*7.95*	*0.00*	
	3	831	213	*10.6*	*0.00*	
	4	1121	205	*8.03*	*1.92*	
	5	1522	175	*5.93*	*14.2*	
	6	1947	141	*5.48*	50.6	
	7	2732	128	*5.30*	56.2	
	8	3221	107	*3.88*	58.3	
NC 1869 F59PH 3,000 hp EMD 12-710	Idle	11	233	*66.3*	*0.00*	14.3
	1	184	234	*16.1*	*0.00*	6.04
	2	425	262	*12.1*	*0.00*	4.05
	3	830	276	*10.8*	*0.00*	3.51
	4	1120	260	*8.05*	*0.00*	3.48
	5	1521	229	*7.20*	*5.76*	3.46
	6	1947	188	*4.65*	28.6	3.36
	7	2724	165	*5.40*	40.2	3.53
	8	3225	134	*5.60*	50.8	3.62
NC 1792 GP40 3,000 hp EMD 16-645	Idle	20	147	*104*	150	40.5
	1	183	232	*43.5*	*30.8*	24.7
	2	419	188	*25.0*	*19.5*	17.3
	3	827	188	*17.7*	*9.02*	13.5
	4	1119	182	*12.9*	*9.04*	15.5
	5	1514	165	*12.7*	*7.61*	13.6
	6	1938	178	15.2	*5.42*	12.3
	7	2710	184	19.6	*4.03*	9.70
	8	3160	168	17.2	*6.40*	10.7

[a] The 95-percent confidence intervals on the mean emission rates are typically ±2% or less for all notches and pollutants, except for a few of the very low CO emission rates measured for NC 1869.

[b] A multiplicative correction factor of 1.053 is included to approximate for total NO_x.

[c] A multiplicative correction factor of 2.5 is included to approximate for total HC.

[d] For HC and CO, measured exhaust gas concentrations below the nominal detection limit of the PEMS are denoted with italics, and thus are subject to random variations and to uncertainty.

[e] A multiplicative correction factor of 5 is included to approximate for total PM.

[f] PM emission rates not available for three replicate measurements of NC 1859 and two replicate measurements of NC 1869 because the flow through the PEMS PM detection system was too low to obtain a valid measurement. The low flow rate through the sensor during the measurement could not be corrected for during post-processing of the data. PM emission rates for NC 1869 are based on one measurement.

Table 2-3: Average Engine Output-Based Prime Mover Engine Fuel Use and Emission Rates from Dynamometer Measurements[a]

Locomotive and Prime Mover	Notch Position	Engine Output (hp)	FSEO (bhp-hr/gal)	NO as NO_2[b] (g/bhp-hr)	HC[c,d] (g/bhp-hr)	CO[d] (g/bhp-hr)	Opacity-based PM[e,f] (g/bhp-hr)
NC 1859 F59PH 3,000 hp EMD 12-710	Idle	9	2.73	80.9	*24.1*	*1.60*	N/A
	1	184	16.7	12.4	*0.95*	*0.00*	
	2	422	18.8	11.2	*0.55*	*0.00*	
	3	831	19.7	10.8	*0.50*	*0.00*	
	4	1121	20.1	10.3	*0.43*	*0.09*	
	5	1522	20.2	8.69	*0.33*	*0.71*	
	6	1947	19.8	7.19	*0.28*	2.57	
	7	2732	20.3	6.38	*0.25*	2.80	
	8	3221	19.9	5.44	*0.20*	2.94	
NC 1869 F59PH 3,000 hp EMD 12-710	Idle	11	2.71	86.2	*23.2*	*0.00*	5.32
	1	184	16.5	14.2	*1.20*	*0.00*	0.36
	2	425	19.1	13.8	*0.73*	*0.00*	0.21
	3	830	20.0	13.9	*0.55*	*0.00*	0.17
	4	1120	20.2	13.0	*0.40*	*0.00*	0.17
	5	1521	20.4	11.3	*0.35*	*0.29*	0.17
	6	1947	20.2	9.40	*0.25*	1.41	0.16
	7	2724	20.5	8.11	*0.28*	1.96	0.17
	8	3225	20.1	6.67	*0.28*	2.54	0.18
NC 1792 GP40 3,000 hp EMD 12-710	Idle	20	3.16	46.8	*32.8*	47.3	12.8
	1	183	15.4	15.1	*2.83*	*2.00*	1.60
	2	419	18.5	10.2	*1.35*	*1.05*	0.95
	3	827	19.1	9.86	*0.93*	*0.47*	0.70
	4	1119	19.2	9.48	*0.68*	*0.47*	0.80
	5	1514	19.3	8.59	*0.65*	*0.39*	0.70
	6	1938	19.4	9.17	0.78	*0.28*	0.65
	7	2710	19.7	9.36	1.00	*0.20*	0.50
	8	3160	19.6	8.61	0.88	*0.33*	0.55

[a] The 95-percent confidence intervals on the mean emission rates is typically ±2% or less for all notches and pollutants, except for a few of the very low CO emission rates measured for NC 1869.

[b] A multiplicative correction factor of 1.053 is included to approximate for total NO_x.

[c] A multiplicative correction factor of 2.5 is included to approximate for total HC.

[d] For HC and CO, measured exhaust gas concentrations below the nominal detection limit of the PEMS are denoted with italics, and thus are subject to random variations and to uncertainty.

[e] A multiplicative correction factor of 5 is included to approximate for total PM.

[f] PM emission rates not available for three replicate measurements of NC 1859 and two replicate measurements of NC 1869 because the flow through the PEMS PM detection system was too low to obtain a valid measurement. The low flow rate through the sensor during the measurement could not be corrected for during post-processing of the data. PM emission rates for NC 1869 are based on one measurement.

Table 2-4: Comparison of EPA Line-Haul Duty Cycle Average Emission Rates for Measured Prime Mover Engines from Dynamometer Measurements to Published Emission Rates

Model	Locomotive	NO_x[a] (g/bhp-hr)	HC[b] (g/bhp-hr)	CO (g/bhp-hr)	Opacity-based PM[c,d] (g/bhp-hr)
F59PH	NC 1859	9.5	0.52	3.1	N/A
	NC 1869	11.9	0.63	2.5	0.21
	EPA Data[e]	10.6	0.36	0.9	0.25
GP40	NC 1792	12.6	1.70	1.2	1.01
	EPA Data[e]	13.6	0.48	1.9	0.29

[a] Adjusted results include a multiplicative correction factor of 1.053 to approximate for total NO_x.

[b] Adjusted results include a multiplicative correction factor of 2.5 to approximate for total HC.

[c] Adjusted results include a multiplicative correction factor of 5 to approximate total PM.

[d] PM emission rates not available for NC 1859 because the flow through the PEMS PM detection system was too low to obtain a valid measurement. The low flow rate through the sensor during the measurement could not be corrected for during post-processing of the data.

[e] EPA reported cycle average emission rates for same engine make and model [EPA, 1998].

Rail Yard Measurements

Fuel- and engine output-based average fuel use and emission rates measured during RY measurements for the three locomotives are shown in Tables 2-5 and 2-6, respectively. Fuel use and emission rates for NC 1792 are reported for both pre- and post-rebuild measurements. The ratio of standard error of the mean to the mean value among each notch position and each measurement for NO and PM averaged less than 1 percent. The average ratio for CO and HC were less than 2 percent, except for the pre-rebuild measurements for the GP40, during which the measurements were very low. Thus, the confidence intervals on the reported mean emission rates are typically below ±2 to ±4 percent.

The fuel-based NO_x emission rate at Notch 8 is 35 to 47 percent lower than at Low Idle for all locomotives. NO_x emission rates remain generally constant during both sets of measurements of the GP40. Engine output-based NO_x emission rates decrease as engine load increases with notch position for all locomotives, with some scatter of the data.

The HC emission rate at Notch 8 is 67 to 82 percent lower than at idle for all locomotives. Engine output-based HC emission rates decrease as engine load increases with notch position for all locomotives, with some scatter of the data.

For the F59PHs, CO and PM emission rates are generally highest at Idle and Notch 8 and lowest at Notch 3. For the GP40, CO and PM emission rates are highest at Idle, decrease as engine output increases, and generally level off at highest notch positions. PM emission rates range from 4 to 20 g/gal for the F59PHs and between 5 and 30 g/gal for GP40. The trends in emission rates as engine output increases during RY measurements are generally similar to trends seen from dynamometer measurements.

Average FSEO for Notches 2 through 8, on an engine output basis, were 19.8 bhp-hr/gal for the F59PHs, 18.8 bhp-hr/gal for the pre-rebuild GP40, and 19.2 bhp-hr/gal for the post-rebuild GP40. Average FSEOs for the three locomotives are within 10 percent of the 20.8 bhp-hr/gal value typically used by EPA.

Table 2-5: Average Fuel-Based Prime Mover Engine Fuel Use and Emission Rates from Rail Yard Measurements[a]

Locomotive	Notch Position	Engine Output (hp)	NO as NO_2[b] (g/gal)	HC[c,d] (g/gal)	CO[d] (g/gal)	Opacity-based PM[e] (g/gal)
NC 1859 Post-Rebuild F59PH 3,000 hp EMD 12-710	Low Idle	N/A[f]	214	*28.5*	*4.13*	19.2
	High Idle	N/A[f]	175	*33.3*	*2.88*	10.4
	1	190	167	*14.7*	*1.59*	6.15
	2	305	198	*6.83*	*1.11*	5.75
	3	688	205	*4.08*	*0.88*	4.05
	4	985	188	*2.23*	*2.17*	4.20
	5	1310	168	*2.45*	*3.18*	4.20
	6	1600	160	*4.15*	*5.41*	4.55
	7	2300	126	*1.88*	26.9	6.60
	8	2700	114	*5.18*	30.3	10.8
NC 1869 Post-Rebuild F59PH 3,000 hp EMD 12-710	Low Idle	N/A[f]	207	*32.8*	*8.52*	10.9
	High Idle	N/A[f]	184	75.3	*5.45*	7.20
	1	190	187	*20.0*	*6.49*	6.55
	2	345	241	*17.1*	*2.23*	5.10
	3	675	250	17.5	*1.75*	4.30
	4	1000	241	*11.0*	*1.43*	4.45
	5	1300	219	*5.95*	*2.58*	4.55
	6	1600	207	*9.30*	*2.42*	4.20
	7	2400	164	*6.23*	19.3	6.35
	8	2700	134	9.48	29.4	10.1
NC 1792 Pre-Rebuild GP40 3,000 hp EMD 16-645	Idle	20	257	*34.8*	*54.4*	17.5
	1	190	276	*21.3*	*33.2*	10.2
	2	345	240	*20.0*	*14.5*	12.5
	3	675	256	*13.8*	*9.01*	10.2
	4	1000	274	*8.03*	*3.48*	9.00
	5	1300	275	*4.45*	*2.89*	7.95
	6	1600	276	*0.93*	*4.86*	6.75
	7	2400	272	*3.98*	*6.22*	5.35
	8	3000	239	8.85	13.3	7.60
NC 1792 Post-Rebuild GP40 3,000 hp EMD 16-645	Idle	20	155	*71.0*	*102*	19.5
	1	190	183	86.5	*62.5*	15.4
	2	345	146	44.8	*25.9*	16.8
	3	675	155	30.0	*14.7*	16.0
	4	1000	176	*17.3*	*5.63*	14.4
	5	1300	167	*13.3*	*9.41*	12.5
	6	1600	165	*10.9*	*9.03*	14.5
	7	2400	153	*9.08*	*7.52*	17.4
	8	3000	148	23.7	*8.52*	29.9

[a] The ratio of standard error of the mean to the mean value among each notch position and each test for NO and PM averaged less than 1%. The average ratio for CO and HC were less than 2% except for the pre-rebuild measurements for the GP40, during which the measurements were very low. Thus, the confidence intervals on the reported mean emission rates are typically below ±2 to ±4%.

[b] A multiplicative correction factor of 1.053 is included to approximate for total NO_x.

[c] A multiplicative correction factor of 2.5 is included to approximate for total HC.

[d] For HC and CO, measured exhaust gas concentrations below the nominal detection limit of the PEMS are denoted with italics, and thus are subject to random variations and to uncertainty.

[e] A multiplicative correction factor of 5 is included to approximate for total PM.

[f] HP output was recorded from the digital display of the locomotive activity data recorder in the locomotive cab, and is not available for Low and High Idle of the F59PH locomotives.

Table 2-6: Average Engine Output-Based Prime Mover Engine Fuel Use and Emission Rates from Rail Yard Measurements[a]

Locomotive	Notch Position	Engine Output (hp)	FSEO (bhp-hr/gal)	NO as NO_2[b] (g/bhp-hr)	HC[c,d] (g/bhp-hr)	CO[d] (g/bhp-hr)	Opacity-based PM[e] (g/bhp-hr)
NC 1859 Post-Rebuild F59PH 3,000 hp EMD 12-710	Low Idle	N/A[f]	2.71	79.0	*10.5*	*1.52*	7.10
	High Idle	N/A[f]	1.04	167	*32.0*	*2.77*	10.0
	1	190	16.6	10.1	*0.88*	*0.10*	0.35
	2	305	18.7	10.5	*0.38*	*0.06*	0.30
	3	688	19.6	10.5	*0.20*	*0.04*	0.20
	4	985	20.0	9.47	*0.10*	*0.11*	0.20
	5	1310	20.1	8.40	*0.12*	*0.16*	0.20
	6	1600	19.7	8.10	*0.20*	*0.27*	0.20
	7	2300	20.1	6.27	*0.10*	1.33	0.35
	8	2700	19.8	5.73	*0.25*	1.53	0.55
NC 1869 Post-Rebuild F59PH 3,000 hp EMD 12-710	Low Idle	N/A[f]	2.72	76.4	12.0	*3.14*	4.00
	High Idle	N/A[f]	1.02	180	*73.5*	*5.33*	7.00
	1	190	16.5	11.4	*1.20*	*0.39*	0.40
	2	345	19.1	12.6	*0.90*	*0.12*	0.25
	3	675	20.0	12.4	0.88	*0.09*	0.20
	4	1000	20.2	11.9	*0.55*	*0.07*	0.20
	5	1300	20.4	10.7	*0.30*	*0.13*	0.20
	6	1600	20.2	10.3	*0.45*	*0.12*	0.20
	7	2400	20.5	8.00	*0.30*	0.94	0.30
	8	2700	20.2	6.65	0.48	1.46	0.50
NC 1792 Pre-Rebuild GP40 3,000 hp EMD 16-645	Idle	20	2.98	86.2	*11.7*	*18.2*	5.85
	1	190	14.2	19.5	*1.50*	*2.34*	0.70
	2	345	17.5	13.7	*1.15*	*0.82*	0.70
	3	675	18.5	13.8	*0.75*	*0.49*	0.55
	4	1000	18.8	14.6	*0.43*	*0.19*	0.50
	5	1300	19.3	14.3	*0.23*	*0.15*	0.40
	6	1600	19.2	14.4	*0.05*	*0.25*	0.35
	7	2400	18.8	14.4	*0.20*	*0.33*	0.30
	8	3000	19.4	12.3	0.45	0.69	0.40
NC 1792 Post-Rebuild GP40 3,000 hp EMD 16-645	Idle	20	3.16	49.0	*22.4*	*32.1*	6.15
	1	190	15.4	11.9	5.63	*4.06*	1.00
	2	345	18.5	7.88	2.40	*1.40*	0.90
	3	675	19.1	8.13	1.58	*0.77*	0.85
	4	1000	19.2	9.17	*0.90*	*0.29*	0.75
	5	1300	19.3	8.70	*0.68*	*0.49*	0.65
	6	1600	19.4	8.52	*0.55*	*0.46*	0.75
	7	2400	19.7	7.76	*0.45*	*0.38*	0.90
	8	3000	19.5	7.57	1.23	*0.44*	1.55

[a] The ratio of standard error of the mean to the mean value among each notch position and each test for NO and PM averaged less than 1%. The average ratio for CO and HC were less than 2% except for the pre-rebuild measurements for the GP40, during which the measurements were very low. Thus, the confidence intervals on the reported mean emission rates are typically below ±2 to ±4%.

[b] A multiplicative correction factor of 1.053 is included to approximate for total NO_x.

[c] A multiplicative correction factor of 2.5 is included to approximate for total HC.

[d] For HC and CO, measured exhaust gas concentrations below the nominal detection limit of the PEMS are denoted with italics, and thus are subject to random variations and to uncertainty.

[e] A multiplicative correction factor of 5 is included to approximate for total PM.

[f] HP output was recorded from the digital display of the locomotive activity data recorder in the locomotive cab, and is not available for Low and High Idle of the F59PH locomotives.

For the GP40, the post-rebuild FSEO increased 4 percent, on average, compared to pre-rebuild. The engine output-based NO_x emission rate decreased an average of 41 percent. These are successful outcomes. However, HC and PM emission rates more than doubled after the engine rebuild. CO emission rates increased 83 percent, on average, after engine rebuild for idle through Notch 7. However, the Notch 8 post-rebuild CO emission rate was 36 percent less than pre-rebuild. The reduction in NO_x emissions may have also lead to the increase in emissions of CO, HC, and PM. However, the CO emission rates are approximately comparable to those of the F59PHs and thus are not high on an absolute basis.

Table 2-7 depicts the cycle average emission rates for NO_x, HC, CO, and PM for the three locomotives measured and emission rates previously published by EPA. All measured emission rates for the F59PHs and GP40 are of the same magnitude of published emission rates for the same locomotive engine models.

Dynamometer versus Rail Yard Measurements

Engine output-based fuel use and NO_x emission rates measured on the dynamometer and in the RY are compared for F59PH locomotive NC 1859, as shown in Figure 2-2. Not shown are results for CO and HC. CO and HC emission concentrations tended to be at or below the PEMS detection limit during both sets of measurements, so large relative, but statistically insignificant, differences between emission rates are observed.

Table 2-7: Comparison of EPA Line-Haul Duty Cycle Average-Based Emission Rates for Measured Prime Mover Engines from Rail Yard Measurements to Published Emission Rates

Model	Locomotive	NO_x[a] (g/bhp-hr)	HC[b] (g/bhp-hr)	CO (g/bhp-hr)	Opacity-based PM[c] (g/bhp-hr)
F59PH	NC 1859 (Post-Rebuild)	7.3	0.30	1.1	0.47
	NC 1869 (Post-Rebuild)	8.7	0.58	1.0	0.42
	EPA Data[d]	10.6	0.36	0.9	0.25
GP40	NC 1792 (Pre-Rebuild)	14.1	0.58	0.8	0.48
	NC 1792 (Post-Rebuild)	8.4	1.43	0.9	1.31
	EPA Data[d]	13.6	0.48	1.9	0.29

[a] Adjusted results include a multiplicative correction factor of 1.053 to approximate for total NO_x.

[b] Adjusted results include a multiplicative correction factor of 2.5 to approximate for total HC.

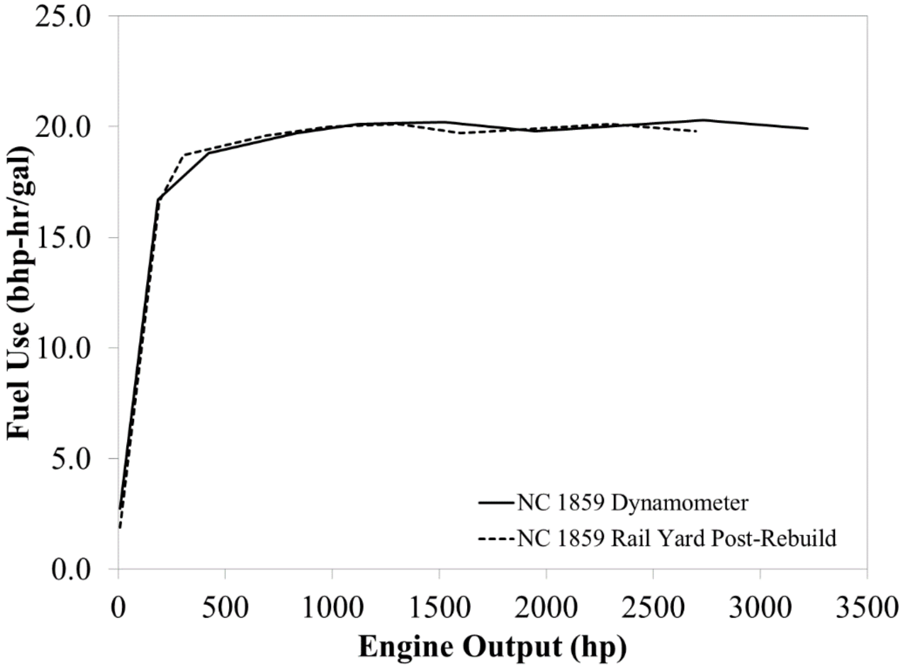
[c] Adjusted results include a multiplicative correction factor of 5 to approximate total PM.

[d] EPA reported cycle average emission rates for same engine make and model [EPA, 1998].

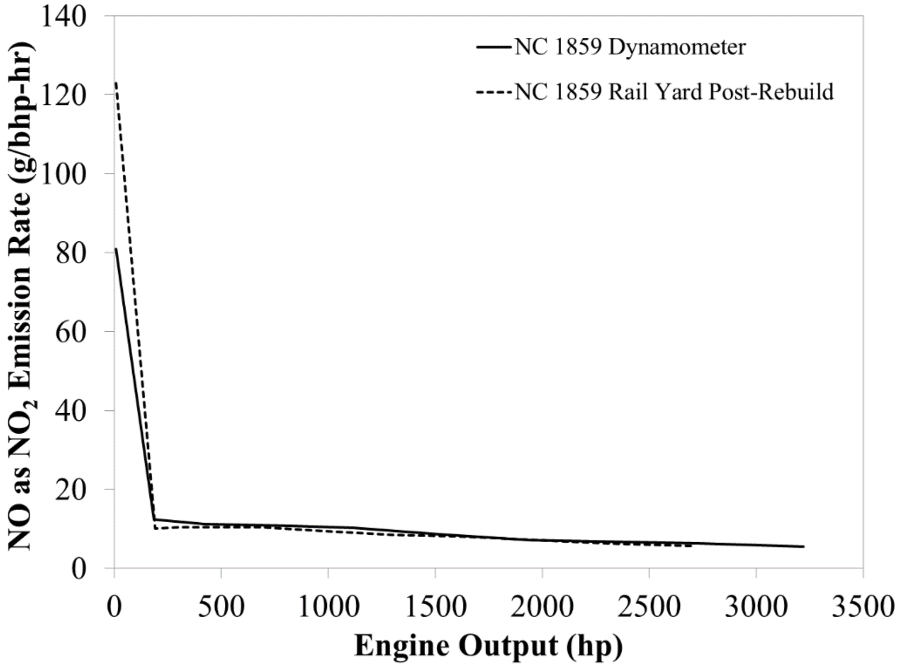
The trends in fuel use are similar between dynamometer and RY measurements, as expected since the estimate of RY fuel use is based on calibration of VE from dynamometer measurements. In Figure 2-2(a), F59PH engine output-based fuel use rates increase up to approximately 400 hp, then approximately level off between 19.5 and 20.0 bhp-hr/gal. While not shown, the GP40 fuel use rates reach a maximum of 18.0 and 18.5 bhp-hr/gal for dynamometer and RY measurements, respectively.

There is little variability in the dynamometer and RY measured time-based NO_x emission rates at low engine output, as shown in Figure 2-2(b). Engine output-based NO_x emission rate is very sensitive to engine output at low engine output. Above 250 hp, the NO_x emission rate is approximately constant for all locomotives.

RY measurements produced engine output-based NO_x emission rates that were 8 to 17 percent less than those observed during dynamometer measurements, perhaps in part because the engine load was somewhat lower at higher notches during RY measurements.



(a) Engine output-based fuel use rates



(b) Engine output-based NO_x emission rates

Figure 2-12: Comparison of Fuel Use and NO_x Emission Rates versus Engine Output from Dynamometer and Rail Yard Measurements for F59PH Locomotive NC 1859

CHAPTER 3

COMPARISION OF OVER-THE-RAIL AND RAIL YARD MEASUREMENTS OF DIESEL LOCOMOTIVES

The objectives in this chapter are to determine: (1) if RY emission measurements are representative of emissions produced during real-world locomotive operation; (2) if the regulatory duty cycle differs from duty cycles measured during passenger rail service, and assess whether duty cycles affect trip total emission estimates; and (3) if PME transient operation affects trip total emission estimates.

METHODS

A PEMS is used to quantify fuel use and emission rates of locomotive PMEs during RY static load and OTR measurements.

Field Study Design

PMEs from seven locomotives were instrumented and exhaust emission concentrations measured both in the RY and during revenue-generating passenger rail service. RY static load measurements were conducted at the NCDOT Capital Yard Maintenance Facility in Raleigh, NC. OTR measurements were conducted during North Carolina Amtrak Piedmont passenger rail service between Raleigh and Charlotte, NC. The locomotives operated on ULSD for all measurements.

Locomotives

NCDOT owns two EMD F59PHI and four EMD F59PH locomotives, which are used for passenger rail service. Each locomotive has a 12-cylinder, 140-Liter, 2,240-kW EMD 12-710 diesel PME. An EMD GP40 locomotive, with a 16-cylinder, 169-Liter, 2,240-kW EMD 16-645 diesel PME was previously owned and operated by NCDOT. All seven locomotives were remanufactured within the last 4 years, and all measurements were conducted within 2 years of remanufacture. Technical specifications for all of the locomotives are included in Appendix A.

Data Collection

For RY measurements, the same test schedule described in Test Schedule subsection of Chapter 2 was used. Three replicate RY measurements were conducted on the F59PH and F59PHI locomotives, except for one case when only two could be completed because of inclement weather conditions. One RY measurement was conducted on the GP40.

For OTR measurements, the locomotives were operated normally during revenue-generating Piedmont passenger service by Amtrak engineers. The twice-daily Piedmont rail service covers a distance of 278 kilometers, with a scheduled duration of 3 hours and 10 minutes. A map of the Piedmont route is depicted in Figure 3-1. Typically, each train is comprised of one locomotive, one baggage/lounge car, and two passenger cars. Between 2 and 14 one-way OTR measurements were conducted on all locomotives, with the exception of one F59PHI where only a single one-way OTR measurement was conducted.

Figure 3-1: Route Map of North Carolina Amtrak Piedmont Passenger Rail Service

RGH: Raleigh, CYN: Cary, DNC: Durham, BNC: Burlington, GRO: Greensboro, HPT: High Point, SAL: Salisbury, KAN: Kannapolis, CLT: Charlotte

For both RY and OTR measurements, the locomotives were instrumented and exhaust concentration and engine activity data were measured continuously. However, for RY measurements, data during notch transitions were excluded from analysis.

Portable Emissions Measurement System

The PEMS units used here are the OEM-2100 Montana and OEM-2100AX Axion systems. A full description of the PEMS and its precision, accuracy, and calibration was discussed previously in the Portable Emissions Measurement System subsection of Chapter 2.

Duty Cycle Derivation

Each locomotive has an activity data recorder. Real-time RPM, notch positon, and engine output data are provided on a digital display in the locomotive cab, but not archived by the data recorder. Engine RPM is measured with the sensor array. An analyst records engine output at each notch from the digital display for every RY replicate and at least one OTR measurement. The data recorder archives engine solenoid operation from which notch is inferred.

Data Quality Assurance

A full description of data time aligning and error screening was discussed previously in the Data Quality Assurance subsection of Chapter 2.

Fuel Use and Emission Rate Estimation

For both types of measurements, the methods to estimate fuel use and emission rates are the same. A full description of these methods was discussed previously in the Fuel Use and Emission Rate Estimation subsection of Chapter 2.

In addition, for OTR measurements, locomotive emissions for each one-way trip were calculated using two approaches. Approach 1 is based on time-weighted average notch-based emission rates, which are based on steady-state average emission rates for each notch. Approach 2 is based on the summation of second-by-second emissions data, which include transients. By comparing Approach 2 versus Approach 1, the role of transients in cycle average emissions is assessed.

Approach 1: Steady State

In Approach 1, notch average emission rates at steady-state are estimated for each notch. The PME is in a specific notch as soon as the engineer changes the throttle position. However, in this approach, transients in emission rates associated with transitioning between steady-state notches are not accounted for. Only 1 Hz emission rates from steady-state operation within a notch are used to estimate notch average emission rate. Two criteria were used for steady-state: (1) change in engine speed from one second to the next is ≤10 RPM; and (2) engine speed is within ±20 RPM of the expected average engine speed at the given notch based on previous dynamometer measurements of the same model engine.

Steady-state emission rates are weighted by the percentage of time spent in each notch in the EPA line-haul or Piedmont duty cycle. Cycle average emission rates are estimated by summing the weighted emission rates. This method is similar to how the EPA estimates PME cycle average emission rates for comparison to applicable emission standards [CFR, 2013]. Dynamic brake is utilized during OTR operation, and cannot be reproduced during RY measurements. Since dynamic braking has low engine load, the percent of time allocated to dynamic brake in the duty cycle is added to the percent time allocated to idle.

Approach 2: Transients

In Approach 2, total emissions for a one-way trip are quantified by summing time-based emission rates for each second of data between Raleigh and Charlotte. This approach accounts for the emission rates associated with transitions between notches.

Statistical Comparisons

Two-sample *t*-tests were used for comparisons of results taking into account the mean, standard deviation of inter-run or inter-replicate variability, and sample size. Comparisons were made for individual locomotives and for the entire set of runs or replicates for OTR versus RY-based cycle average rates for the EPA line-haul cycle, for Piedmont versus EPA cycle averages based on OTR notch rates, and for OTR cycle average rates based on transients versus steady state notch average rates.

RESULTS

Results include cycle average RY and OTR emission rates for each engine, real-world duty cycles observed during OTR measurements, and a comparison of trip total emissions using two approaches. This paper focuses on NO_x, HC, CO, and PM because they are regulated by emission standards. While CO_2 is not regulated, emission rates are estimated to provide insight on fuel use. The amount of carbon emitted as CO_2 averages over 99 percent.

Approximately 19 and 160 hours of data were collected during RY and OTR measurements, respectively. Typically, less than one percent of total data collected were excluded due to errors that could not be corrected.

Rail Yard Measurements

For each locomotive, notch average engine output-based emission rates were estimated for idle and eight notch positions. As engine load increases, engine RPM, MAP, and exhaust CO_2 concentrations increase. This leads to an increase in air, fuel, and exhaust flow for the engine. IAT remained relatively constant across all notches for each locomotive. The coefficient of variation (CV), which is the ratio of the standard deviation to the mean, for inter-replicate variations for a given engine was 0.04 or less for RPM, IAT, and MAP. Thus, engine parameter measurements were highly repeatable. Notch average engine parameters and emission rates are included in Appendix C.

Engine output-based NO_x emission rates for all locomotives generally decrease as the PME shifts from idle to Notch 8. As notch position increases, engine output increases, air-to-fuel ratio decreases, and measured NO concentration typically increases. The latter is expected since the rate of NO formation typically increases with flame temperature, which in turn increases as AFR becomes less lean [Cooper and Alley, 2011]. However, when normalized to engine output, NO emission rate decreases with notch position. NO_x emission rates, on a g/kW-hr basis, were approximately 81, 91, and 94 percent lower at Notch 8 versus idle for the GP40, F59PH, and F59PHI locomotives, respectively. CV ranged from 0.01 to 0.08 for Notch 8, indicating high repeatability of measurements.

As engine output increases, exhaust PM concentration increases. However, notch average PM emission rates were highest at idle for all locomotives, ranging from 3.9 to 10.4 g/kW-hr. For each locomotive, PM emission rates at Notches 1 through 8 were similar. For example, the NC 1810 mean non-idle notch average emission rate was 0.27 g/kW-hr with a 95% confidence interval (CI) on the mean of ±0.09 g/kW-hr. Among the six locomotives with EMD 12-710 engines, the mean non-idle emission rate was 0.35 g/kW-hr with a 95% CI on the mean of ±0.10 g/kW-hr. For the GP40, the non-idle mean PM emission rate was 1.16 g/kW-hr, with a 95% CI on the mean of ±0.30 g/kW-hr. Thus, non-idle emission rates were approximately consistent among the eight notches and were substantially lower than during idle. Compared to idle, non-idle PM emission rates were approximately 82, 95, and 97 percent less for the GP40, F59PH, and F59PHI locomotives, respectively. CV values averaged 0.09 for Notch 8, indicating high repeatability of measurements.

There is substantial inter-replicate variability in notch average HC and CO emission rates for all engines, with CV values as high as 1.33 and 1.65, respectively, for a given locomotive and notch position. However, concentrations of these pollutants were typically below the detection limit for all notches, which contributes to the high relative variation. As expected for diesel engines, emission rates of HC and CO tend to be low versus other types of emission sources [Cooper and Alley, 2011].

Cycle average emission rates were estimated based on the EPA line-haul duty cycle as shown in Table 3-1. All measured emission rates are of the same magnitude as published emission rates of the same locomotive model [EPA, 1998]. Cycle average NO_x and PM rates for all locomotives are highly repeatable across RY replicates for a given locomotive, with CV values between 0.01 and 0.10. High inter-replicate variability in notch average HC and CO emission rates lead to high inter-replicate variability in cycle average rates. The NO_x emission rates were highly variable across the measured locomotives. For three locomotives, the rates were relatively low, ranging from 9.4 to 10.6 g/kW-hr, including the EMD16-645 engine and two mechanically governed EMD12-710 engines. Two locomotives had moderate NO_x emission rates of 12.0 to 12.7 g/kW-hr, both with mechanically governed EMD12-710 engines. Two had relatively high NO_x emission rates of 14.2 to 15.0 g/kW-hr, both with electronically governed EMD12-710 engines. The results indicate substantial inter-engine variability for engines of the same general design. HC and CO emission rates are of low magnitude. There is not a clear trend in the relationship between PM and NO_x emission rates, although there is some hint of a trade-off between these. For example, two of the lowest NO_x emitting locomotives, NC 1792 and NC 1859, have higher PM emission rates than the highest NO_x emitting locomotives, NC 1797. However, NC 1869, which has a moderate NO_x emission rate, also tends to have a high PM emission rate compared to all but the GP40.

Table 3-1: Comparison of EPA Line-Haul Duty Cycle Average Emission Rates for Measured Prime Mover Engines Based on Rail Yard Measurements

Model	**Locomotive**	**NO_x[a]** **(g/kW-hr)**	**HC[b]** **(g/kW-hr)**	**CO** **(g/kW-hr)**	**Opacity-based PM[c]** **(g/kW-hr)**	**CO_2** **(g/kW-hr)**
GP40 EMD 16-645E3	NC 1792 1 replicate	10.1[d]	2.7[d]	1.2[d]	1.69[d]	698[d]
F59PHI EMD 12-710G3 (Electronically governed)	NC 1755 2 replicates	14.2 (*0.02*)	5.7 (*0.92*)	1.5 (*0.44*)	n/a[e]	676 (*0.02*)
	NC 1797 3 replicates	15.0 (*0.01*)	1.4 (*0.33*)	0.8 (*0.20*)	0.26 (*0.05*)	677 (*0.01*)
F59PH EMD 12-710G3 (Mechanically governed)	NC 1810 3 replicates	10.6 (*0.01*)	5.1 (*0.09*)	1.6 (*0.10*)	0.40 (*0.10*)	695 (*0.00*)
	NC 1859 3 replicates	9.4 (*0.02*)	6.0 (*0.18*)	2.6 (*0.15*)	0.52 (*0.02*)	713 (*0.00*)
	NC 1869 3 replicates	12.7 (*0.07*)	0.80 (*0.17*)	1.2 (*0.19*)	0.59 (*0.07*)	712 (*0.05*)
	NC 1893 3 replicates	12.0 (*0.04*)	1.1 (*0.24*)	0.5 (*0.13*)	0.36 (*0.08*)	733 (*0.01*)

Italicized values in parentheses are coefficients of variation (standard deviation divided by the mean) on the mean emission rate.

[a] Results include multiplicative correction factor of 1.053 to approximate total NO_x.

[b] Results include multiplicative correction factor of 2.5 to approximate total HC.

[c] Results include multiplicative correction factor of 5 to approximate total PM.

[d] Only one rail yard measurement was completed. Therefore, a coefficient of variation could not be calculated.

[e] Malfunction of the PEMS photometer lead to no valid opacity-based PM data during measurement.

Over-the-Rail Measurements

Cycle average emission rates are estimated using the EPA line-haul duty cycle and duty cycles observed during each one-way Piedmont trip.

Duty Cycles

Observed duty cycles for each locomotive model, and the average duty cycle inferred from all measured locomotives, are compared to the EPA line-haul and passenger duty cycles in Table 3-2. Each individual duty cycle is given in Appendix D. Across models, results are

Table 3-2: Comparison of Measured Duty Cycles during Piedmont Rail Service to EPA Line-Haul Duty Cycle

Notch	Percent Time in Notch					
	Locomotive Model[a]				EPA (1998)	
	F59PH	F59PHI	GP40	Average[b]	Line-Haul	Passenger
Idle	26.5 (*10.6, 40.6*)	35.7 (*23.2, 51.8*)	24.9 (*20.9, 28.1*)	28.4	38.0	47.4
Dynamic Brake	13.0 (*3.8, 18.6*)	3.0 (*0.0, 7.0*)	14.6 (*11.6, 17.7*)	11.1	12.5	6.2
1	3.9 (*0.6, 14.0*)	3.4 (*1.0, 7.9*)	5.1 (*1.7, 8.7*)	3.8	6.5	7.0
2	5.0 (*1.6, 11.3*)	4.9 (*1.9, 9.9*)	4.3 (*3.7, 4.8*)	4.8	6.5	5.1
3	4.0 (*1.4, 10.7*)	3.7 (*0.7, 10.3*)	2.5 (*1.5, 3.8*)	3.7	5.2	5.7
4	4.1 (*1.4, 11.4*)	4.1 (*1.2, 10.7*)	3.0 (*0.9, 5.8*)	4.0	4.4	4.7
5	2.2 (*0.4, 4.5*)	2.2 (*1.0, 4.6*)	2.3 (*0.9, 3.6*)	2.2	3.8	4.0
6	2.5 (*0.2, 11.0*)	2.8 (*0.5, 10.2*)	2.0 (*1.2, 2.6*)	2.5	3.9	2.9
7	0.7 (*0.0, 2.5*)	1.3 (*0.1, 3.7*)	1.1 (*0.3, 2.1*)	0.9	3.0	1.4
8	38.2 (*22.7, 52.0*)	38.9 (*29.0, 48.0*)	40.3 (*34.6, 45.4*)	38.6	16.2	15.6
Number of Runs	32	10	6	48		
Avg. Travel Time (s)	11,744	11,918	12,269	11,846		

[a] Italicized values in parentheses are the minimum and maximum percentages of time spent in a notch position.

[b] "Average" is the average of the forty-eight duty cycles from measurements of all locomotives.

similar for the fraction of time spent in Notches 1 through 8. There is variability among locomotive models in the amount of time spent in idle and dynamic braking. However, all three locomotive models spent 38.7 to 39.5 percent of the duty cycle, on average, in these lowest engine power demand settings. Differences in the allocation of low engine power demand between idle and dynamic braking are an artifact of engineer preference and not a distinguishing feature of locomotive model. Therefore, locomotive model is judged not to be an explanatory factor in duty cycle variability and an average duty cycle based on 48 one-way trips was derived. The observed average cycle typically has less time in idle, less time in Notches 1 through 7, and more time in Notch 8 than the EPA cycles.

Emission Rates from Approach 1: Steady-State

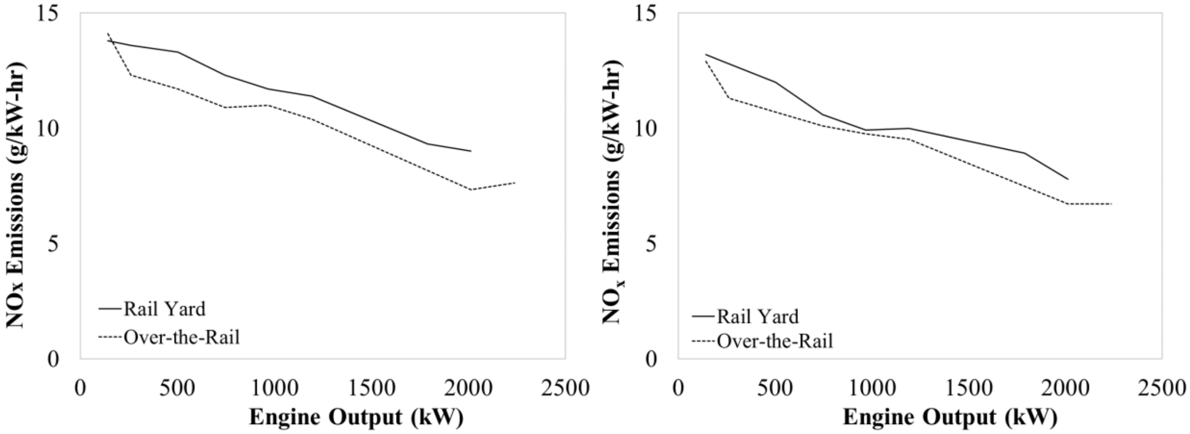
For each locomotive, notch average engine output-based emission rates were estimated for idle, dynamic brake, and the eight notch positions. OTR measured values of RPM, IAT, and MAP for each notch position were similar to those measured in the RY. Therefore, differences, if any, in cycle average emission rates between RY and OTR measurements are not attributed to these engine parameters. Furthermore, OTR measured notch average values of RPM, IAT, and MAP were repeatable, with inter-run CV typically less than 0.05. PME output was similar between RY and OTR measurements for idle through Notch 6. Engine output at Notches 7 and 8 were 220 kW higher for OTR versus RY measurements for all locomotives, with the exception of NC 1755. This is due to the way the engine is programmed for load testing by the engine manufacturer. Notch average engine parameters

Nearly two-thirds of all NO_x emission rates are statistically different and systematically lower during OTR measurements, as shown in Figure 3-2. For the four F59PH locomotives, the OTR emission rates are less than during RY measurements, depicted in Figures 3-2(a) through 3-2(d). For NC F59PHI locomotive NC 1755, shown in Figure 3-2(e), OTR emission rates were higher than during RY measurements for Notches 4 through 6. OTR emission rates for NC 1797 were higher at every notch compared to RY emission rates..

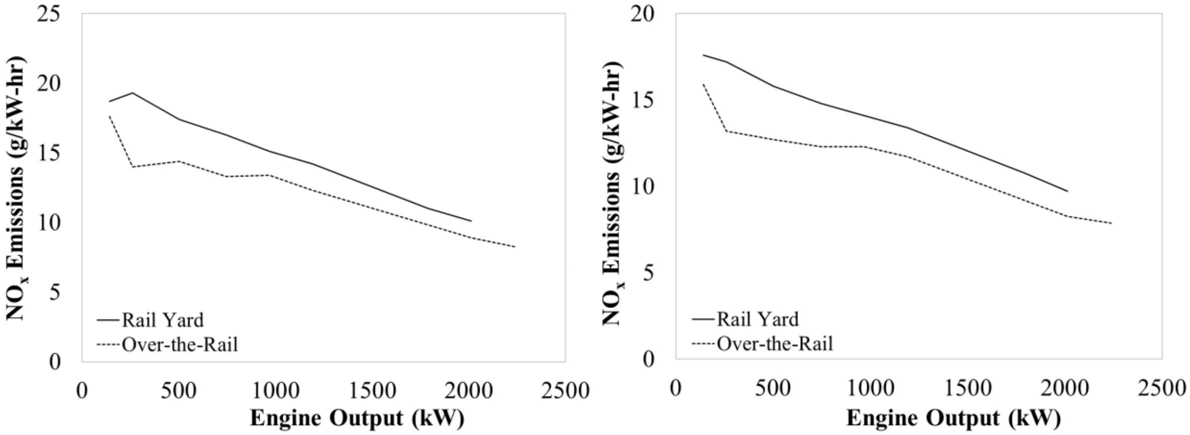
For CO, HC, and PM, approximately one-third of notch average emission rates measured in the RY and OTR are statistically different and systematically higher during OTR measurements, with rates at Notches 7 and 8 being statistically similar for four locomotives. Nearly half of OTR notch average CO_2 emission rates were statistically different and systematically lower than RY rates, especially at Notch 8.

Cycle average emission rates based on both the EPA line-haul and Piedmont duty cycles are given in Table 3-3. All measured emission rates are of the same magnitude as published emission rates of the same locomotive model [EPA, 1998].

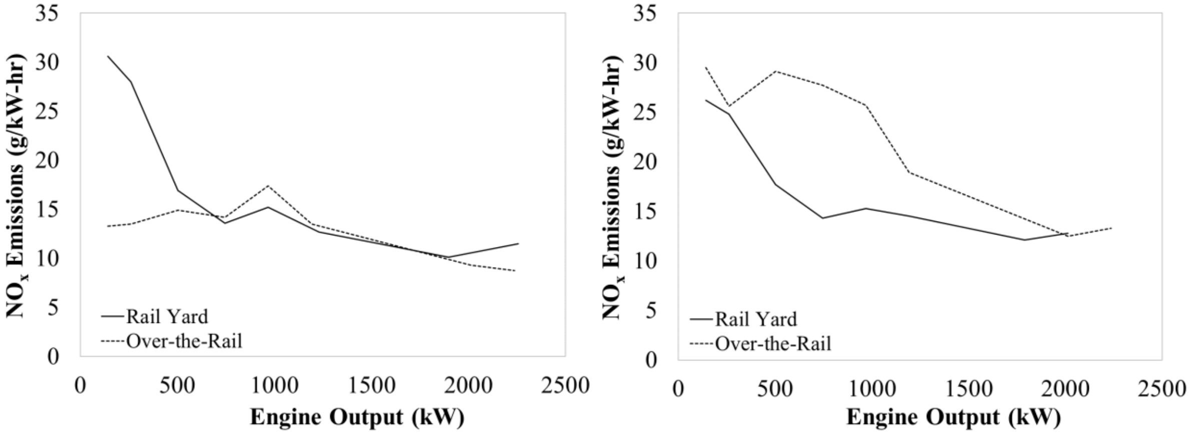
Locomotives NC 1810, 1859, and 1893 each had statistically significant 14 percent lower cycle average NO_x rates based on OTR versus RY notch average rates. For NC 1797 and 1869, differences in cycle average rates were not significantly different. For NC 1755 and 1792, the differences in cycle average rates based on OTR versus RY notch average rates were -19 and 47 percent, respectively. NC 1792 was unusual in that the cycle average rate based on OTR notch rates was higher than based on RY notch rates. Overall, cycle averages for the F59PH and F59PHI locomotives based on OTR notch average rates were a statistically insignificant 3 percent lower than those based on RY average rates, in part



(a) NC 1810 (b) NC 1859



(c) NC 1869 (d) NC 1893



(e) NC 1755 (f) NC 1797

Figure 3-2: Comparison of NO_x Emission Rates versus Engine Output from Rail Yard and Over-the-Rail Measurements for NCDOT Locomotives at Notches 1 through 8

Table 3-3: EPA Line-Haul and Observed Piedmont Duty Cycle Average Emission Rates for Measured Prime Mover Engines Based on Over-the-Rail Measurements Using Approach 1 – Steady-State Emission Factors

(a) EPA Line-Haul Duty Cycle

Model	Locomotive	NO$_x$[a] (g/kW-hr)	HC[b] (g/kW-hr)	CO (g/kW-hr)	Opacity-based PM[c] (g/kW-hr)	CO$_2$ (g/kW-hr)
GP40 EMD 16-645E3	NC 1792 (6 trips)	11.0[d]	1.77[d]	0.5[d]	n/a[e]	817[d]
F59PHI EMD 12-710G3 (Electronically governed)	NC 1755 (1 trip)	11.7[d]	1.26[d]	0.7[d]	0.26[d]	567[d]
	NC 1797 (6 trips)	17.9 (*0.05*)	4.66 (*0.46*)	1.1 (*0.35*)	0.21 (*0.09*)	607 (*0.10*)
F59PH EMD 12-710G3 (Mechanically governed)	NC 1810 (6 trips)	9.1 (*0.05*)	5.05 (*0.34*)	1.9 (*0.28*)	0.37 (*0.09*)	667 (*0.02*)
	NC 1859 (6 trips)	8.1 (*0.05*)	4.88 (*0.77*)	1.0 (*0.34*)	0.56 (*0.14*)	611 (*0.03*)
	NC 1869 (2 trips)	11.0 (*0.00*)	1.68 (*0.19*)	1.7 (*0.06*)	0.67 (*0.05*)	724 (*0.00*)
	NC 1893 (14 trips)	9.7 (*0.09*)	1.66 (*1.27*)	0.7 (*0.64*)	0.32 (*0.42*)	625 (*0.10*)
Average of All		11.2 (*0.05*)	2.99 (*0.61*)	1.1 (*0.33*)	0.40 (*0.16*)	660 (*0.05*)

(b) Piedmont Duty Cycle

Model	Locomotive	NO$_x$[a] (g/kW-hr)	HC[b] (g/kW-hr)	CO (g/kW-hr)	Opacity-based PM[c] (g/kW-hr)	CO$_2$ (g/kW-hr)
GP40 EMD 16-645E3	NC 1792 (6 trips)	10.8[d]	1.28[d]	0.3[d]	n/a[e]	771[d]
F59PHI EMD 12-710G3 (Electronically governed)	NC 1755 (1 trip)	9.8[d]	0.70[d]	0.8[d]	0.22[d]	546[d]
	NC 1797 (6 trips)	15.0 (*0.03*)	2.90 (*0.45*)	1.0 (*0.25*)	0.20 (*0.10*)	592 (*0.08*)
F59PH EMD 12-710G3 (Mechanically governed)	NC 1810 (6 trips)	8.4 (*0.05*)	3.62 (*0.44*)	2.0 (*0.23*)	0.39 (*0.08*)	667 (*0.02*)
	NC 1859 (6 trips)	7.3 (*0.03*)	4.02 (*0.66*)	1.1 (*0.18*)	0.55 (*0.12*)	599 (*0.02*)
	NC 1869 (2 trips)	9.4 (*0.00*)	0.85 (*0.24*)	2.0 (*0.05*)	0.63 (*0.01*)	713 (*0.00*)
	NC 1893 (14 trips)	9.0 (*0.10*)	0.93 (*1.17*)	0.7 (*0.54*)	0.30 (*0.37*)	614 (*0.09*)
Average of All		10.0 (*0.04*)	2.04 (*0.59*)	1.1 (*0.25*)	0.38 (*0.14*)	643 (*0.04*)

Italicized values in parentheses are coefficients of variation (standard deviation divided by the mean) on the mean emission rate.

[a] Results include multiplicative correction factor of 1.053 to approximate total NO$_x$.

[b] Results include multiplicative correction factor of 2.5 to approximate total HC.

[c] Results include multiplicative correction factor of 5 to approximate total PM.

[d] Cycle average emission rates were estimated for only one trip. Therefore, a coefficient of variation could not be calculated.

[e] Malfunction of the PEMS photometer lead to no valid opacity-based PM data during measurement.

because most engines operated at higher power output in Notches 7 and 8 OTR than in the RY.

For HC, only the NC 1797 cycle average emission rates are statistically different, and the cycle average based on OTR notch average rates was 270 percent higher than that based on RY notch average rates. For CO, the cycle average OTR emission rates for NC 1859, 1869, and 1893 are significantly different than those based on RY notch average rates, differing by -56, 30, and 88 percent, respectively. However, these large differences are typically for rates that are relatively low. There were no significant differences in cycle average PM emission rates based on OTR versus RY notch average rates. Overall, the OTR NO_x and HC cycle averages were 1 and 9 percent higher, and the PM and CO cycle averages were 3 and 16 percent lower, across the entire locomotive fleet; however, these differences were not statistically significant. This is due to the wide range of differences in the cycle average emission rates between each locomotive in the fleet.

The comparison of cycle average CO_2 emission rates has similar qualitative trends as for cycle average NO_x emission rates. NC 1810, 1859, and 1893 each had significantly lower, by 4 to 14 percent, cycle average CO_2 emission rates based on OTR versus RY notch average rates. For NC 1797 and 1869, differences were not significant. For NC 1755 and 1792, the cycle average rates differed significantly by -16 and 17 percent, respectively. Overall, based on combined data for all replicates and runs over all locomotives, cycle averages for the

EMD12-710 engine-equipped did not differ for the EPA line haul cycle when using OTR versus RY notch average rates.

Based on notch average OTR rates, cycle average emission rates are estimated for and compared between the average Piedmont duty cycle and the EPA line-haul duty cycle for six locomotives for which multiple runs were made. The Piedmont cycle average NO_x emission rates for these locomotives were statistically significantly lower by an average of 9 percent, with a range of 2 to 16 percent. For NC 1755, the cycle average NO_x emission rate was 16 percent lower, which is comparable to the other locomotives.

The Piedmont cycle average HC emission rates were a statistically significant 32 percent lower, on average, for all locomotives. The cycle average HC emission rates were lower for all six locomotives and were significantly lower for three locomotives. The Piedmont cycle average emission rates were systematically 1 percent higher for CO and 3 percent lower for PM, with differences in CO significant for two locomotives and for PM for only one locomotive. Observed differences in cycle average emission rates are due to differences in the fraction of time spent in each notch, especially Notch 8.

Inter-locomotive cycle average CO_2 emission rates were 0 to 6 percent lower when estimated using the Piedmont versus EPA duty cycle. The mean Piedmont duty cycle average CO_2 rate for the seven locomotives was a statistically significant 2 percent lower than the EPA line-haul duty cycle average CO_2 rate. In practical terms, there is no difference in Piedmont and EPA duty cycle average CO_2 rates.

Emission Rates from Approach 2: Transients

When throttle notch is changed, the time it takes for the engine to reach steady-state differs depending on the number of notches that are skipped. For example, when switching from idle directly to Notch 8, the transition period can be as much as 30 seconds. However, when switching from one notch to an adjacent notch, the transition period is approximately 5 seconds. On average, over 500 notch transitions occur during each one-way Piedmont trip. The interaction between throttle change, engine parameters, and emission rates is observed from second-by-second time traces. Upon a transition to a higher notch, emission rates decrease before increasing to a steady-state value. Conversely, upon transition to a lower notch, emission rates increase in the seconds immediately after the transition before decreasing to a steady-state value. For example, the CO_2 emission rate of an F59PH locomotive increased 25 to 100 percent immediately for a short period after downshifting from a higher notch. The NO_x and PM emission rates nearly doubles and triples, respectively, immediately after downshifting from a higher notch.

Among four locomotives, there were 15 one-way trips for which 95 percent or more of raw data for all pollutants were valid after quality assurance, thereby enabling complete characterization of second-by-second emissions for Approach 2. Trip total emissions are shown in Table 3-4.

Table 3-4: Comparison of Steady-State versus Transient Trip Total Emissions for Measured Prime Mover Engines Based on Observed Piedmont Duty Cycles

(a) Approach 1 – Steady-State

Model	Locomotive	NO_x[a] (kg)	HC[b] (kg)	CO (kg)	Opacity-based PM[c] (kg)	CO_2 (kg)
F59PHI	NC 1755	31.4[d]	2.50[d]	2.22[d]	0.63[d]	554[d]
	NC 1797	53.1 (*0.04*)	10.2 (*0.43*)	3.48 (*0.25*)	0.72 (*0.09*)	690 (*0.12*)
F59PH	NC 1810	26.0 (*0.10*)	11.0 (*0.33*)	6.18 (*0.18*)	1.20 (*0.12*)	747 (*0.10*)
	NC 1869	31.5 (*0.03*)	1.77 (*0.15*)	6.18 (*0.04*)	2.04 (*0.07*)	755 (*0.04*)

(b) Approach 2 – Transients

Model	Locomotive	NO_x[a] (kg)	HC[b] (kg)	CO (kg)	Opacity-based PM[c] (kg)	CO_2 (kg)
F59PHI	NC 1755	35.7[d]	2.73[d]	2.44[d]	0.93[d]	553[d]
	NC 1797	56.0 (*0.05*)	11.0 (*0.43*)	3.39 (*0.25*)	0.66 (*0.10*)	637 (*0.14*)
F59PH	NC 1810	27.3 (*0.05*)	11.1 (*0.26*)	5.94 (*0.15*)	1.65 (*0.05*)	638 (*0.06*)
	NC 1869	31.0 (*0.05*)	1.81 (*0.18*)	5.50 (*0.01*)	2.02 (*0.05*)	706 (*0.06*)

(c) Percent Difference – Approach 1 vs. Approach 2

Model	Locomotive	NO_x	HC	CO	Opacity-based PM	CO_2
F59PHI	NC 1755	- 12.0	- 8.2	- 9.2	- 32.5	0.0
	NC 1797	- 5.2 [< 0.01]	- 7.7 [0.01]	2.8 [0.08]	9.0 [< 0.01]	8.0 [0.30]
F59PH	NC 1810	- 4.9 [0.15]	- 1.3 [0.91]	3.9 [0.32]	- 27.3 [< 0.01]	17.0 [0.02]
	NC 1869	- 2.0 [0.16]	33.0 [0.14]	15.7 [0.01]	0.8 [0.59]	7.0 [0.32]

Italicized values in parentheses are coefficients of variation (standard deviation divided by the mean) on the mean emission rate.

Values in brackets are parentheses are p-values. Differences in Approach 1 and Approach 2 emission rates are statistically significant if $p \leq 0.05$ and are shaded in light grey.

Trip total emission estimates based on the following number of one-way trips: 1 for NC 1755, 6 for NC 1797, 6 for NC 1810, and 2 for NC 1869.

[a] Results include multiplicative correction factor of 1.053 to approximate total NO_x.

[b] Results include multiplicative correction factor of 2.5 to approximate total HC.

[c] Results include multiplicative correction factor of 5 to approximate total PM.

[d] Trip total emissions were estimated for only one trip. Therefore, a coefficient of variation could not be calculated.

Trip total NO_x emissions estimated from Approach 1 are systematically underestimated by a statistically significant 5 percent over all trips compared to Approach 2. Although the percentage differences for three locomotives, NC 1755, 1810, and 1869, were not statistically significant, they were all negative. For NC 1797, not accounting for transients underestimates total NO_x emissions by a statistically significant 5 percent.

Using Approach 1 to estimate trip total HC and CO emissions produces statistically insignificant overestimates of less than 1 percent and 4 percent, respectively, over all trips.

Over all one-way trips, trip total PM was systematically underestimated by a statistically significant 9 percent if transients were neglected. For NC 1755 and 1810, PM emissions are underestimated by 33 and 27 percent, respectively, with the former being statistically significant. For NC 1869, PM emissions are not significantly different. For NC 1797, PM emissions are overestimated by a statistically significant 9 percent. Although inter-locomotive trip total CO_2 emissions were not statistically different for NC 1755, 1797, and 1869, the estimates from Approach 1 were higher than for Approach 2. For NC 1810, the Approach 1 trip total CO_2 emissions were significantly higher by 17 percent. The mean difference in trip total CO_2 emissions over all trips of the four locomotives estimated from Approach 1 versus 2 is significantly overestimated by 10 percent.

Although differences in cycle average rates for Approach 2 versus 1 were modest or insignificant in many cases, differences are likely to be more substantial at higher spatial and temporal resolution, such as near a train station. Therefore, Approaches 1 and 2 were used to evaluate emission totals for 30 seconds prior to the arrival of NC 1797 at a rail station and 30 seconds after station departure for each of the six trips. The PME was at steady-state Notch 8 prior to downshifting to lower notch positions as the train approached the station, and was ratcheted up to Notch 8 when departing the station. Approach 1 overestimated NO_x emissions by 28 percent for station arrival and underestimated NO_x emissions by 17 percent for station departure, with both differences being statistically significant. Therefore, differences in estimated emission rates at specific locations can be much larger than those for cycle averages over an entire trip.

CHAPTER 4

EFFECT OF BIODIESEL FUELS ON REAL-WORLD EMISSIONS OF PASSENGER LOCOMOTIVES

The objectives in this chapter are to determine if, compared to ULSD: (1) biodiesel use significantly affects locomotive prime mover engine (PME) fuel use and emissions; and (2) biodiesel use affects PME performance.

METHODS

A PEMS was used to quantify fuel use and emission rates of three locomotive PMEs during RY static load and OTR measurements during operation on ULSD and multiple soy-based biodiesel blends. The Supporting Information includes additional details regarding locomotive specifications, a description of PEMS precision, accuracy, and calibration, photographs of the PEMS and associated sensors installed on the PME, NO_x and HC bias corrections, and PME volumetric efficiency, fuel use, and emission rate calculation approaches.

Field Study Design

RY measurements were conducted at the North Carolina Department of Transportation (NCDOT) Capital Yard Maintenance Facility in Raleigh, NC. OTR measurements were conducted during passenger rail service between Raleigh and Charlotte, NC.

Locomotives

One F59PHI and two F59PH locomotives were selected. Each locomotive has a 12-cylinder, 140-Liter, 2,240-kW EMD 12-710 diesel PME. For the F59PHI, the PME is electronically governed, while for the F59PHs, the PME is mechanically governed. These engines do not use diesel particulate filter (DPF) or selective catalytic reduction (SCR) control technologies. Technical specifications for the locomotives are included in Appendix A.

Each locomotive has a data recorder that archives a limited amount of information related to engine operation, such as solenoid valve settings from which throttle notch position can be inferred. Notch position, engine speed, and engine output data are provided on a digital display in the locomotive cab, but are not archived by the data recorder. An analyst recorded engine output at each notch from the digital display for every RY replicate and at least one OTR measurement. Also recorded on a digital display is the volume of fuel remaining in the locomotive fuel tank. The digital display updates for every 10 gallons of fuel consumed.

Fuels

F59PHI locomotive NC 1797 and F59PH locomotives NC 1810 and 1859 were fueled with ULSD, B10, B20, and B40 biodiesel blends. In addition, NC 1810 was fueled with B60, B80, and B100 biodiesel blends. Each biodiesel blend is a mixture of ULSD and an ASTM D6751 compliant soy-based biodiesel stock. Each locomotive was operated for at least two weeks prior to RY and OTR measurements after each fuel change to ensure complete purging of the previous fuel. Samples of each fuel type were analyzed for physical and chemical properties.

Data Collection

A full description of RY and OTR measurement methods were discussed in the Data Collection Procedure subsection of Chapter 2.

Portable Emissions Measurement System

The PEMS used is the OEM-2100AX Axion system. A full description of the PEMS and its precision, accuracy, and calibration was discussed previously in the Portable Emissions Measurement System subsection of Chapter 2.

The Axion PEMS uses NDIR for HC detection instead of heated flame ionization detection (FID) used in the FRM. FID requires the use of hydrogen as a “fuel” to burn the HC sample without contributing carbon to the sample. However, transporting a hydrogen gas mixture onboard the locomotive was prohibited by the owner. Therefore, FID was not used in OTR measurements. For the purpose of developing bias corrections that could be applied to the Axion with regard to total NO_x and total HC (THC), RY measurements were made with a SEMTECH-DS PEMS that measures both NO and NO_2, as well as HC with FID, using a heated sample line. The NO_x/NO ratio for each notch position of each locomotive for various fuels were estimated from the SEMTECH-measured exhaust concentrations of NO and NO_2. The FID/NDIR ratio for HC was calculated as a ratio of the THC exhaust concentrations measured using FID and NDIR by the SEMTECH.

Data Quality Assurance

A full description of data time aligning and error screening was discussed previously in the Data Quality Assurance subsection of Chapter 2.

Emission Rate Estimation

For both types of measurements, the methods to estimate fuel use and emission rates are the same. A full description of these methods was discussed previously in the Fuel Use and Emission Rate Estimation subsection of Chapter 2.

The notch average NO_x/NO ratio and FID/NDIR ratio for HC were measured for the same locomotives measured here using a SEMTECH-DS PEMS [Hu *et al.*, 2015]. NO_x emission rates are affected by ambient temperature and humidity [Lindhjem *et al.*, 2003]. The calculated NO_x/NO ratios from the RY SEMTECH measurements, ambient temperature and humidity during measurements, and equations from Lindhjem *et al.* [2003] were used to correct the Axion RY and OTR NO_x emission rates for bias. The ratios of HC measured using the SEMTECH FID to the SEMTECH NDIR were used as the bias corrections of the RY and OTR Axion HC emission rates. PM emission rates are based on a correction factor of 5 to approximate total PM. Prior work found that laser-light scattering PM detection-based emission rates were as much as 80 percent lower compared to the FRM [Durbin *et al.*, 2007]. As such, these PM emission rates are subject to considerable uncertainty when comparing to other studies. Emission rates reported here are used for relative comparisons between RY versus OTR measurements, locomotives, and fuels.

Time-based cycle average emission rates were estimated for each PME and fuel blend, based on the EPA line-haul duty cycle. For each locomotive, Analysis of Variance (ANOVA) analyses were conducted to determine if:

$$H_0: \mu_{ULSD} = \mu_{B10} = \mu_{B20} = \mu_{B40} = \mu_{B60} = \mu_{B80} = \mu_{B100}$$

H_1: *at least one of the means are different*

If the null hypothesis was rejected, then two-sample t-tests, assuming unequal variances, were conducted to identify statistically significant differences. There are a total of twelve RY t-tests for each pollutant, three for each locomotive and three for the combined locomotive fleet. There are a total of fifteen OTR t-tests for each pollutant, three for NC 1797 and NC 1859, six for NC 1810, and three for the combined locomotive fleet.

Locomotive Durability and Performance

To determine the effect of biofuel use on locomotive durability, periodic tests were conducted by NCDOT to assess engine wear. These included engine lubrication oil analyses and PME piston-cylinder head and piston-ring clearance measurements.

As part of 90-day inspections of each locomotive, lubrication oil samples were analyzed for trace metals that may indicate excessive engine wear. For example, iron (Fe) indicates wear of gears, shafts, cylinders, liners, valve train components, other steel components, and rust, including components in the combustion flow path. Some metals, such as lead (Pb), tin (Sn), copper (Cu) and nickel (Ni), are bearing and bushing wear indicators, many of which are not in the combustion flow path [Bently, 2015].

As part of 180-day locomotive inspections, the piston-cylinder head clearance was measured using a lead wire inserted into the cylinder that was compressed when the crankshaft was rotated and the cylinder obtains top dead center. The piston-ring clearance involved measuring the top piston, or compression, ring for its “land clearance,” which is the vertical “play” between the ring and the groove in the piston within which it fits. NCDOT also inspected filters for clogging at regular intervals and replaced them, if necessary.

NCDOT and Amtrak were solicited for comments on whether any noticeable operational impacts were observed while the locomotives were operating on biofuels, such as lower engine output at a particular notch position, fuel gelling, and increased filter replacement.

RESULTS

Results include RY and OTR cycle average time-based emission rates for each PME and an evaluation of engine wear and operational impact of biodiesel. The Appendices contain detailed results for engine activity, NO_x and HC correction factors, notch and cycle average time-based emission rates for each locomotive and fuel, and lubrication oil analysis results.

Approximately 40 and 270 hours of 1 Hz data were collected during RY and OTR measurements, respectively. Typically, less than one percent of total data collected were excluded after quality assurance screening.

Measured characteristics of ULSD and each of six biodiesel blends are given in Table 1. As the percentage of biodiesel stock in the fuel blend increases, fuel density typically increases. The cetane numbers for the biodiesel blends are higher than for ULSD. This is in agreement with the literature [EPA, 2002]. As the percentage of biofuel blend increases, the net heat of combustion and carbon and hydrogen content decreases, while oxygen content increases. Based on fuel characteristics, B100 emits 1.5 percent more CO_2 per MJ than ULSD.

Rail Yard Measurements

Three replicate RY measurements of engine parameters and exhaust concentrations were conducted for each locomotive on each fuel blend, with a few exceptions. Because of scheduling constraints, only one RY measurement was conducted on B10 and B20 and only two RY replicates were conducted on B40 for NC 1810.

At the start and finish of each RY measurement, the volume of fuel in the locomotive fuel tank was recorded. The amount of fuel consumed was also estimated from the PEMS-measured exhaust emissions. On average, the difference between the estimated and displayed fuel use was 3 percent over the 41 RY measurements, with a 95-percent confidence interval of ±3 percent.

Table 4-1: Selected Measured and Inferred Properties of Ultra-Low Sulfur Diesel and Biodiesel Blends

Fuel	Percent Petrodiesel	Percent Biodiesel	Measured					Inferred		
			Density (mg/L)	Net Heat of Combustion (MJ/kg)	Cetane Number	Carbon Content (wt-%)	Hydrogen Content (wt-%)	Oxygen Content (wt-%)	CO_2 Emission Factor	
									(kg/L)	(g/mJ)
ULSD	100	0	0.8412	42.963	47.2	86.74	13.02	0.24	2.68	74.0
B10	90	10	0.8411	42.517	49.0	85.72	13.29	0.99	2.64	73.9
B20	80	20	0.8530	41.231	48.6	83.41	12.87	3.73	2.61	74.2
B40	60	40	0.8576	40.634	53.0	82.36	12.78	4.87	2.59	74.3
B60	40	60	0.8667	39.437	48.8	80.64	12.46	6.90	2.56	75.0
B80	20	80	0.8748	38.653	49.2	78.90	12.01	9.09	2.53	74.8
B100	0	100	0.8805	37.540	49.8	76.96	11.98	11.06	2.48	75.2

ASTM methods used: ASTM D4052 for Density, ASTM D240 for Net Heat of Combustion, ASTM D613 for Cetane Number, ASTM D5291 for Carbon Content and Hydrogen Content

ULSD reported fuel properties are based on the average of three fuel samples.

B10, B60, B80, and B100 reported fuel properties are based on one sample of each fuel.
B20 and B60 reported fuel properties are based on the average of two samples of each fuel.

For all locomotives and fuels, as the PME shifts from idle to Notch 8, engine load, RPM, and MAP increased. IAT remained relatively constant across all notches for each locomotive. The coefficient of variation (CV), which is the ratio of the standard deviation to the mean, representing inter-replicate variations for a given PME and notch position was 0.05 or less for RPM, MAP, and IAT. Thus, the engine parameter measurements were highly repeatable. There was no statistically significant difference in engine parameters for a given PME across fuel blends.

The notch average NO_x/NO ratios ranged from 1.03 to 1.11 for ULSD and from 1.05 to 1.18 for B40. The NO_x bias corrections based on ambient temperature and humidity ranged from 0.65 to 0.87 for ULSD and from 0.70 to 0.87 for B40. The notch average HC correction factors ranged from 2.15 to 7.13 for ULSD and from 1.31 to 5.61 for B40. The NO_x and HC bias correction factors used for each locomotive are included in Appendix G.

Notch average time-based emission rates from RY measurements are given in Appendix H. Notch average time-based NO_x, PM, and CO_2 emission rates for all locomotives and all fuel blends generally increase as the PME load increases. The same trends were observed in a previous study that compared RY PME emissions on ULSD and B20 biodiesel [Fritz, 2004]. The marginal rate of increase in mass per time NO_x emission rate tends to decline with engine load, whereas the marginal rate of increase in mass per time PM emission rate tends to increase with engine load. For each locomotive and fuel blend, inter-replicate CV values for NO_x and PM emission rates were less than 0.10 for Notch 8, indicating high measurement repeatability.

There is substantial inter-replicate variability in notch average time-based HC and CO emission rates for all engines and fuel blends at each notch position. However, concentrations of these pollutants were typically below the PEMS detection limit, which contributes to the high relative variation. HC and CO emission rates for diesel engines tend to be low versus other types of emission sources [Cooper and Alley, 2011].

Table 4-2 depicts differences in biodiesel versus ULSD time-based cycle average fuel use and emission rates for each locomotive, as well as an average across the three locomotives, and biofuel blend.

The null hypotheses were rejected for the NO_x ANOVA analyses of each locomotive. For 4 of 12 combinations of locomotive and fuel blend pairs, statistically significant 19 to 27 percent higher cycle average NO_x emission rates were estimated compared to ULSD. For NC 1810, B40 NO_x emission rates were 26 to 31 percent higher than ULSD, but it was not possible to complete replicates from which statistical significance of this difference could be inferred. The 1 to 9 percent higher NO_x emission rates from NC 1810 on B60, B80, and B100 and from NC 1859 on B10, compared to ULSD, were not statistically significant.

Table 4-2: Comparison of Biodiesel to Ultra-Low Sulfur Diesel Time-Based Cycle Average Emission Rates for Measured Prime Mover Engines Based on Rail Yard Measurements

Locomotive	Fuel	Percent Difference in Fuel Use and Emission Rates versus ULSD					
		Fuel	**NO_x[a]**	**PM[b]**	**CO_2**	**CO**	**HC[c]**
NC 1797 (F59PHI)	B10	+ 12 (0.08)	+ *23* *(<0.01)*	+ 12 (0.18)	+ 11 (0.09)	+ 10 (0.48)	+ *255* *(0.04)*
	B20	- 4 (0.44)	+ *19* *(0.01)*	- *28* *(0.02)*	- 5 (0.34)	0 (0.98)	+ *311* *(<0.01)*
	B40	+ 10 (0.11)	+ *20* *(<0.01)*	+ 3 (0.82)	+ 9 (0.14)	+ 5 (0.86)	+ 27 (0.49)
NC 1810 (F59PH)	B10	+ 4	- 2	+ 3	+ 4	+ 17	- 84
	B20	- 9	- 4	- 61	- 9	- 43	- 89
	B40	- 19	+ 31	+ 26	- 19	- 43	- 90
	B60	+ 5 (0.07)	+ 9 (0.05)	- *35* *(0.01)*	+ 3 (0.24)	- 32 (0.14)	- *94* *(0.01)*
	B80	- 1 (0.85)	+ 2 (0.15)	+ *61* *(0.02)*	- 2 (0.49)	- *38* *(<0.01)*	- *96* *(0.01)*
	B100	+ *11* *(<0.01)*	+ 1 (0.66)	- 3 (0.89)	+ *9* *(<0.01)*	- *64* *(<0.01)*	- *65* *(0.01)*
NC 1859 (F59PH)	B10	- 1 (0.72)	+ 2 (0.40)	- *39* *(0.01)*	0 (0.95)	- *85* *(0.02)*	- *89* *(0.01)*
	B20	- 5 (0.21)	- 5 (0.11)	- *39* *(<0.01)*	- 4 (0.24)	- *80* *(0.02)*	- *86* *(<0.01)*
	B40	- 4 (0.38)	+ *27* *(<0.01)*	- *44* *(<0.01)*	- 4 (0.36)	- *68* *(0.01)*	- *90* *(0.01)*
Average of 3 Locomotives	B10	+ 5 (0.10)	+ 23 (0.22)	- 20 (0.09)	+ 5 (0.09)	- *53* *(0.03)*	- 57 (0.06)
	B20	- *5* *(0.01)*	+ 17 (0.34)	- *41* *(<0.01)*	- *5* *(0.01)*	- *59* *(0.02)*	- 50 (0.10)
	B40	0 (0.98)	+ 31 (0.05)	- 21 (0.15)	- 1 (0.87)	- *50* *(0.04)*	- *79* *(0.01)*

Values in parentheses are p-values. Statistically significant differences ($p < 0.05$) between emission rates are in italics.

[a] NO_x includes NO and NO_2. Only NO was measured. Results include multiplicative correction factors based on NO and NO_2 measurements of the prime mover engines in the rail yard with a SEMTECH-DS PEMS.

[b] HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factors based on FID measurements of the prime mover engines in the rail yard with a SEMTECH-DS PEMS.

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

The null hypotheses were rejected for the PM ANOVA analyses of each locomotive. Cycle average PM emission rates are typically lower for the biodiesel blends than for ULSD, with five such comparisons being statistically significant. In three comparisons, the biodiesel PM emission rate was higher than for ULSD. For NC 1797, there are two comparisons for which apparent increases in PM emission rates are not statistically significant. The PM emission rate for NC 1810 on B80 was statistically significantly higher than for ULSD. There is not a clear trend in the comparisons with respect to biofuel blend ratio. Although there is inter-engine variability, the results indicate that PM emission rates are typically lower for biofuel blends than for ULSD.

The null hypotheses were rejected for the fuel use and CO_2 ANOVA analyses of NC 1797 and NC 1810. Cycle average CO_2 emission rates for the biofuel blends are within 5 percent of that for ULSD for 7 of 12 comparisons, and within 10 percent for 10 of 12 comparisons. There is inter-engine variability in the results. However, there is not a clear trend with respect to blend ratio.

The null hypotheses were rejected for the fuel use and CO_2 ANOVA analyses of NC 1797 and NC 1810. Cycle average CO_2 emission rates for the biofuel blends are within 5 percent of that for ULSD for 7 of 12 comparisons, and within 10 percent for 10 of 12 comparisons. There is inter-engine variability in the results. However, there is not a clear trend with respect to blend ratio.

The null hypotheses were rejected for the CO ANOVA analyses of NC 1859. Cycle average CO emission rates for 8 of 12 comparisons are lower, on average, for biodiesel blends versus ULSD even if some are not significant, and there are no comparisons that are statistically significantly higher. There is clearly inter-engine variability in the results. CO exhaust concentrations tend to be at or below the PEMS detection limit; thus, large relative, but statistically insignificant, differences between emission rates are observed.

The null hypotheses were rejected for the HC ANOVA analyses of each locomotive. Cycle average HC emission rates are lower for each biofuel blend than for ULSD for NC 1810 and NC 1859. However, there is not a clear trend with respect to blend ratio. In contrast, for NC 1797, the cycle average HC emission rates were higher for the biofuel blends than for ULSD, with the comparisons for B10 and B20 being statistically significant. Like with CO, there is not a clear trend with respect to blend ratio, there is inter-engine variability, and HC exhaust concentrations were frequently at or below the gas analyzer detection limit. The results for NC 1797 are counter-intuitive since increased oxygenation of the biofuels would be expected to lead to lower HC emission rates, as was the case for the other two locomotives.

The results for NC 1797 are often contrary to hypothesized expectations, with higher HC and CO emission rates for all biofuel blends, and the CO_2 emission rates were higher on two blends, compared to the other locomotives measured. There is not an obvious confirmed reason for these findings. However, among the three engines tested, NC 1797 differs in that it is electronically governed. Thus, there could be some differences in injection timing compared to the other engines.

To assess the overall average effect of fuels measured on all three locomotives, a comparison was made in the cycle average emission rates based on all replicates on each of B10, B20, and B40 versus ULSD. Although the cycle average NO_x emission rates for each biodiesel blend were higher than for ULSD, the average differences were not statistically significant. The average HC emission rate was significantly lower for B40, but not significantly different for B10 or B20. The average CO emission rates were significantly lower for each biofuel versus ULSD. Although the average PM emission rates were lower for each biofuel blend, the only significant difference was for B20. For CO_2, the average rates were approximately the same or somewhat lower than for ULSD.

For a given locomotive and fuel, the inter-replicate variability in the NO_x and CO_2 cycle average emission rates were typically less than 7 percent, indicating good repeatability. There was greater inter-replicate variability in the HC, CO, and PM cycle average emission rates.

Overall, the results imply little difference in NO_x and CO_2 emission rates, and decreases in HC, CO, and PM emission rates. The measurements for each individual engine and fuel were found to be repeatable, thus differences in measurements for a given fuel among locomotives is attributed to inherent inter-engine variability.

The differences in measured RY emissions between biodiesel and ULSD are in general agreement with differences described in previous literature, based on differing fuel properties. Biodiesel has a higher cetane number, which leads to increased NO_x and decreased PM emissions, which were observed in the B10, B20, and B40 comparisons based on all three locomotives. There is also more oxygen in biodiesel than ULSD, leading to the lower PM, HC, and CO emission rates, which were observed for the locomotive fleet average.

Over-the-Rail Measurements

For each locomotive and one-way run, notch average time-based emission rates were estimated for idle, dynamic brake, and the eight notch positions. OTR-measured RPM, IAT, and MAP values for each notch position were similar to those measured in the RY. Therefore, differences, if any, in cycle average emission rates between RY and OTR measurements are not attributed to these engine parameters. Furthermore, OTR-measured notch average RPM, IAT, and MAP values were repeatable, with inter-run CV typically less than 0.05. PME output was similar between RY and OTR measurements for idle through Notch 6. Engine output at Notches 7 and 8 were 220 kW higher for OTR versus RY measurements for all locomotives, because of the way the engine is programmed for load testing by the engine manufacturer.

Time-based cycle average emission rates were estimated using the EPA line-haul duty cycle, and are included in Appendix I. Table 4-3 depicts differences in biodiesel versus ULSD time-based cycle average fuel use and emission rates for each locomotive and biofuel blend from OTR measurements, as well as an average across the three locomotives.

For NO_x, two individual locomotive and biofuel comparisons, NC 1797 on B40 and NC 1810 on B60, have statistically significant higher values, by 20 to 21 percent, compared to ULSD. The NO_x emission rates on biofuels are typically either the same or higher than for ULSD, with the exception of NC 1859 on B20 and NC 1810 on B40, which had significantly lower time-based cycle average NO_x emission rates of 13 and 30 percent, respectively.

For NC 1810, the PM emission rate was significantly higher for B10, but did not differ significantly for the five other biofuel blends. For NC 1797, the PM emission rate was significantly lower for B20. For NC 1859, the emission rates on biofuels are significantly lower than for ULSD by 41 to 52 percent.

The CO_2 emission rates were not significantly different for 9 of 15 comparisons. For NC 1797, they are significantly higher for B10, but are significantly lower for B20 and B40 for NC 1810 and B20 for NC 1859.

Table 4-3: Comparison of Biodiesel to Ultra-Low Sulfur Diesel Time-Based Cycle Average Emission Rates for Measured Prime Mover Engines Based on Over-the-Rail Measurements

Locomotive	Fuel	Percent Difference in Fuel Use and Emission Rates versus ULSD					
		Fuel	NO$_x$[a]	PM[b]	CO$_2$	CO	HC[c]
NC 1797 (F59PHI)	B10	*+ 10 (0.05)*	- 11 (0.07)	+ 5 (0.44)	*+ 10 (0.05)*	- 21 (0.35)	*- 51 (<0.01)*
	B20	- 5 (0.39)	- 10 (0.18)	*- 22 (0.01)*	- 5 (0.38)	- 41 (0.09)	*- 84 (<0.01)*
	B40	+ 8 (0.08)	*+ 20 (0.02)*	+ 47 (0.05)	+ 7 (0.13)	+ 19 (0.45)	- 16 (0.29)
NC 1810 (F59PH)	B10	- 5 (0.10)	- 10 (0.21)	*+ 60 (<0.01)*	- 5 (0.09)	*- 70 (0.01)*	*+ 75 (<0.01)*
	B20	*- 11 (0.03)*	+ 1 (0.91)	- 5 (0.55)	*- 11 (0.03)*	*- 78 (<0.01)*	*- 42 (<0.01)*
	B40	*- 12 (0.01)*	*- 30 (0.01)*	0 (0.95)	*- 13 (0.01)*	*- 96 (<0.01)*	*- 62 (<0.01)*
	B60	- 8 (0.16)	*+ 21 (0.04)*	+ 56 (0.09)	- 9 (0.07)	*- 61 (<0.01)*	*- 46 (<0.01)*
	B80	- 7 (0.13)	+ 2 (0.86)	- 4 (0.53)	- 8 (0.06)	*- 45 (0.02)*	*- 61 (<0.01)*
	B100	+ 2 (0.50)	+ 6 (0.51)	- 4 (0.62)	0 (0.99)	- 32 (0.08)	*- 48 (<0.01)*
NC 1859 (F59PH)	B10	+ 4 (0.18)	- 11 (0.30)	*- 48 (<0.01)*	- 13 (0.07)	- 20 (0.54)	*- 64 (<0.01)*
	B20	+ 1 (0.71)	*- 13 (0.01)*	*- 41 (<0.01)*	*- 15 (0.02)*	- 30 (0.38)	*- 71 (<0.01)*
	B40	+ 2 (0.56)	+ 8 (0.26)	*- 52 (<0.01)*	- 12 (0.08)	- 56 (0.11)	*- 65 (<0.01)*
Average of 3 Locomotives	B10	+ 3 (0.28)	- 10 (0.38)	- 3 (0.85)	- 7 (0.06)	*- 37 (0.02)*	+ 7 (0.82)
	B20	- 4 (0.11)	- 18 (0.08)	*- 23 (0.05)*	*- 11 (<0.01)*	*- 42 (0.01)*	*- 62 (<0.01)*
	B40	- 1 (0.71)	+ 8 (0.64)	- 17 (0.11)	*- 11 (0.03)*	*- 43 (0.02)*	*- 55 (<0.01)*

Values in parentheses are p-values. Statistically significant differences ($p < 0.05$) between emission rates are in italics.

[a] NO$_x$ includes NO and NO$_2$. Only NO was measured. Results include multiplicative correction factors based on NO and NO$_2$ measurements of the prime mover engines in the rail yard with a SEMTECH-DS PEMS.

[b] HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factors based on FID measurements of the prime mover engines in the rail yard with a SEMTECH-DS PEMS.

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

For CO, there are five statistically significant comparisons, all for NC 1810, ranging from 45 to 96 percent lower than for ULSD. Eleven of 15 comparisons are lower on average, even if some are not significant, and there are no significantly higher comparisons. For HC, ten of the statistically significant comparisons have lower emission rates on biofuels, while NC 1810 on B10 had a statistically significant higher rate compared to ULSD. Thus, HC emission rates tend to be similar to or lower than for ULSD.

For a given locomotive and fuel, higher inter-run variability was observed in the OTR cycle average emission rates compared to the RY inter-replicate variability. The variability in NO_x, CO_2, and PM emission rates were typically less than 15 percent.

The B40 biodiesel blend produced higher NO_x emission rates across the three locomotives, compared to ULSD, while B20 produced an 18 percent reduction in the NO_x emission rate. However, these differences were not statistically significant. All three biodiesel blends produced lower PM, CO_2, CO, and HC emission rates across the three locomotives, compared to ULSD, with the exception of HC with B10 that had a 7 percent higher emission rate that was not statistically significant. The lower PM emission rates were not statistically significant for B10 and B40. However, the 23 percent lower PM emission rate for B20 was statistically significant. Both the B20 and B40 CO_2 emission rate was statistically lower than for ULSD with a reduction of 11 percent. The lower CO emission rates for all biodiesel blends versus ULSD were statistically significant. The lower HC emission rates for B20 and B40 were statistically significant.

Overall, for the locomotive fleet, B20 is the best biodiesel blend option versus ULSD during OTR measurements. Statistically significantly lower PM, CO_2, CO, and HC time-based cycle average emission rates were observed for B20 compared to ULSD. There were no statistically significant differences in fuel use and NO_x emission rates.

The difference in measured OTR emissions between biodiesel and ULSD were in general agreement with previous literature describing the effect on emissions of changing fuel properties. Biodiesel has a higher cetane number, which leads to increased NO_x and decreased PM emissions, which were observed in the B10 and B40 comparisons over the average of the three locomotives. There is also more oxygen in biodiesel than ULSD, leading to the lower PM, HC, and CO emission rates, which were observed for the locomotive fleet average.

Comparisons were made to determine if the direction of relative difference (i.e. higher or lower) in cycle average emission rates for a biodiesel blend versus ULSD is consistent between RY and OTR measurements. A total of 72 comparisons were analyzed, inclusive of each pollutant, biofuel blend, and locomotive, to determine if there were any sign changes in the biofuel versus ULSD comparison between RY and OTR measurements. The focus is just on cases for which the opposite signs were each statistically significant. Only two such cases were found, both for HC with NC 1797. The RY B10 HC emission rate for NC 1797 was significantly 255 percent higher than the ULSD HC rate, but significantly 51 percent lower for OTR. The B20 HC emission rate for NC 1797 was significantly 311 percent higher than the ULSD rate in the RY, but significantly 84 percent lower for OTR. In both of these cases, the OTR results are more consistent with the expectation of lower HC emission rates. There were 14 additional comparisons where there was a sign change between RY and OTR measurements; however, in each comparison, one or more of the differences in biodiesel versus ULSD emission rates were not statistically significant. Therefore, the comparisons of biodiesel versus biodiesel for the three locomotives are generally consistent when comparing RY and OTR measurements.

Locomotive Durability and Performance

From July 2010 through May 2014, 34 analyses of trace metals in lubricating oil were obtained for the three locomotives, including the time in which each locomotive was operating on biodiesel. All analyses came back as “No Action Required” during operation on all biodiesel blends. More information on the lubricating oil analyses results are included in Appendix J.

NCDOT mechanics reported no changes in any clearance measurements. There were no reports by NCDOT mechanics or by Amtrak engineers of any unanticipated adverse operational effect of biodiesel. Filters were replaced more frequently due to the solvent action of biodiesel. To prevent possible B100 gelling in NC 1810 during cold temperatures, the PME was not turned off, but rather idled, between trips. However, for use of B100 in NC 1859, the fuel filter required more frequent replacement.

CHAPTER 5

HIGHWAY VEHICLE EMISSIONS AVOIDED BY DIESEL PASSENGER RAIL SERVICE BASED ON REAL-WORLD DATA

The objectives in this chapter are to determine if: (1) rail travel has lower per passenger-kilometer emission factors compared to travel with a highway vehicle; (2) rail travel emission factors are sensitive to where on the route a rider boards the train; (3) rail travel delays significantly increase per passenger-kilometer emission factors; and (4) highway travel delays significantly increase per passenger-kilometer emission factors.

METHODS

Per passenger-kilometer locomotive emission factors are quantified based on PEMS-measured exhaust concentrations, engine activity data, and locomotive duty cycles observed during passenger rail service. The EPA's Motor Vehicle Emissions Simulator (MOVES) is used to estimate fleet average emission factors from light-duty gasoline vehicles (LDGVs), which include passenger cars and trucks. Emission factors are compared to determine how much emissions would be reduced based on a shift from transport by passenger cars (PCs) or passenger trucks (PTs) to passenger rail.

Field Study Design

Six locomotives were instrumented and exhaust emission concentrations measured during Amtrak Piedmont passenger rail service between Raleigh and Charlotte, NC. The locomotives operated on ultra-low sulfur diesel (ULSD) for all measurements.

Locomotives

One of the fastest growing routes for Amtrak, in terms of relative change in ridership, is the Piedmont in North Carolina. Through a joint effort between the North Carolina Department of Transportation (NCDOT) and Amtrak, daily passenger rail service is provided between Raleigh and Charlotte, and seven cities in between. Currently, two trains operate in both directions each day. Typically, each train is comprised of one locomotive, one baggage/lounge car, and two passenger cars. Additional passenger cars are added, if warranted by ridership figures, such as during the weekends. The capacity of each passenger car varies between 56 and 66 seats.

The NCDOT owns two Electro-Motive Diesel (EMD) F59PHI model and four EMD F59PH model locomotives and associated rolling stock. Each locomotive has a 12-cylinder, 140-Liter, 2,237-kW EMD 12-710 prime mover engine (PME) used to provide direct current electric power for propulsion. A smaller 671-kW head-end power (HEP) engine is used to generate alternating current power for "hotel services" in the passenger cars, such as lighting, heating, and cooling. All locomotives were remanufactured within the last four years to meet the Tier 0+ and Tier 1+ emission standards for the F59PH and F59PHI locomotives, respectively. New locomotives manufactured in 2015 must meet Tier 4 emission standards, which have NO_x emission rates 82 to 86 percent lower than the Tier 0+ and Tier 1+ standards, respectively. Tier 4 PM emission rate standards are 86 percent lower than the Tier 0+ and Tier 1+ standards [CFR, 2013b].

Portable Emissions Measurement System

The PEMS units used here are the OEM-2100 Montana and OEM-2100AX Axion systems. A full description of the PEMS and its precision, accuracy, and calibration was discussed previously in the Portable Emissions Measurement System subsection of Chapter 2. A full description of the NO_x and HC correction factors used to adjust for biases associated with the Axion measurement methods was discussed previously in the Portable Emissions Measurement System and Emission Rate Estimation subsections of Chapter 4.

Data Collection Procedure

For both RY and OTR measurements, the locomotives were instrumented and exhaust concentration and engine activity data were measured continuously. RY measurements were conducted since HEP operation remains constant regardless of locomotive operation. In addition, RY measurement of the HEP allows for the need of only one PEMS during OTR measurements. The PME of each locomotive was measured OTR since it better reflects real-world locomotive operation than RY measurements. RY HEP measurements were conducted since HEP operation typically remains constant regardless of locomotive operation.

For OTR PME measurements, the locomotives were operated normally during revenue-generating Piedmont passenger service by Amtrak engineers. The twice-daily Piedmont rail service covers a distance of 278 kilometers, with a scheduled duration of 3 hours and 10 minutes. Typically, each train is comprised of one locomotive, one baggage/lounge car, and two passenger cars. Sixty-eight one-way OTR measurements were conducted on six locomotives.

For RY HEP measurements, the HEP engine was run at multiple electrical loads for a period of five to ten minutes for each load. Electrical loads were created by coupling passenger cars to the locomotive and operating the lighting and air condition/heating systems in each car. The electrical load conditions correspond to the number of passenger cars, from zero to four, being powered by the HEP. Because of variability in availability of passenger cars in the rail yard on a given measurement day, there was some measurement-to-measurement variability in the number of cars used. During the measurements, voltages and currents for each load were measured to estimate the electrical loads.

Data Quality Assurance

A full description of data time aligning and error screening was discussed previously in the Data Quality Assurance subsection of Chapter 2.

Locomotive Emission Rate Estimation

The base case PME and HEP emission factors are based on on-time travel, which is defined as within 10 minutes of the scheduled travel time between Raleigh and Charlotte.

Prime Mover Engine

A full description of the methods used to estimate PME emission rates was discussed previously in the Fuel Use and Emission Rate Estimation subsection of Chapter 2.

The Piedmont route was divided into eight segments between consecutive rail stations, as shown in Table 1. The activity data collected for each trip were stratified to create individual duty cycles for travel over each segment. Piedmont ridership data were obtained from Amtrak for fiscal years 2007 through 2013.

For each segment on each trip, the time spent in each notch position was multiplied by the average time-based PME emission factors for each notch and summed over all notches to derive the total PME emissions released over a segment. Total PME emissions released over a route are the summation of the total emissions released over all of the segments between nonadjacent stations at the route origin and destination.

Table 5-1: Distance, Scheduled Travel Time, and Average Ridership by Segment for the Piedmont Route from Raleigh to Charlotte, NC

Segment	Station Pair	Distance (km)	Scheduled Travel Time (s)	Average One-Way Ridership (passengers)
A	Raleigh ↔ Cary	13.4	900	39
B	Cary ↔ Durham	29.0	1200	58
C	Durham ↔ Burlington	53.4	2160	80
D	Burlington ↔ Greensboro	34.3	1500	83
E	Greensboro ↔ High Point	24.8	960	80
F	High Point ↔ Salisbury	55.3	2040	75
G	Salisbury ↔ Kannapolis	25.3	960	70
H	Kannapolis ↔ Charlotte	42.8	1860	67

Segments are not directional-specific. For example, Segment A consists of travel from Raleigh to Cary and from Cary to Raleigh.

Average one-way ridership includes all passengers on the train during the segment.

Mass per passenger emission factors over a segment were derived by dividing the total emissions released over the segment by the average ridership over the segment. Mass per passenger-kilometer emission factors over a segment were calculated by dividing the mass per passenger emission factors over a segment by the distance of the segment. Mass per passenger-kilometer emission factors between a station pair are the summation of the mass per passenger emission factors over all segments between the station pair, divided by the distance between the station pair.

Based on the CO_2 emission factors for the locomotive chassis, involving both the PME and HEP engine, energy intensity was estimated using a published diesel net heating value of

35,873 kJ/L and a conversion factor of 2,690 grams of direct CO_2 emissions per liter of diesel [Davis et al., 2015].

To determine if rail travel delays significantly increase Raleigh to Charlotte per passenger-kilometer emission factors, locomotive emissions analyses were conducted for three trip duration scenarios: (1) 10-19 minutes; (2) 20-29 minutes; and (3) more than 30 minutes. Trip duration was estimated from activity data recorder data for each one-way trip, and characterized as on-time or in one of the delayed travel scenarios. In addition, for each trip, the duration and duty cycle for each rail segment was estimated from locomotive activity data.

Head-End Power (HEP) Engine

All six locomotives have the same make and model HEP engine. Thus, the emission factors from the three measured HEP engines represent the emission factors for the entire fleet.

Mass per gallon emission factors were estimated based on exhaust gas and fuel composition. From the mole fractions of CO_2, CO, and HC, the fraction of carbon in the fuel emitted as CO_2 is estimated. Therefore, the conversion of carbon in the fuel to CO_2 per gallon of fuel consumed can be estimated, since the weight percent of carbon in the fuel is known. Exhaust molar ratios of NO, CO, and HC to CO_2 and the ratio of PM mg/m^3 concentration to CO_2 were used to estimate the amount of each pollutant emitted per gallon of fuel consumed.

Often, fuel specific engine output (FSEO) is reported or used in regulatory work to describe fuel consumption. EPA reports a typical FSEO of 4.1 kWhr/L [EPA, 2009]. Therefore, HEP fuel flow is estimated to be 38 g/s at full load, based on this FSEO and assuming a fuel density of 0.8412 mg/L.

Total HEP emissions released between stations were estimated by multiplying mass per gallon emission factors measured during rail yard testing, the estimated fuel flow rate, and travel time. HEP mass per passenger-kilometer emission factors were estimated by multiplying mass per time emission factors by total travel time, and dividing by trip distance and ridership.

To compare differences in HEP emission factors due to delayed travel, sensitivity analyses were conducted with trips that had trip durations longer than the scheduled travel time. The same three delay scenarios used for the PME emission rate sensitivity analyses were used for the HEP sensitivity analyses.

Light-Duty Gasoline Vehicle (LDGV) Emissions

The EPA's Motor Vehicle Emissions Simulator (MOVES) was used to estimate mass per passenger-kilometer emission factors for LDGVs. The user specifies vehicle types, geographical areas, pollutants, vehicle operating characteristics (e.g. vehicle speed), and road types (e.g. rural/urban, restricted/unrestricted access) [EPA, 2010b].

Input data related to the distributions of vehicle type and age, fuel type, emissions inspection compliance, and meteorology were obtained from the Division of Air Quality at the North Carolina Department of Environment and Natural Resources. Data from Wake County, NC, where Raleigh is located, were assumed to be representative of the state average for vehicle type, vehicle age, and fuel type. The LDGV population was 58 percent passenger cars (PC) and 42 percent passenger trucks (PT). Sensitivity analyses were conducted to provide insight regarding how much the LDGV results vary when comparing an average PC and PT.

To obtain speed and road grade profiles between terminus rail stations, a passenger vehicle was instrumented with an On-Board Diagnostic (OBD) electronic control unit (ECU) data recorder and a handheld global positioning system (GPS) receiver with barometric altimeter, and driven between Raleigh and Charlotte rail stations. The driver observed speed limits during arterial driving and maintained the speed of the vehicles traveling in the middle lane of a six-lane highway and the left lane of a four-lane highway. Latitude, longitude, and elevation were used to estimate road grade using a methodological approach reported elsewhere [Sandhu and Frey, 2013]. The speed profile from the ECU data recorder and the estimated road grade profile were used as inputs into MOVES.

The instrumented passenger vehicle was driven on three segments, as summarized in Table 5-2. Vehicle travel and associated emissions were estimated for five station pairs. Travel between the Raleigh and Charlotte station pair is estimated using Segment Road-A. For the other four station pairs, a combination of two additional road segments is needed. For

Table 5-2: Road Segments Used in the Motor Vehicle Emissions Simulator (MOVES) Software to Estimate Light-Duty Gasoline Vehicle Emissions

Segment	Station Pair	Travel Distance (km)	Travel Time (sec)
Road-A	Raleigh and Charlotte	264.4	8,713
Road-B	Cary and Durham	31.7	1,377
Road-C	Durham and Greensboro	83.2	3,152

Segments are not directional-specific. For example, Segment Road-A consists of travel from Raleigh to Charlotte and from Charlotte to Raleigh.

example, parts of Segments Road-A and Road-C are used to obtain speed and road grade profiles for travel between the Durham and Charlotte station pair. Segment Road-C is used for travel from the Durham train station to the interstate, where it overlaps with Segment Road-A. Segment Road-A is used from the interstate to Charlotte train station. Likewise, data were spliced to represent vehicle travel between Greensboro and Charlotte, Cary and Charlotte, and Raleigh and Greensboro.

Many passengers of the Piedmont are commuting for work. Therefore, for this analysis, it is assumed that the LDGV is a single occupancy vehicle (SOV), and that the driver is traveling between rail stations by the shortest roadway route. The route tested was determined by readily available online tools, such as Google Maps, and evaluated based on judgment as to the route that was most likely to be selected by knowledgeable drivers. No locomotive idling time at the terminus rail stations is considered because an LDGV driver typically would not idle at trip origin and destination.

RESULTS

Mass per passenger-kilometer emission factors were estimated for travel between the terminus rail stations of Raleigh and Charlotte for both the NCDOT locomotive fleet and an average LDGV, as well as for PT versus PC. In addition, rail travel emission factors were estimated for the five station pairs with the highest ridership, which includes the Raleigh and Charlotte station pair, as shown in Table 5-3.

Differences in the locomotive and LDGV emission factors are discussed. Analyses were conducted to determine the sensitivity of locomotive and LDGV emission factors to travel delays, as well as the sensitivity of avoided emissions to locomotive certification standard.

Table 5-3: Piedmont Rail Station Pairs with Highest Ridership for Fiscal Year 2013

Station Pair	Average One-Way Ridership (passengers)	Segments	One-Way Distance (km)
Raleigh, NC ↔ Charlotte, NC	18.6	A through H	278.3
Greensboro, NC ↔ Charlotte, NC	12.9	E through H	148.2
Cary, NC ↔ Charlotte, NC	12.5	B through H	264.9
Durham, NC ↔ Charlotte, NC	11.5	C through H	235.9
Raleigh, NC ↔ Greensboro, NC	9.1	A through D	130.0

Station pairs are not directional-specific.

Average one-way ridership includes only passengers who boarded and disembarked at the indicated stations.

Duty Cycles

The observed duty cycles from 68 one-way trips between Raleigh and Charlotte are summarized in Table 5-4. Duty cycles are statistically generally similar for travel in both directions. Planned slow orders, which affect all rail traffic passing at particular locations for an extended period of time, were prevalent during most OTR measurements because of on-going rail improvement projects. Often, dispatchers instruct passenger trains to change tracks to bypass slow-moving freight traffic. To safely traverse rail switches, locomotives must reduce speed. While rare, locomotives may have to stop because of malfunctioning rail crossing safety equipment or mechanical breakdowns, which increase travel time and percentage of time spent in idle. Engineers attempted to minimize overall trip delays by

Table 5-4: Comparison of Mean Measured Duty Cycles during One-Way Piedmont Trips based on Various Differences in Travel Duration[a]

Notch	Difference in Travel Time from Scheduled Travel Duration			
	< 10 min	10-19 min	20-29 min	> 30 min
Idle	26.4 (*0.27*)	33.1 (*0.21*)	41.3 (*0.16*)	37.3 (*0.12*)
Dynamic Brake	11.5 (*0.40*)	11.5 (*0.49*)	7.4 (*0.82*)	9.7 (*0.50*)
1	3.9 (*0.71*)	2.4 (*0.50*)	2.5 (*0.76*)	2.6 (*0.11*)
2	5.4 (*0.57*)	4.5 (*0.78*)	2.6 (*0.34*)	4.2 (*0.76*)
3	4.2 (*0.60*)	2.9 (*0.34*)	3.2 (*0.27*)	5.4 (*0.60*)
4	4.3 (*0.60*)	3.1 (*0.39*)	2.7 (*0.42*)	4.8 (*0.38*)
5	2.4 (*0.47*)	2.0 (*0.58*)	2.2 (*0.31*)	2.9 (*0.62*)
6	2.8 (*1.01*)	2.0 (*0.60*)	1.8 (*0.40*)	4.0 (*0.90*)
7	0.8 (*0.91*)	0.9 (*1.00*)	0.6 (*0.55*)	5.0 (*1.36*)
8	38.3 (*0.20*)	37.8 (*0.15*)	35.6 (*0.12*)	24.0 (*0.16*)
Number of Trips	45	13	8	2
Mean Travel Time (s)[b]	11,480 (*0.03*)	12,261 (*0.01*)	12,852 (*0.01*)	14,449 (*0.11*)

[a] Mean percentage of duty cycle in each notch position with the coefficient of variation (standard deviation divided by the mean) in italics.

[b] Mean travel time with the coefficient of variation (standard deviation divided by the mean) in italics.

altering the locomotive duty cycle to allow for higher speeds in sections where they could so safely. Thus, not all trips encumbered by slow orders were delayed.

A majority of the trips were on-time, with travel times of less than 200 minutes. For trips delayed by less than 30 minutes, the coefficients of variation (CV) of the mean travel time amongst the trips in each of the three delay scenarios are less than 3 percent of the mean travel time. Therefore, the trips included in each of the three delay scenarios are of consistent trip duration.

As mean travel time increased from on-time to the highest category of delay, the percentage of time spent in Notch 8 decreased from 38 to 24 percent. A higher percentage of time was spent in idle for the three travel delay scenarios, ranging from 33 to 41 percent, compared to the on-time cycles at 26 percent. There is less relative variability in the time spent in Idle and Notch 8 versus any other notch. On average, for each travel duration scenario, Idle and Notch 8 comprise 61 to 77 percent of the total travel time. There is more variability in the percentage of time spent in Dynamic Brake through Notch 7 due to the preference of each individual engineer to use these intermediary notch positions.

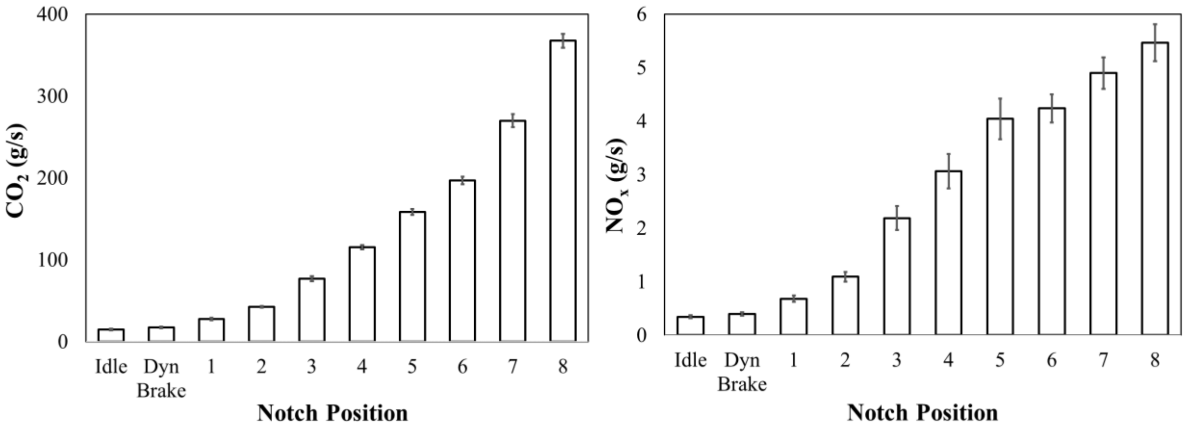
Passenger Load Factor

Each Piedmont train is comprised of one locomotive, one baggage/lounge car, and two passenger cars, with additional passenger cars added if warranted by ridership figures. The capacity of each passenger car varies between 56 and 66 seats, not 84 seats as characterized in the NCRRP report. The average load factor for the Piedmont in Fiscal Year 2013, based on Amtrak ridership data was approximately 77 percent, or 35 percentage points higher than the average load factor used in NCRRP calculations [NCRRP, 2015]. The results in subsequent sections uses actual Piedmont ridership, rather than a previously-published average load factor.

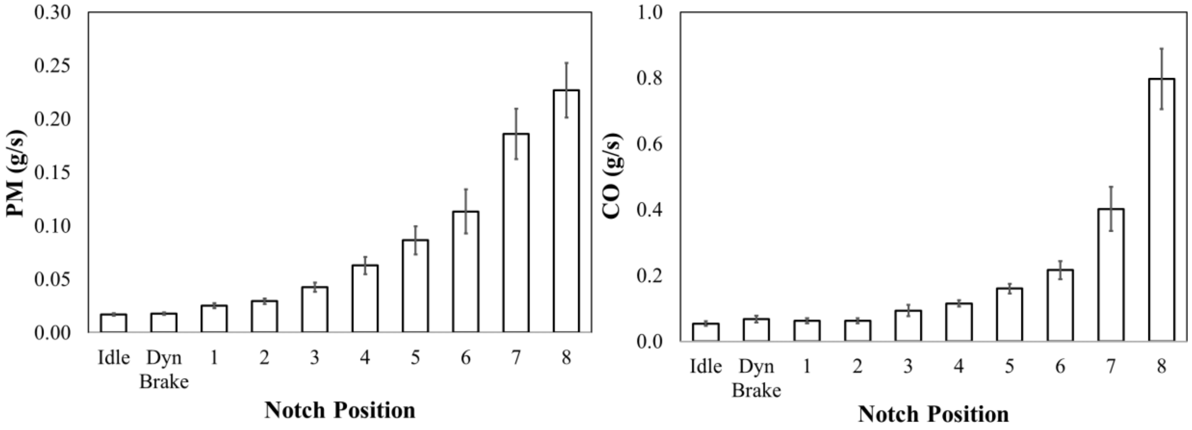
Locomotive Emission Factors

For each locomotive, notch average emission factors were estimated for idle, dynamic brake, and the eight notch positions of the PME. The measured notch average values of RPM, IAT, and MAP used to estimate emission factors were repeatable, with inter-run variability of typically less than 5 percent. On average, as the load on the PME increases, the notch average emission factors of all pollutants increase. Figure 5-1 shows fleet average time-based emission rates at each notch position. The lowest emission factors are typically observed at idle and the highest emission factors are at Notch 8. There is not a monotonic trend in the HC emission factors with increasing engine load because most HC concentrations were at or below the PEMS detection limit.

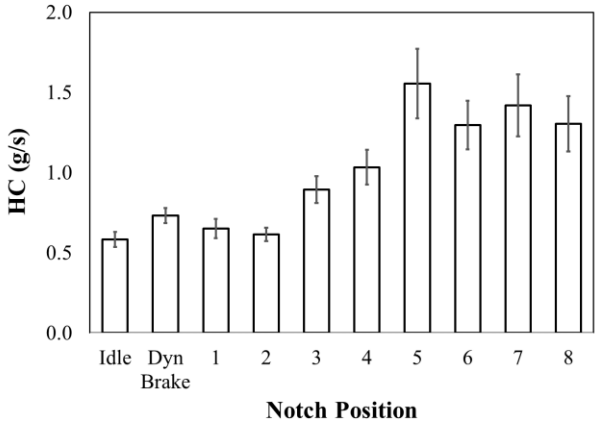
Mass per passenger-kilometer emission factors for on-time travel between Raleigh and Charlotte were estimated for the six NCDOT locomotives and are shown in Table 5-5. For each locomotive, per passenger-kilometer emission factors were estimated for every rail segment of 45 on-time duty cycles using the mean emission factors measured for each individual locomotive, for a total of 270 estimated duty cycle average emission factors.



(a) Carbon Dioxide (b) Nitrogen Oxides



(c) Particulate Matter (d) Carbon Monoxide



(e) Hydrocarbons

Figure 5-1: Fleet Average Emission Factors of the Prime Mover Engine at Each Notch Position from Thirty-Six Over-the-Rail Measurements Using Six Locomotives. Error Bars Represent 95-Percent Confidence Intervals on the Mean Emission Factor

Table 5-5: Locomotive Per Passenger-Kilometer Emission Factors for On-Time One-Way Piedmont Trips between Raleigh and Charlotte, NC

(a) Prime Mover Engine

Locomotive	Emission Factor (g/pkm)[a]				
	CO_2	NO_x[b]	PM[c]	CO	HC[d]
NC 1810	120 (*0.17*)	1.55 (*0.02*)	0.07 (*0.18*)	0.38 (*0.19*)	1.01 (*0.09*)
NC 1859	109 (*0.17*)	1.37 (*0.14*)	0.10 (*0.16*)	0.20 (*0.17*)	1.20 (*0.10*)
NC 1869	129 (*0.16*)	1.74 (*0.13*)	0.12 (*0.15*)	0.35 (*0.20*)	0.24 (*0.17*)
NC 1893	99.0 (*0.16*)	1.62 (*0.14*)	0.05 (*0.15*)	0.13 (*0.18*)	0.30 (*0.10*)
F59PH Average	114 (*0.16*)	1.57 (*0.11*)	0.09 (*0.16*)	0.27 (*0.19*)	0.69 (*0.12*)
NC 1755	99.1 (*0.16*)	1.62 (*0.14*)	0.05 (*0.15*)	0.13 (*0.19*)	0.30 (*0.11*)
NC 1797	108 (*0.16*)	2.85 (*0.13*)	0.04 (*0.17*)	0.18 (*0.15*)	0.87 (*0.09*)
F59PHI Average	104 (*0.16*)	2.24 (*0.14*)	0.05 (*0.16*)	0.16 (*0.17*)	0.59 (*0.10*)
Fleet Average	111 (*0.16*)	1.79 (*0.12*)	0.07 (*0.16*)	0.23 (*0.18*)	0.65 (*0.11*)

(b) Head-End Power (HEP) Engine

Locomotive	Emission Factor (g/pkm)[e]				
	CO_2	NO_x[b]	PM[c]	CO	HC[d]
NC 1810	7 (*0.11*)	0.07 (*0.11*)	<0.01 (*0.11*)	0.03 (*0.11*)	0.02 (*0.11*)
NC 1859	7 (*0.11*)	0.07 (*0.11*)	<0.01 (*0.11*)	0.03 (*0.11*)	0.01 (*0.11*)
NC 1869	7 (*0.11*)	0.05 (*0.11*)	<0.01 (*0.11*)	0.04 (*0.11*)	0.01 (*0.11*)
Average	7 (*0.10*)	0.06 (*0.17*)	<0.01 (*0.14*)	0.03 (*0.14*)	0.01 (*0.23*)

[a] Mean emission factor with the coefficient of variation (standard deviation divided by the mean) in italics.

[b] NO_x includes NO and NO_2. Only NO was measured. Results include multiplicative correction factors based on NO and NO_2 rail yard prime mover engine measurements with a SEMTECH-DS PEMS.

[c] PM emission factors include multiplicative correction factor of 5 to approximate total PM.

[d] HC is measured using NDIR, which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factors based on FID rail yard prime mover engine measurements with a SEMTECH-DS PEMS.

Mean emission factors and coefficients of variation estimated for the PME of each locomotive are shown in Table 5-5(a).

Emission factors for the HEP engines are shown in Table 5-5(b). The HEP fuel use and emission factors used to estimate the per passenger-kilometer emission factors are based on the electrical load corresponding to three or four passenger cars for each locomotive. The average electrical load was approximately 9 percent of full load. Therefore, it is estimated that the HEP fuel flow rate is approximately 3.9 g/s.

The NCDOT locomotive fleet average energy intensity estimated is reasonable based on comparisons to published values. The fleet average energy intensity of 1,696 kJ/pkm is 22 percent higher than the published Amtrak intercity rail energy intensity of 1,389 kJ/pkm [Davis et al., 2015]. An energy intensity of 1,067 kJ/pkm was cited by the U.S. Department of Transportation's Bureau of Transportation Statistics (BTS) [2016] for the Amtrak fleet in 2011. However, not all Amtrak locomotives are diesel-electric powered, like the NCDOT fleet, and the energy intensity accounts for both diesel-electric and electric locomotives. The electric locomotives, which are used on Amtrak's Northeast Corridor, have lower energy intensities than diesel-electric powered locomotives [NCRRP, 2015]. The breakdown of Amtrak revenue passenger-kilometers between electric and diesel locomotives was not published. However, the Northeast Corridor has Amtrak's second largest ridership [Amtrak, 2012].

The energy intensity for a Piedmont train estimated by the MMPASSIM and reported in the NCRRP report is 1,063 kJ/pkm, similar to the energy intensity from BTS and 37 percent lower than the energy intensity estimated based on measured CO_2 emission factors. The NCRRP report [2015] states that train weight, length, rolling resistance, and seating capacity are needed to calculate energy intensity in MMPASSIM. The number of passenger cars and seating capacity of each car was incorrectly assumed in the NCRRP report for the Piedmont. This will affect the overall weight and length of the train consist and, therefore, the energy intensity estimation. The NCDOT fleet average CO_2 emission factor was approximately 88 percent higher than the 904 kJ/pkm emission factor published for Metrolink locomotives with larger remanufactured engines that meet more stringent emission standards than the NCDOT locomotives [Barth *et al*., 1996]. Metrolink commuter service also had average ridership of 275 passengers per train, approximately 2.2 times greater ridership than the average Piedmont service.

On-Time Scenario

While all six locomotives have the same model PME and HEP, there was inter-locomotive variability in emission factors. The range in the mean NO_x emission factors for F59PH locomotives was 0.37 g/pkm, or nearly 24 percent of the average NO_x emission factor of 1.57 g/pkm over the four locomotives. The mean NO_x emission factor for F59PHI NC 1797 was 76 percent higher than for NC 1755. The range in the mean CO_2 emission factors for the F59PHIs and F59PHs was 9 and 26 percent of the average CO_2 emission factor over the respective locomotive models. Differences in mean per passenger-kilometer emission factors for each pollutant amongst locomotives are mostly due to differences in mass per time emission factors at Notch 8, where a plurality of time for each trip is spent. For example, the range in mean NO_x emission factors for individual F59PHs at Notch 8 is 0.97 g/s, or 20 percent of the mean NO_x emission rate over all F59PHs at Notch 8 of 4.76 g/s.

Variability in the on-time duty cycles contributes to variability in the per passenger-kilometer emission factors. However, the inter-trip emission factor variability was 20 percent or less for the PME of each locomotive.

The mean per passenger-kilometer NO_x emission rate was 43 percent higher for the F59PHIs than for the F59PHs, whereas the mean CO_2, HC, CO, and PM emission factors were 10, 14, 42, and 50 percent lower, respectively. If NCDOT were to prioritize reduction in per passenger-kilometer NO_x emissions, then the F59PH locomotives should be utilized more often. However, if CO_2, CO, HC, or PM were the targets for reduction, then the F59PHI locomotives should be utilized most often.

There is negligible variability in the HEP engine pollutant emission factors. The HEP is a small, but significant, contributor to emissions from the chassis, representing up to 20 percent of total emissions depending on the pollutant and locomotive. For example, the PM and CO per passenger-kilometer emission factors from the HEP constituted 10 and 18 percent, respectively, of total chassis emissions from the average F59PHI locomotive.

A sensitivity analysis was conducted to determine the difference in PME emissions if Piedmont passenger rail service was operated by a Tier 4 locomotive, rather than the locomotives in the NCDOT fleet. The Tier 4 NO_x emission standard is 90 percent lower than the OTR-measured fleet average NO_x emission rate of 10.0 g/bhp-hr. The Tier 4 PM and HC emission standards are 96 and 99 percent lower, respectively, than the fleet average PM and HC emission rates of 0.40 and 9.65 g/bhp-hr, respectively, for the locomotives in the NCDOT fleet. There was no difference between the fleet average CO emission rate and the Tier 4 standard.

Sensitivity of Locomotive Emission Factors to Delays

The mean per passenger-kilometer emission factors for all pollutants are generally higher for delayed travel compared to on-time trips, as shown in Table 5-6. On average for the entire locomotive fleet, the NO_x, CO_2, CO, and PM emission factors were 12 to 19 percent higher, while the HC emission factor was 55 percent higher, for the greater than 30-minute delay scenario compared to on-time travel. The delay scenario with the highest frequency, between 10 to 20 minutes late, had fleet average emission factors that were 2 to 7 percent higher than for the on-time scenario, with the exception of PM for which a negligible difference was estimated.

The location of a delay also has an impact on the per passenger-kilometer emission factors. A delay on Segment A between Raleigh and Cary, the shortest rail segment with the lowest average ridership, had a larger impact on the emission factors than a delay on Segment F between High Point and Salisbury, which is 4 times longer and has twice the ridership. For example, for NC 1810 operating an on-time train over Segment A, the segment average NO_x emission factor was 3.71 g/pkm. A 10-minute delay, with ten additional minutes of idling, increases the segment average NO_x emission factor by 11 percent. For NC 1810, the Segment F NO_x emission factor for the 10-minute delay was 3 percent higher than for on-time. The longer distance and higher ridership of Segment F, compared to Segment A, lead to a smaller increase in the per passenger-kilometer emission factor.

Sensitivity of Locomotive Emission Factors to Station Pair

Average emission factors vary depending on the O/D pair, as shown in Table 5-7. For example, the fleet average CO_2 emission factors vary from 96.9 to 135 g/pkm when comparing the lowest rate, for the Durham and Charlotte station pair, to the highest rate, for the Raleigh and Greensboro station pair. The per passenger-kilometer emission rates for the Durham and Charlotte station pair are 28 to 31 percent higher among each of the pollutants when compared to the Raleigh and Greensboro station pair. There are a larger number of station stops per kilometer between Raleigh and Greensboro than for other portions of the Piedmont route. In addition, the rail segments between Raleigh, Cary, and Durham have the lowest ridership. Therefore, station pairs that include these segments have higher per passenger-kilometer emission rates than the station pairs that exclude these segments.

Table 5-6: Locomotive Per Passenger-Kilometer Emission Factors for Piedmont Service between Raleigh and Charlotte, NC for On-Time and Delayed Trips

(a) On-Time (45 trips, average trip duration: 11,480 seconds)

	Emission Factor (g/pkm)[a]				
Locomotives	**CO_2**	**NO_x[b]**	**PM[c]**	**CO**	**HC[d]**
F59PH	121 (*0.13*)	1.63 (*0.14*)	0.09 (*0.15*)	0.30 (*0.17*)	0.70 (*0.17*)
F59PHI	110 (*0.13*)	2.30 (*0.16*)	0.05 (*0.15*)	0.19 (*0.16*)	0.60 (*0.16*)
Fleet	**118 (*0.13*)**	**1.86 (*0.15*)**	**0.08 (*0.15*)**	**0.26 (*0.16*)**	**0.67 (*0.17*)**

(b) 10 to 20 minutes late (13 trips, average trip duration: 12,261 seconds)

	Emission Factor (g/pkm)[a]				
Locomotives	**CO_2**	**NO_x[b]**	**PM[c]**	**CO**	**HC[d]**
F59PH	125 (*0.11*)	1.67 (*0.15*)	0.09 (*0.14*)	0.31 (*0.14*)	0.74 (*0.19*)
F59PHI	113 (*0.12*)	2.34 (*0.15*)	0.05 (*0.14*)	0.20 (*0.14*)	0.63 (*0.18*)
Fleet	**121 (*0.11*)**	**1.89 (*0.15*)**	**0.08 (*0.14*)**	**0.27 (*0.14*)**	**0.70 (*0.19*)**

(c) 20 to 30 minutes late (8 trips, average trip duration: 12,852 seconds)

	Emission Factor (g/pkm)[a]				
Locomotives	**CO_2**	**NO_x[b]**	**PM[c]**	**CO**	**HC[d]**
F59PH	122 (*0.09*)	1.63 (*0.13*)	0.09 (*0.11*)	0.31 (*0.12*)	0.75 (*0.18*)
F59PHI	111 (*0.09*)	2.30 (*0.13*)	0.05 (*0.11*)	0.20 (*0.12*)	0.65 (*0.18*)
Fleet	**118 (*0.09*)[e]**	**1.85 (*0.13*)[e]**	**0.08 (*0.11*)**	**0.27 (*0.12*)**	**0.71 (*0.18*)**

(d) More than 30 minutes late (2 trips, average trip duration: 14,449 seconds)

	Emission Factor (g/pkm)[a]				
Locomotives	**CO_2**	**NO_x[b]**	**PM[c]**	**CO**	**HC[d]**
F59PH	130 (*0.06*)	1.87 (*0.12*)	0.10 (*0.10*)	0.31 (*0.12*)	1.07 (*0.23*)
F59PHI	118 (*0.06*)	2.73 (*0.14*)	0.06 (*0.16*)	0.22 (*0.15*)	0.96 (*0.25*)
Fleet	**126 (*0.06*)**	**2.15 (*0.13*)**	**0.09 (*0.12*)**	**0.28 (*0.13*)**	**1.04 (*0.24*)**

[a] Locomotive per passenger-kilometer emission factors are the sum of the mean PME and HEP emission factors with the coefficient of variation (standard deviation divided by the mean) in italics.

[b] NO_x includes NO and NO_2. Only NO was measured. Results include multiplicative correction factors based on NO and NO_2 rail yard prime mover engine measurements with a SEMTECH-DS PEMS.

[c] PM emission factors include multiplicative correction factor of 5 to approximate total PM.

[d] HC is measured using NDIR, which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factor based on FID rail yard prime mover engine measurements with a SEMTECH-DS PEMS.

[e] Trend of increased CO_2 and NO_x emission factors with respect to delay was not observed for the 20- to 30-minute delay scenario. Lower CO_2 and NO_x per passenger-kilometer emission factors were observed for Rail Segments A, C, E, and G for the 20- to 30-minute delay scenario compared to the on-time scenario.

Table 5-7: Locomotive and Light-Duty Gasoline Vehicle Per Passenger-Kilometer Emission Factors for On-Time Piedmont Service Between Five Origin and Destination Station Pairs

(a) Raleigh (RGH) ↔ Charlotte (CLT)

	Emission Factor (g/pkm)[a]				
Transport Method	**CO_2**	**NO_x[b]**	**PM[c]**	**CO**	**HC[d]**
F59PH Locomotive	121 (*0.13*)	1.63 (*0.14*)	0.09 (*0.15*)	0.30 (*0.17*)	0.70 (*0.17*)
F59PHI Locomotive	110 (*0.13*)	2.30 (*0.16*)	0.05 (*0.15*)	0.19 (*0.16*)	0.60 (*0.16*)
Locomotive Fleet	**118 (*0.13*)**	**1.86 (*0.15*)**	**0.08 (*0.15*)**	**0.26 (*0.16*)**	**0.67 (*0.17*)**
LDGV	**265**	**0.59**	**0.008**	**5.39**	**0.14**

(b) Greensboro (GRO) ↔ Charlotte (CLT)

	Emission Factor (g/pkm)[a]				
Transport Method	**CO_2**	**NO_x[b]**	**PM[c]**	**CO**	**HC[d]**
F59PH Locomotive	103 (*0.13*)	1.39 (*0.14*)	0.08 (*0.15*)	0.25 (*0.16*)	0.58 (*0.17*)
F59PHI Locomotive	93.9 (*0.13*)	1.96 (*0.15*)	0.04 (*0.15*)	0.16 (*0.15*)	0.49 (*0.16*)
Locomotive Fleet	**100 (*0.13*)**	**1.58 (*0.14*)**	**0.06 (*0.15*)**	**0.22 (*0.16*)**	**0.55 (*0.17*)**
LDGV	**262**	**0.58**	**0.008**	**5.08**	**0.14**

(c) Cary (CYN) ↔ Charlotte (CLT)

	Emission Factor (g/pkm)[a]				
Transport Method	**CO_2**	**NO_x[b]**	**PM[c]**	**CO**	**HC[d]**
F59PH Locomotive	105 (*0.12*)	1.42 (*0.13*)	0.08 (*0.14*)	0.26 (*0.16*)	0.60 (*0.16*)
F59PHI Locomotive	96.0 (*0.12*)	2.00 (*0.15*)	0.04 (*0.14*)	0.16 (*0.15*)	0.51 (*0.15*)
Locomotive Fleet	**102 (*0.12*)**	**1.62 (*0.14*)**	**0.07 (*0.14*)**	**0.23 (*0.15*)**	**0.57 (*0.16*)**
LDGV	**262**	**0.58**	**0.008**	**5.13**	**0.14**

(d) Durham (DNC) ↔ Charlotte (CLT)

	Emission Factor (g/pkm)[a]				
Transport Method	**CO_2**	**NO_x[b]**	**PM[c]**	**CO**	**HC[d]**
F59PH Locomotive	100 (*0.13*)	1.35 (*0.13*)	0.07 (*0.14*)	0.30 (*0.17*)	0.70 (*0.17*)
F59PHI Locomotive	90.9 (*0.13*)	1.90 (*0.15*)	0.04 (*0.14*)	0.15 (*0.15*)	0.48 (*0.16*)
Locomotive Fleet	**96.9 (*0.13*)**	**1.53 (*0.14*)**	**0.06 (*0.14*)**	**0.22 (*0.16*)**	**0.54 (*0.16*)**
LDGV	**262**	**0.58**	**0.008**	**5.13**	**0.14**

(e) Raleigh (RGH) ↔ Greensboro (GRO)

	Emission Factor (g/pkm)[a]				
Transport Method	**CO_2**	**NO_x[b]**	**PM[c]**	**CO**	**HC[d]**
F59PH Locomotive	139 (*0.14*)	1.88 (*0.15*)	0.10 (*0.16*)	0.35 (*0.17*)	0.82 (*0.17*)
F59PHI Locomotive	127 (*0.14*)	2.64 (*0.16*)	0.06 (*0.15*)	0.22 (*0.16*)	0.71 (*0.17*)
Locomotive Fleet	**135 (*0.14*)**	**2.13 (*0.15*)**	**0.09 (*0.15*)**	**0.30 (*0.17*)**	**0.78 (*0.17*)**
LDGV	**264**	**0.58**	**0.008**	**5.17**	**0.14**

[a] Locomotive per passenger-mile emission factors are the sum of the mean PME and HEP emission factors with the coefficient of variation (standard deviation divided by the mean) in italics.

[b] NO_x includes NO and NO_2. Only NO was measured. Locomotive results include multiplicative correction factor based on NO and NO_2 rail yard prime mover engine measurements with a SEMTECH-DS PEMS.

[c] Locomotive PM emission factors include multiplicative correction factor of 5 to approximate total PM.

[d] Locomotive HC is measured using NDIR, which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factor based on FID rail yard prime mover engine measurements with a SEMTECH-DS PEMS.

Light-Duty Gasoline Vehicles (LDGVs)

Fleet average emission factors based on MOVES for travel by PC and PT are shown in Table 5-8. The LDGV emission factors for CO_2, NO_x, and CO are within approximately 10 percent of national average emission factors estimated using EPA total emissions and U.S. Department of Transportation highway statistics [Davis et al., 2015]. The HC and PM emission factors based on MOVES are lower by approximately 80 percent. The EPA total emissions used to estimate the national average HC and PM emission factors included motorcycles, which emit higher levels of HC and PM compared to LDGVs [EPA, 2012]. Thus, the emission factor estimates for these pollutants are appropriately comparable to other reported values and appear to be valid.

The LDGV fleet average energy intensity based on MOVES is estimated at 3,674 kJ/pkm. The MMPASSIM-estimated energy intensity for a LDGV traveling between Raleigh and Charlotte was 3,528 kJ/pkm, or 4 percent lower. MMPASSIM estimates LDGV energy intensity based on chosen route characteristics and the vehicle characteristics of purchased and driven vehicles of recent years [NCRRP, 2015]. MOVES uses an age distribution to account for differences in energy use and emissions of LDGV of different model years that may be more representative of the vehicle fleet than just recent model years. However, the LDGV energy intensity from MOVES and the NCRRP report are quite similar given the differences in estimation methodologies.

Table 5-8: Light-Duty Gasoline Vehicle Per Passenger-Kilometer Energy Intensity and Emission Factors for Travel between Raleigh and Charlotte, NC Under Various Delay Scenarios

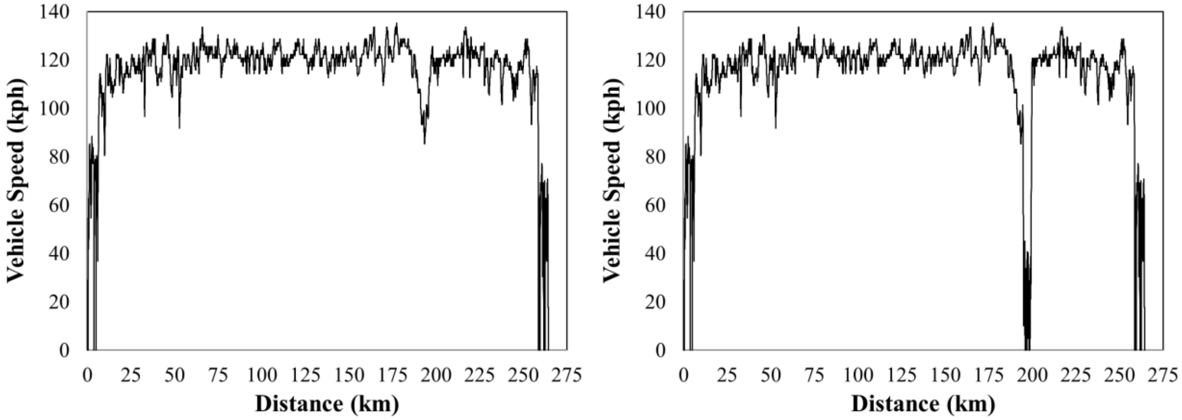
Delay Scenario	Trip Average Speed (kph)	Energy Intensity (kJ/pkm)	Emission Factor (g/pkm)[a,b]				
			CO_2	NO_x	PM	CO	HC
On-Time		**3,681**	**265**	**0.59**	**0.008**	**5.39**	**0.14**
Passenger Car	109	*2,969*	*213*	*0.31*	*0.005*	*3.05*	*0.07*
Passenger Truck		*4,464*	*321*	*0.89*	*0.011*	*7.96*	*0.21*
15 minutes		**3,742**	**269**	**0.60**	**0.008**	**5.40**	**0.14**
Passenger Car	100	*3,025*	*217*	*0.32*	*0.005*	*3.06*	*0.07*
Passenger Truck		*4,531*	*326*	*0.90*	*0.011*	*7.97*	*0.22*
30 minutes		**3,801**	**273**	**0.63**	**0.008**	**5.40**	**0.15**
Passenger Car	90.6	*3,077*	*221*	*0.34*	*0.005*	*3.06*	*0.07*
Passenger Truck		*4,596*	*330*	*0.94*	*0.011*	*7.99*	*0.23*
45 minutes		**3,859**	**277**	**0.63**	**0.008**	**5.43**	**0.15**
Passenger Car	83.3	*3,130*	*225*	*0.34*	*0.005*	*3.06*	*0.07*
Passenger Truck		*4,660*	*335*	*0.94*	*0.011*	*8.02*	*0.24*
60 minutes		**3,916**	**281**	**0.65**	**0.008**	**5.43**	**0.16**
Passenger Car	77.2	*3,181*	*229*	*0.35*	*0.005*	*3.06*	*0.08*
Passenger Truck		*4,725*	*340*	*0.97*	*0.011*	*8.04*	*0.24*

[a] The LDGV emission factors are in bold and are based on a population that was 58 percent passenger cars (PC) and 42 percent passenger trucks (PT).

[b] It is assumed that the LDGV is a single occupancy vehicle (SOV)

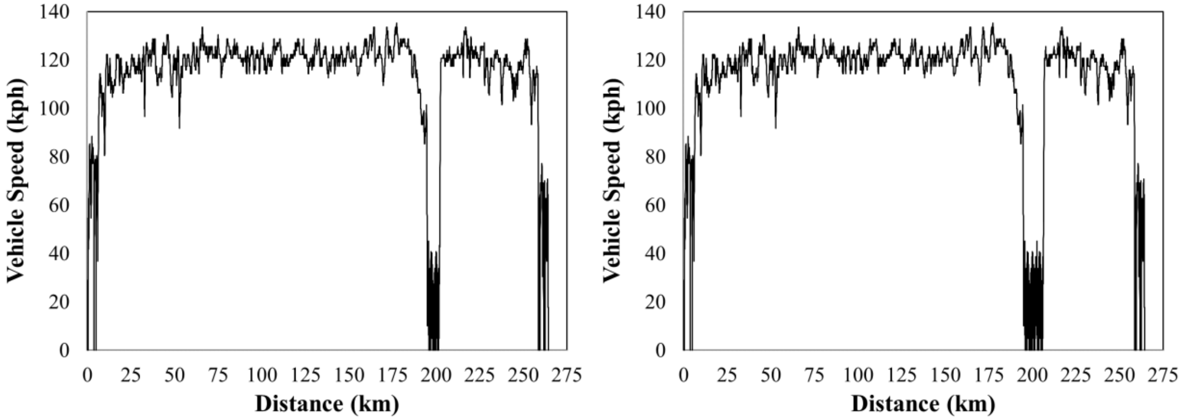
To represent congested traffic conditions and to simulate traffic-related delay, a 1 Hz speed versus time profile was extracted from a portion of a prior real-world measurement of an LDGV on a freeway and used to replace a portion of the Raleigh to Charlotte trip corresponding to free flow travel [Frey *et al.*, 2013]. The distance of the delay and free flow portions are both 5.3 km. The amount of time to travel this distance at free flow speed is approximately 3 minutes. The time duration of the delay portion is 18 minutes, or 15 minutes longer than the free flow portion, leading to a net change in travel time of 15 minutes for the same total travel distance. This process was repeated to add incremental travel time delays of 30, 45, and 60 minutes. The new driving schedules, shown in Figure 5-2, were used as input into MOVES to estimate LDGV emission factors.

The LDGV fleet average emission rates for all pollutants increased as the duration of the delay increased. This is in agreement with previous literature [Frey et al., 2008; Liu and Frey, 2015; Unal et al., 2003]. Based on real-world measurements of older Tier 1 certified vehicles, Unal *et al.* [2013] found that the magnitude of increase in total emission for the same distance is comparable to the percentage increase in travel time. Here, for 15 minutes of delay, which increased travel time by 10 percent, the trip average emission rates for HC increased by 3 percent, NO_x and CO_2 increased by 2 percent, and CO and PM increased by less than 0.2 percent. For 45 minutes of delay, the trip average HC emission rates increased by 12 percent, NO_x increased by 11 percent, CO_2 increased by 6 percent, and CO and PM increased by less than 1 percent. Although the increase in trip average emission rates was modest, the emission rates for the delay segments were higher than for the rest of the trip for HC, CO_2, CO, NO_x, and PM by 172 percent, 83 percent, 36 percent, 11 percent, and 4 percent, respectively. Each 15-minute delay on the highway equates to an additional 1.2 grams of HC, 2.8 grams of CO, 3.6 grams of NO_x, 1.2 kilograms of CO_2, and 0.5 milligrams of PM.



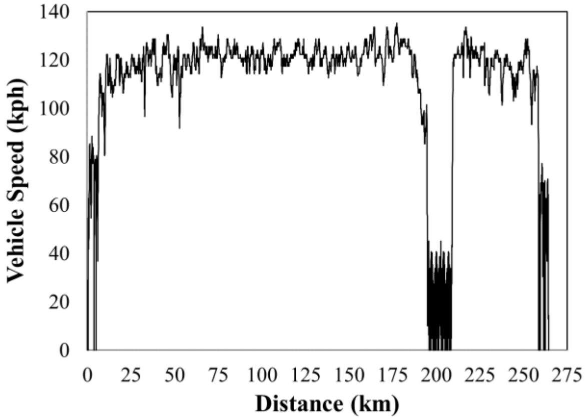
(a) On-Time

(b) 15min Delay



(c) 30min Delay

(d) 45min Delay



(e) 60min Delay

Figure 5-2: Highway Vehicle Drive Schedules Used in the Motor Vehicle Emissions Simulator (MOVES) Software for On-Time and Delayed One-Way Trips Between Raleigh and Charlotte, NC

As trip duration increases with increasing delays, energy intensity and fuel use increases, as shown in Table 5-8. For an average LDGV and a one-way trip, every 15-minute delay on the highway equates to an additional 0.46 liters of gasoline.

There is little variation in the average LDGV per passenger-kilometer emission rates when comparing amongst the five rail station pairs, as shown in Table 5-7, with the exception of CO. The CO emission factor for the Raleigh and Charlotte station pair, which was the highest of the five station pairs, was 6 percent higher than the lowest CO emission factor, for the Greensboro and Charlotte station pair.

The energy intensities for PCs and PTs estimated by MOVES were similar to published values. The on-time PC energy intensity from MOVES of 2,962 kJ/pkm is 7 percent lower than the 3,195 kJ/vehicle-km in the literature, assuming one person per vehicle [Davis et al., 2015]. The on-time PT energy intensity of 4,458 kJ/pkm from MOVES is 5 percent greater than the 4,227 kJ/vehicle-km published energy intensity [Davis et al., 2015]. The BTS [2016] estimates the PC and PT energy intensities to be 2,547 and 3,588 kJ/pkm, respectively, assuming an average of 1.39 and 1.34 people in the vehicle, respectively. The on-time PC and PT energy intensities from MOVES are 16 and 7 percent lower, respectively, than the BTS values, adjusted for single occupancy. Assuming the LDGV fleet is 52 percent PC and 48 percent PT, the fleet average energy intensity from BTS is 4,073 kJ/pkm, which is 11 percent higher than the MOVES estimate. Thus, the energy intensity estimates reported here are similar to other estimates and appear to be valid.

Compared to a PC, a PT traveling between Raleigh and Charlotte without delay would have 50 percent higher CO_2 emissions and energy intensity, and more than double NO_x, CO, HC, and PM emissions per kilometer. For a one-way trip, a PT would emit 1.8 grams of PM, 38 grams of HC, 151 grams of NO_x, 1.3 kilograms of CO, and 28 kilograms of CO_2 more than a PC. The PT would also consume nearly 11 liters more gasoline than the PC.

Comparison of Locomotive to LDGV Emission Factors

For the Raleigh to Charlotte trip, the train has clear advantages with respect to emissions of CO_2 and CO compared to an LDGV. The locomotive fleet CO_2 emission rate of 118 g/pkm is 55 percent lower than LDGVs. The CO emission rate for the locomotive fleet is 95 percent lower compared to LDGVs. Gasoline vehicles tend to produce high levels of engine-out CO emissions. Even though gasoline vehicles have very effective control of CO emissions using three-way catalytic converters, their exhaust emissions are higher than those of the diesel engines used in the locomotives [Cooper and Alley, 2011].

The locomotive fleet average NO_x emission factor of 1.86 g/pkm in Table 5-6 is approximately 3 times higher than the LDGV emission factor of 0.59 g/pkm in Table 5-8, assuming on-time travel. The locomotive PM emission factors average 10 times higher than for LDGVs. The NCDOT fleet average HC emission factor is approximately 5 times higher than for LDGVs. There is wide variability in the per passenger-kilometer HC emission factors when comparing individual locomotives in the NCDOT fleet. Locomotives NC 1869, NC 1893, and NC 1755 had HC emission factors of between 0.25 and 0.31 g/pkm, when accounting for both the PME and HEP. These emission factors are 79 to 121 percent higher than the LDGV HC emission factor of 0.14 g/pkm. Locomotive NC 1859 had the highest HC emission factor at 1.20 g/pkm, which is more than 8.5 times greater than for an LDGV.

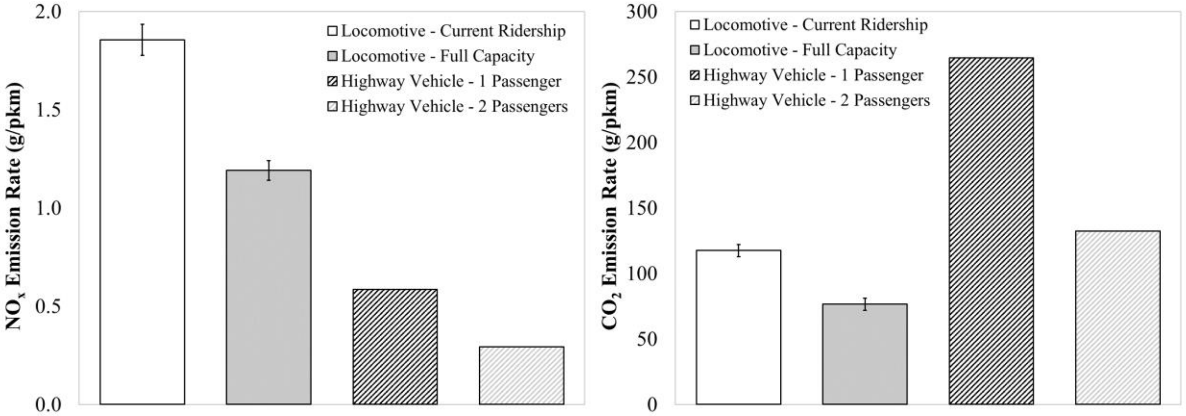
To assess the validity of the Piedmont to LDGV emission factor comparisons, the results were compared to Barth *et al*. [1996], who compared Metrolink commuter rail service in California to commuting by personal vehicle. They report that the train had lower CO per passenger emissions, but higher NO_x and PM per passenger emissions. This was also seen with the Piedmont for NO_x, PM, and CO. The Metrolink study reported lower rail HC emissions per passenger than for a highway vehicle. However, Metrolink carries 2.2 times more riders per train than the Piedmont.

For locomotive fleet travel delays in excess of 30 minutes, the advantage of rail to on-time highway travel with respect to CO_2 is reduced from 44 percent lower to 37 percent. Train delays exacerbate differences for NO_x, PM, and HC. There was a negligible difference in the comparison in CO emission factors for a delayed locomotive and an on-time LDGV. Fleet average NO_x emission factors increase from 3 times higher for on-time travel to nearly 5 times higher for travel delayed by more than 30 minutes. Fleet average PM emission factors increase to 14 times higher than on-time LDGV for rail delays in excess of 30 minutes.

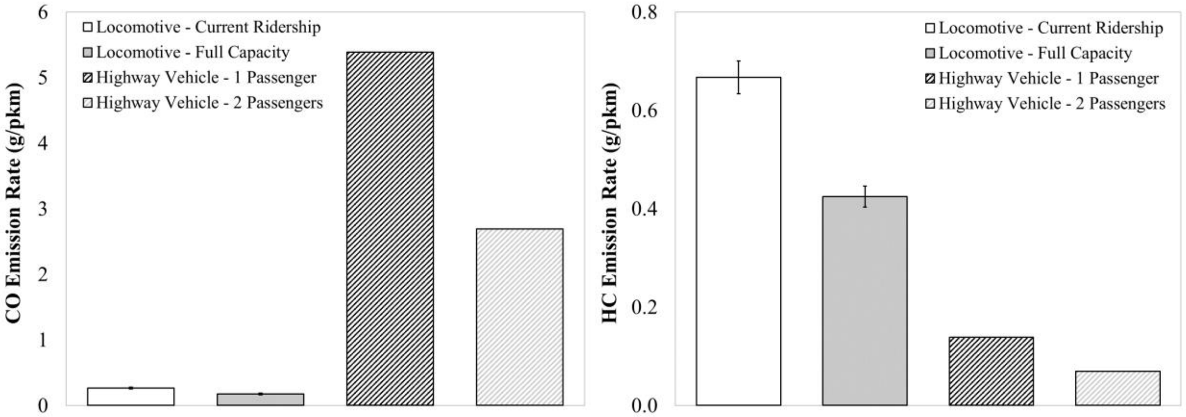
With only modest variations in LDGV emission rates with respect to travel delay, the comparison of emission factors for on-time locomotive travel to delayed LDGV travel are similar to the comparison of on-time locomotive travel to on-time LDGV travel. For example, the on-time locomotive CO_2 emission rate is 46 and 47 percent lower than for an LDGV experiencing a 30- and 60-minute delay, respectively, compared to 44 percent lower than an on-time LDGV.

If more passengers ride the train, per passenger-kilometer emission factors would decrease. For example, if Piedmont ridership increased to full capacity of a train consist configuration of two 66-seat passenger cars, then fleet average per passenger-kilometer NO_x, HC, and PM emission rates would decrease by 36 percent, as shown in Figure 5-3. However, the locomotive NO_x, HC, and PM emission rates would still be higher than for an LDGV traveling between Raleigh and Charlotte; even higher rail ridership and additional passenger cars in the consist would be needed to achieve similar emission rates compared to LDGVs. For the PM emission rate to be equal for the locomotive and LDGV, an unrealistic ridership increase is necessary, given the current locomotive fleet.

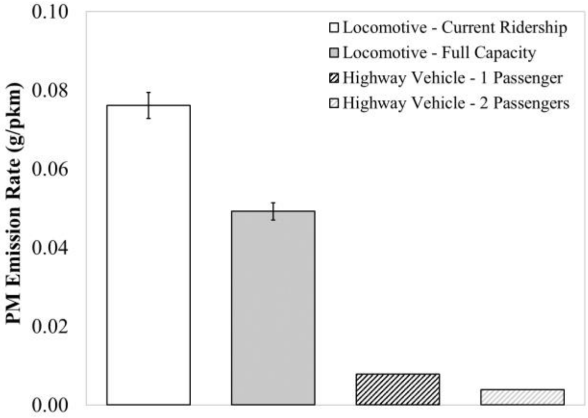
This study included locomotives that are currently in the NCDOT fleet, which are certified to meet the EPA Tier 0+ and Tier 1+ emission standards. If locomotives that met Tier 4 standards were used, rather than the current locomotive fleet, then ridership increases would not be necessary for rail NO_x, PM, and HC emission factors to be less than from LDGV. For on-time travel, a Tier 4 locomotive would have NO_x, CO, HC, and PM emission rates of 0.19, 0.26, 0.003, and 0.003 g/pkm, respectively, on the Piedmont based on current ridership, which are all lower than the emission rates for an average LDGV.



(a) Nitrogen Oxides (b) Carbon Dioxide



(c) Carbon Monoxide (d) Hydrocarbons



(e) Particulate Matter

Figure 5-3: Comparison of Per Passenger Kilometer Emission Rates for On-Time Locomotive and Highway Vehicle Travel between Raleigh and Charlotte, NC with Varying Passenger Loads

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This dissertation was motivated by the need for an easier way of measuring locomotive engine activity and emissions. There are few facilities in the United States that can measure locomotive engine exhaust emissions on a dynamometer. Therefore, these measurements can be costly, time-consuming, and logistically challenging. This makes it prohibitive for locomotive operators to measure their fleet emissions in order to confirm the efficacy of engine rebuild to reduce fuel use and emission rates. The lack of an easy emissions measurement methodology also limits research on alternative fuels and technologies that may reduce locomotive exhaust emissions and the comparison of locomotive emissions to other modes of transportation.

CONCLUSIONS

A review of the literature did not populate any studies where locomotive emissions were directly measured from the engine during routine locomotive operations. A novel, convenient locomotive emissions measurement methodology was developed that utilizes a portable emissions measurement system (PEMS) for the collection of real-world engine activity and emissions data. Locomotive measurements can be conducted while the locomotive is still in service without having to remove the engine. The methodology was used to assess the efficacy of engine rebuilds and fuel switching as emission control strategies and to estimate per passenger emission rates for comparison to highway vehicle emission rates.

Locomotive Emissions Measurement

In general, rail yard (RY) measurements produced similar engine-output based emission rates to those observed during dynamometer measurements. PEMS data for the prime mover engines measured on both a dynamometer and in the rail yard were found to be comparable to cycle average emission rates reported by EPA.

Over-the-rail (OTR) and RY measurements produce statistically different notch average NO_x, CO_2, CO, HC, and PM emission rates. Therefore, RY measurements may not be representative of emissions produced during real-world locomotive operation. Although notch average rates often differed based on OTR versus RY measurements, the effect on cycle average emission rates was less pronounced. In most cases, cycle average emission rates estimated based on RY notch average rates were within 10 percent of those estimated based on OTR notch average rates. Thus, if errors of 10 percent in cycle average emission rates are tolerable for a given purpose, then measurement of RY notch average emission rates may be adequate. Otherwise, for a more accurate representation of real-world emission rates, OTR measurements are preferred.

OTR measurements contributed new insights on how real-world operation of the prime mover engine affects emissions, with respect to duty cycle and the transition between notches in the duty cycle. Real-world duty cycles differ from those used for regulatory analyses. During Piedmont passenger rail service, a larger percentage of time is typically spent in Notch 8 and a smaller percentage of time in idle and dynamic brake compared to the EPA line-haul duty cycle. These variations in duty cycles lead to statistically significant lower cycle average NO_x and HC rates. However, there was no significant difference in cycle average CO and PM rates. Similar to using RY measurements to represent real-world emission rates, a locomotive operator can use the regulatory duty cycle to estimate cycle average emission rates for their fleet within a tolerable error. The extra step of estimating real-world duty cycles may not have to be taken, unless more accurate emission rates are desired or the actual cycle differs from those considered here.

The impact of transients on real-world locomotive emissions had not previously been quantified. For OTR measurements, locomotive emissions for each one-way trip were calculated using two approaches. Approach 1 was based on time-weighted average notch-based emission rates, which are based on steady-state average emission rates for each notch. Approach 2 was based on the summation of second-by-second emissions data, which include transients. By comparing Approach 2 versus Approach 1, the role of transients on cycle average emissions was assessed. Neglecting to consider transient engine operations systematically biased trip total NO_x, CO_2, CO, and PM emissions estimates for the four locomotives analyzed. Total emissions should be estimated based on the sum of second-by-second emission rates, and not based on steady-state notch average emission rates.

Estimating trip total emissions using Approach 2 rather than Approach 1 does not add significant time to data analysis.

The number of notch transitions over this route may not be representative of all passenger rail service. NCDOT locomotives make stops at nine stations on the 278-kilometer Piedmont route. Microscale emission rate changes are important in modeling ambient concentrations in areas where locomotives sharply decelerate or accelerate, such as arriving at or departing a rail station. Engineers typically downshift before entering curves with reduced speed limits. A route with fewer curves may have fewer notch transitions. Engineers may increase engine output to climb a hill and decrease engine output when descending. Flatter routes may require fewer notch transitions than the Piedmont route.

Biodiesel

The PEMS measurement methodology that were developed were used to determine if biofuel use affected fuel use and emissions from a locomotive prime mover engine. The results of the biodiesel measurements agree with those of previous studies on smaller truck and nonroad equipment engines with regard to qualitative trends in emission rates when comparing biodiesel to ULSD, including higher NO_x emission rates, typically significantly lower HC and CO emission rates, and an indication of lower PM emission rates. There was little difference in CO_2 emission rates during RY measurements when comparing ULSD to biodiesel, but CO_2 emission rates were lower during OTR measurements. If the comparison of biodiesel versus ULSD were based on RY data, instead of OTR data, the relative increase in NO_x emission rates would be overestimated, the relative decrease in HC emission rates would be underestimated, and the relative decrease in CO and PM emission rates would be overestimated. This is due to the differences in locomotive engine operation during RY and OTR measurements.

Since OTR measurements are more representative of emissions produced during real-world, point-to-point locomotive operation, these results are of most interest to passenger rail operators. For the NCDOT locomotive fleet, the expected average reduction in exhaust emission rates from switching from ULSD to B20 based on OTR measurements is 53 percent for HC, 38 percent for CO, and 23 percent for PM, with an average increase in NO_x emission rate of 6 percent and potentially a reduction in exhaust CO_2 emission rate of 5 percent. The latter, coupled with reduction in fossil-fuel content of the biofuel and reduced fuel cycle CO_2 emissions, could lead to the net reduction in total CO_2 emissions of 9 percent that was observed in a nonroad construction equipment study [Pang *et al*., 2009].

With regard to fuel blends, the results are somewhat surprising in not indicating a clear trend in differences in emission rates with changes in biofuel blend. Overall, the results imply that biofuels offer the potential to reduce exhaust emissions of in-use locomotives, but that B20 may be a reasonable choice. These results also indicate that the two-stroke engines measured here may not have the same quantitative trends in emission rates versus biofuel blends as reported previously by EPA for smaller four-stroke engines [EPA, 2002 and 2003].

There was no indication of adverse operational effect of the biodiesel blends, except at B100, with a more noticeable fuel solvent effect in terms of deposit loading on the fuel filters. Such an effect is expected to be transitory; longer-term use of the biofuel might ultimately clean the fuel tank and fuel lines of deposits and later entail less loading to the fuel filter.

Comparison with Highway Travel

The OTR measurement methodology was used to quantify per passenger emission rates for passenger rail travel and compare them to emission rates from personal vehicle highway travel. An LDGV was instrumented with GPS to measure the speed and elevation profiles used in MOVES to estimate highway vehicle emission factors. For on-time travel, passenger rail emits 44 and 94 percent less CO_2 and CO per passenger-kilometer, respectively, compared to a LDGV with only one passenger. However, higher NO_x, HC, and PM emission rates are observed for passenger rail by a factor of 4 to 11, depending on pollutant. Ridership on the Piedmont would have to increase, the existing locomotives would have to be retrofitted with emission controls, or newer locomotives would have to be brought into service for NO_x, HC, and PM emissions to be comparable to highway vehicles. It was assumed that the driver was the only passenger in the LDGV. If the driver carpooled with an additional passenger, then the LDGV emission rates would be halved, and the LDGV would have lower per passenger-kilometer CO_2 emission rates compared to the train.

Rail travel delay substantially affects the per passenger-kilometer emission factors for the locomotives. The locomotive and the location of the delay had larger impacts on the emission factor than the length of the delay. The location of travel delays is typically out of the control of the locomotive operator and engineer. To capture a wider variety of travel times and duty cycles, activity data from additional locomotive trips should be collected to increase the duty cycle sample size for the delayed travel scenarios and may decrease inter-duty cycle variability.

Estimates of train emissions and energy use per passenger-kilometer are affected by passenger load factor, which is comprised of ridership and rolling stock seating capacity data. For the most accurate estimates, actual ridership and capacity data should be used. Underestimating ridership will increase per passenger-kilometer emission factors and energy intensities.

There is substantial variability in locomotive emission rates for portions of the Piedmont route. Depending on where a passenger boards and disembarks, even for the same train service, differences in the per passenger-kilometer emissions can be as much as 39 to 45 percent higher, depending on the pollutant. Besides passenger load factor, the per passenger-kilometer emission rates between two stations is affected by average number of stations stops per kilometer.

Overall

A locomotive engine emission measurement methodology was devised that utilizes a PEMS to measure passenger locomotive during revenue operations. Emission rates from dynamometer and rail yard measurements of the same engines were similar, while emission rates from over-the-rail measurements differed. This methodology allows locomotive operators to measure emissions from their own fleet for a variety of applications, while limiting the amount of time the locomotives are out of service. The PEMS methodology was applied to estimate locomotive emission factors for the purpose of comparing various biodiesel blends versus conventional diesel fuel, and for comparing to emission rates from personal highway vehicles. The results give support to the adoption of B20 as a drop-in fuel to help reduce HC, CO, and PM exhaust emissions for the NCDOT locomotive fleet, with a potential trade-off of a small increase in NO_x emission rate.

RECOMMENDATIONS

Based on the research conducted, future data collection campaigns are recommended. Additional research can also be conducted with data that has already been collected.

Locomotive Emissions Measurements

Multiple RY replicates can be completed in one day, with each replicate taking approximately one hour to complete. It is recommended that at least three RY replicates are completed for each measurement campaign in order to address inter-replicate variability. The locomotive has to be removed from service while the locomotive is instrumented and RY measurements are conducted, but can be completed prior to or after daily passenger rail operations are completed. With OTR measurements, the locomotive remains in service, but several days are needed to collect multiple one-way trip data to yield replicable notch average emission rates.

Cycle average emission rates were repeatable based on typically six one-way trips, or about 20 hours of OTR data, per locomotive. This amount of OTR data is recommended as suitable for future studies. However, to ensure that valid data is collected for at least six one-way trips, it is recommended that four days of OTR measurements are conducted. Therefore, all RY and OTR measurements of a locomotive can be conducted in a typical workweek.

In general, locomotive engine exhaust emissions should be measured from a greater number of locomotives that represent a wider variety of the locomotive models used both in passenger and freight rail operations. The F59PH and F59PHI locomotives measured represent a small, but not a negligible, number of locomotives utilized in the United States. Data should be collected on additional two-stroke locomotive engines and also on large four-stroke engines more typical of freight railroads. Some examples are the General Electric (GE) P42 locomotives, that Amtrak own nearly 200 of, and the GE Dash 8 and Dash 9 locomotives, which Norfolk Southern owns more than 1,400 of for freight operations.

Biodiesel

For the cases in which the comparisons were not statistically significant, it is possible that a larger sample of locomotives could lead to a statistically significant finding, such as with regard to higher average NO_x and lower average PM emission rates. The method described should here be applied in the future to include additional locomotives. It was not possible to test more locomotives in this study because of the significant effort devoted to development and demonstration of the PEMS-based methodology, evaluation of its replicability, coordination by NCDOT to run each locomotive on a different fuel blend, and allowance of sufficient time to switch fuels between measurements. At any given time, the three locomotives were each operating on a different fuel blend, which is a logistical challenge. With the NCDOT fleet consisting of only six locomotives, ideally, it would be best to collect data on all of the locomotives in the fleet.

For locations where NO_x emissions are of concern with respect to ozone formation and attainment of NAAQS, a potential increase in NO_x emissions from transportation sources should be evaluated for air quality impact. In addition, future studies should include quantification of differences in emissions from RY operations due to switching from ULSD to biodiesel and implications for pollutant exposure to nearby communities.

Comparison with Highway Travel

Only one vehicle was instrumented with GPS and driven between Raleigh and Charlotte, and there were no travel delays. Additional instrumented LDGV trips should be completed to capture actual highway delays between the five station pairs with the highest Piedmont ridership. Measurements should be taken during the same time of day and in the same direction of the Piedmont operations, for both weekdays and weekend days.

This methodology of estimating locomotive per passenger emissions could be used by local, state, or national governments to aid in transportation policy decisions with respect to achieving air quality standards. Rail operators could estimate emission factors for their fleet, and use the information to prioritize the retrofitting or replacement of locomotives, or where rail improvement projects should occur in order to decrease travel delays.

Future Research

There are opportunities for further research from the locomotive data that has already been collected beyond what was discussed in this dissertation. There are a number of published models that estimate power demand and fuel use based on train speed and track grade. The elevation and speed data collected by the GPS receivers during OTR measurements could be used to estimate the track grade profile for the Piedmont route. The trip total fuel use estimates from using these models could be compared to actual fuel use quantified from the OTR measurements. The effect of rail grade on fuel use and emissions can be assessed. Relationships between locomotive speed, track grade, and notch position can be evaluated, as well as their effect on emissions. Using the duty cycle data from the OTR measurements, comparisons can be made between Amtrak engineers based on trip-total fuel use and emissions estimates.

Once ongoing track work, which is changing the grade and layout of the track on some portions of the Piedmont route, is completed, it is likely that the locomotive duty cycle will be altered. Re-estimating the average Piedmont duty cycle for multiple one-way trips with multiple engineers is recommended. Per passenger kilometer emission factors can be estimated based on the new duty cycle, and compared to LDGV emission factors to determine if the track work reduced rail travel emissions.

REFERENCES

Agarwal, AK; Bijwe, J; Das, LM (2003) Wear Assessment in a Biodiesel Fueled Compression Ignition Engine. *J. Eng. Gas Turbines Power* **125**(3): 820-826.

Akasaka, Y; Suzuki, T; Sakurai, Y (1997) “Exhaust Emissions of a DI Diesel Engine Fueled with Blends of Biodiesel and Low Sulfur Diesel Fuel.” *Technical Paper No. 972998*; Society of Automotive Engineers: Warrendale, PA.

Amtrak (2014) “Amtrak Ridership and Revenues Continue Strong Growth in FY 2014.” *Press Release*; National Passenger Rail Corporation: Washington, DC.

Amtrak (2013) “Amtrak Annual Report Fiscal Year 2013.” National Passenger Rail Corporation: Washington, DC.

Amtrak (2012) “Amtrak Fleet Strategy Version 3.1.” National Passenger Rail Corporation: Washington, DC.

Amtrak (2011) “Amtrak Biodiesel Heartland Flyer Results Presented at Railroad Environmental Conference.” *Press Release*; National Passenger Rail Corporation: Washington, DC.

Andros, Inc. (2007) “Concentrations Measurement and Span Calibration Using n-Hexane and Propane in the ANDROS 6602/6800 Automotive Exhaust Gas Analyzer.” http://www.andros.com/hmDownloads.htm, accessed January 2007.

Bannikov, MG; Chattha, JA (2006) Oxides of Nitrogen (NO_x) Emission Levels of Diesel Engines of Switch Locomotives. *Proc. Inst. Mech. Eng., Part A* **220**(A5): 449-457.

Barth, MJ; Tadi, RR (1996). Emissions Comparison Between Truck and Rail: Case Study of California I-40. *Transport Res Rec* **1520**: 44-52

Barth, MJ; Younglove, T; Tadi, RR (1996). Emissions Analysis of Southern California Metrolink Commuter Rail. *Transport Res Rec* **1520**: 53-62.

Bently (2015) “Sources of Wear Metals in Oil Analysis.” www.cashmanequipment.com/bently/publications/appnotes/app31.php (accessed November 2015).

Bohac, SV; Feiler, E; Bradbury, I (2013) Effect of Injection Timing on Combustion, NO_x, Particulate Matter and Soluble Organic Fraction Composition in a 2-Stroke Tier 0+ Locomotive Engine. *J. Eng. Gas Turbines Power* **135**(1): 1-7.

Bohac, SV; Feiler, E; Bradbury, I (2012) Exhaust Emissions Characterization of a Turbocharged 2-Stroke Tier 0+ Locomotive Engine: NO_x, Particulate Matter, and Soluble Organic Fraction Composition. *J. Eng. Gas Turbines Power* **134**(7): 1-8.

Brabb, DC; Vithani, AR; Punwani, SK (2007) Onboard Locomotive Exhaust Emissions Measurement. *Fall Tech. Conf. ASME Rail Transp. Div.*: 69-75.

Bryant, AH; Tennyson, TA (1975) Exhaust Emissions of Selected Railroad Diesel Locomotives. *J. Eng. Ind.* **97**(3): 1136-1142.

Bureau of Transportation Statistics (2016) “National Transportation Statistics.” U.S. Department of Transportation, Washington, DC

Burgard, DA; Bishop, GA; Stadtmuller, RS; Dalton, TR; Stedman, DH (2006) Spectroscopy Applied to On-Road Mobile Source Emissions. *Appl. Spectrosc.* **60**(5): 135A-148A.

CATI (2008) “OEM-2100AX Axion System Operation Manual.” Clean Air Technologies International, Inc.: Buffalo, NY.

CATI (2003) “OEM-2100 Montana System Operation Manual.” Clean Air Technologies International, Inc.: Buffalo, NY.

CFR (2013) “National Primary and Secondary Ambient Air Quality Standards.” *Code of Federal Regulations*, Part 50, Title 40.

CFR (2013) “Emission Standards for Locomotives and Locomotive Engines.” *Code of Federal Regulations*, Part 92, Title 40.

CFR (2013) “Control of Emissions from Locomotives.” *Code of Federal Regulations*, Part 1033, Title 40.

Chester, M; Horvath, A (2012) High-speed rail with emerging automobiles and aircraft can reduce environmental impacts in California’s future. *Environ. Research Letters*, **7**(3): 1-11.

Chester, M; Horvath, A (2010) Life-cycle assessment of high-speed rail: the case of California. *Environ. Research Letters*, **5**(1): 1-8.

Choi, HW; Frey, HC (2010) Method for In-Use Measurement and Evaluation of the Activity, Fuel Use, Electricity Use, and Emissions of a Plug-In Hybrid Diesel-Electric School Bus. *Environ. Sci. Technol.*, **44**(9): 3601-3607.

Cooper, CD; Alley, FC (2011) *Air Pollution Control: A Design Approach*. Waveland Press: Long Grove, IL.

Davis, SC; Diegel, SW; Boundy, RG (2015) "Transportation Energy Data Book: Edition 34." *ORNL-6990*; Oak Ridge National Laboratory, Oak Ridge, TN.

Delucchi, M (1996) "Emissions of Criteria Pollutants, Toxic Air Pollutants, and Greenhouse Gases from the Use of Alternative Transportation Modes and Fuels." *UCD-ITS-RR-96-12*; University of California, Davis Institute of Transportation Studies, Davis, CA.

Donaldson Filtration Solutions (2012) "Engine Air Filtration for Light, Medium & Heavy Dust Conditions." http://www.donaldson.com/en/catalogs/engine/057643.pdf. Accessed July 3, 2012.

DOT (2014) "Benefit-Cost Analyses Guidance for TIGER Grant Applicants." U.S. Department of Transportation. http://www.dot.gov/tiger/guidance. Accessed July 4, 2014.

Dunn, R; Eggleton, P (2002) "Influence of Duty Cycles and Fleet Profile on Emissions from Locomotives in Canada." *TP 13945E*; Transport Canada Transportation Development Centre: Montreal.

Durbin, TD; Norbeck, JM (2002) Effects of Biodiesel Blends and Arco EC-Diesel on Emissions from Light Heavy-Duty Diesel Vehicles. *Environ. Sci. Technol.*, **36**(8):1686-1691.

Durbin, TD; Johnson, K; Cocker, DR; Miller, JW; Maldonado, H; Shah, A; Ensfield, C; Weaver, C; Akard, M; Harvey, N; Symon, J; Lanni, T; Bachalo, W; Payne, G; Smallwood, G; Linke, M (2007) Evaluation and Comparison of Portable Emissions Measurement Systems and Federal Reference Methods for Emissions from a Back-Up Generator and a Diesel Truck Operated on a Chassis Dynamometer. *Environ. Sci. Technol*. **41**(17): 6199-6204.

EIA (2015) "Annual Energy Outlook 2015 with projections to 2040." *DOE/EIA-0383(2015)*; U.S. Energy Information Administration: Washington, DC.

EPA (2013) "2013 Final Report: Integrated Science Assessment of Ozone and Related Photochemical Oxidants." *EPA600-R-10-076F*; U.S. Environmental Protection Agency: Washington, DC.

EPA (2012) "In-Depth Information for Motorcycle Owners on EPA's New Emission Standards for Highway Motorcycles (Rev 9/2012)." *EPA420-F-03-045*; U.S. Environmental Protection Agency: Ann Arbor, MI.

EPA (2010) "Regulatory Impact Analysis: Renewable Fuel Standard Program (RFS2)." *EPA420-R-10-006*; U.S. Environmental Protection Agency: Ann Arbor, MI.

EPA (2010) “Motor Vehicle Emission Simulator (MOVES): User Guide for MOVES2010a.” *EPA420-B-10-036*; U.S. Environmental Protection Agency: Ann Arbor, MI.

EPA (2009) “2009 Final Report: Integrated Science Assessment for Particulate Matter.” *EPA600-R-08-139F*; U.S. Environmental Protection Agency: Washington, DC.

EPA (2009) “Emission Factors for Locomotives: Technical Highlights.” *EPA420-F-09-025*; U.S. Environmental Protection Agency: Ann Arbor, MI.

EPA (2008) “EPA Finalizes More Stringent Emissions Standards for Locomotives and Marine Compression-Ignition Engines.” *EPA420-F-08-004*; U.S. Environmental Protection Agency: Ann Arbor, MI.

EPA (2003) “The Effect of Cetane Number Increase Due to Additives on NO_x Emissions from Heavy-Duty Highway Engines.” *EPA420-R-03-002*; U.S. Environmental Protection Agency: Ann Arbor, MI.

EPA (2002) “A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions: Draft Technical Report.” *EPA420-P-02-001*; U.S. Environmental Protection Agency: Ann Arbor, MI.

EPA (2001) “Strategies and issues in correlating diesel fuel properties with emissions.” *EPA420-P-01-001*; U.S. Environmental Protection Agency: Ann Arbor, MI.

EPA (1998) “Locomotive Emission Standards: Regulatory Support Document.” *EPA420-R-98-101*; U.S. Environmental Protection Agency: Ann Arbor, MI.

Facanha, C; Horvath, A (2007) Evaluation of Life-Cycle Air Emission Factors of Freight Transportation. *Environ. Sci. Technol.*, **41**(20): 7138-7144.

Facanha, C; Horvath, A (2006). Environmental Assessment of Freight Transportation in the U.S. *The International Journal of Life Cycle Assessment* **11**(4): 229-239.

Fazal, MA; Haseeb, ASMA; Masjuki, HH (2011) Biodiesel feasibility study: An evaluation of material compatibility; performance; emission and engine durability. *Renew. Sustain. Energy Rev.* **15**(2): 1314-1324.

Frey, HC; Graver, BM (2012) “Measurement and Evaluation of Fuels and Technologies for Passenger Rail Service in North Carolina.” *Report No. 2012-33*; Prepared by North Carolina State University for North Carolina Department of Transportation: Raleigh, NC.

Frey, HC; Kim, K (2009) In-use measurement of the activity, fuel use, and emissions of eight cement mixer trucks operated on each of petroleum diesel and soy-based B20 biodiesel. *Transp. Res. Part D* **14**: 585-592.

Frey, HC; Kim, K (2006) Comparison of Real-World Fuel Use and Emissions for Dump Trucks Fueled with B20 Biodiesel Versus Petroleum Diesel. *Transp. Res. Rec.* **1987**: 110-117.

Frey, HC; Boroujeni, B; Hu, J; Sandhu, GS; Liu, B; Jiao, W; Graver, BM (2013) "Measurements of 1996 to 2013 Model Year Light Duty Gasoline Vehicles." *2013-A-12942-AWMA*; Proceedings of 106th Annual Conference of the Air & Waste Management Association: Chicago, IL.

Frey, HC; Choi, HW; Kim, K (2012) Portable Emission Measurement System for Emissions of Passenger Rail Locomotives. *Transp. Res. Rec.* **2289**: 56-63.

Frey, HC; Kim, K; Pang, S; Rasdorf, WJ; Lewis, P (2008) Characterization of Real-World Activity, Fuel Use, and Emissions for Selected Motor Graders Fueled with Petroleum Diesel and B20 Biodiesel. *J. Air & Waste Manage. Assoc.* **58**(10): 1274-1287.

Frey, HC; Rasdorf, WJ; Kim, K; Pang, S; Lewis, P (2008) Comparison of Real-World Emissions of B20 Biodiesel Versus Petroleum Diesel for Selected Nonroad Vehicles and Engine Tiers. *Transp. Res. Rec.* **2058**: 33-42.

Frey, HC; Rasdorf, WJ; Kim, K; Pang, S; Lewis, P; Ablhansani, S (2008) "Real-World Duty Cycles and Utilization for Construction Equipment in North Carolina." *HWY-2006-08*. Prepared by North Carolina State University for the North Carolina Department of Transportation: Raleigh, NC.

Frey, HC; Zhang, K; Rouphail, NM (2008) Fuel Use and Emissions Comparisons for Alternative Routes Time of Day, Road Grade, and Vehicles Based on In-Use Measurements. *Environ. Sci. Technol.* **42**(7): 2483-2489.

Frey, HC; Unal, A; Rouphail, NM; Colyar, JD (2003) On-Road Measurement of Vehicle Tailpipe Emissions Using a Portable Instrument. *J. Air Waste Manage. Assoc.* **53**(8): 992-1002.

Fritz, SG (2004) "Evaluation of Biodiesel Fuel in an EMD GP38-2 Locomotive." *NREL-SR-510-33436*; Prepared by Southwest Research Institute for National Renewable Energy Laboratory: Golden, CO.

Fritz, SG (2000) “Diesel Fuel Effects on Locomotive Exhaust Emissions.” *Technical Report SwRI Project No. 08.02062*; Prepared for the California Air Resources Board, Sacramento, CA, 2000.

Fritz, SG (1994) Exhaust Emissions from 2 Intercity Passenger Locomotives. *J. Eng. Gas Turbines Power* **116**(4): 774-783.

Fritz, SG; Cataldi, GR (1991) Gaseous and Particulate-Emissions from Diesel Locomotive Engines. *J. Eng. Gas Turbines Power* **113**(3): 370-376.

Fritz, SG; Hedrick, JC; Smith, BE (2005) Exhaust Emissions from a 1,500 kW EMD 16-645-E Locomotive Diesel Engine using Several Ultra-Low Sulfur Diesel Fuels. *Fall Tech. Conf. ASME Intern. Combust. Engine Div.*: 37-46.

Hare, CT; Springer, KJ; Huls, TA (1974) Locomotive Exhaust Emissions and Their Impact. *Mech. Eng.* **96**(8): 57-57.

Hedrick, JC; Fritz, SG (2008) Locomotive Idle and Start-Up Exhaust Emissions Testing. *Spring Tech. Conf. ASME Intern. Combust. Engine Div.*: 385-394.

Hoffman, JC; Springer, KJ; Tennyson, TA (1975) 4 Cycle Diesel Electric Locomotive Exhaust Emissions – Field Study. *Mech. Eng. (Am. Soc. Mech. Eng.)* **97**(7): 91-97.

Hu, J; Graver, BM; Frey, HC (2015). “Comparison of Nitrogen Oxides and Hydrocarbon Exhaust Concentration Detection Methods for Portable Emission Measurement Systems Applied to Locomotive Engines.” *Proceedings of the 108th Annual Meeting of the Air & Waste Management Association*. Air & Waste Management Association: Pittsburgh, PA.

Kim, NS; Van Wee, B (2009) Assessment of CO_2 emissions for truck-only and rail-based intermodal freight systems in Europe. *Transportation Planning and Technology* **32**(4): 313-333.

Kolb, A; Wacker, M (1995) Calculation of energy consumption and pollutant emissions on freight transport routes. *The Science of the Total Environment* **169**(1-3): 283-288.

Komor, P (1995) “Reducing energy use in US freight transport.” *Transport Policy* **2**(2): 119-128.

Lindhjem, C; Chan, LM; Pollack, A; Kite, C (2003) “Applying Humidity and Temperature Corrections to On and Off-Road Mobile Source Emissions.” *Proceedings of the 13th International Emissions Inventory Conference*. U.S. Environmental Protection Agency and Emission Inventory Improvement Program: Clearwater, FL.

Liu, B; Frey, HC (2015) Variability in Light-Duty Gasoline Vehicle Emission Factors from Trip-Based Real-World Measurements. *Environ. Sci. Technol.* **49**(20): 12525-12534.

Liu, H; Barth, M; Scora, G; Davis, N; Lents, J (2010) Using Portable Emissions Measurement Systems for Transportation Emissions Studies: Comparison with Laboratory Methods. *Transp. Res. Rec.* **2158**: 54-60.

Marchese, AJ; Bhatia, KK; Hesketh, RP; McKenna, D (2009) "Evaluation of Emissions and Performance of NJ TRANSIT Diesel Locomotives with B20 Biodiesel Blends." Prepared for NJ TRANSIT: Newark, NJ.

Markworth, VO; Fritz, SG; Cataldi, GR (1992) The Effect of Injection Timing, Enhanced Aftercooling, and Low-Sulfur Low-Aromatic Diesel Fuel on Locomotive Exhaust Emissions. *J. Eng. Gas Turbines Power* **114**(3): 488-495.

Matei, MC; Nes, CS (2012) Extensive Use of the Railway System – An Efficient Way of Reducing CO_2 Emissions in the Transportation Sector. *J. Environ. Protect. Ecology* **13**(2A): 844-851.

McCormick, RL; Graboski, MS; Alleman, TL; Herring, AM (2001) Impact of Biodiesel source material and chemical structure on emissions of criteria pollutants from a heavy-duty engine. *Environ. Sci. Technol.* **35**(9): 1742-1747.

McCormick, RL; Ross, JD; Graboski, MS (1997) Effect of Several Oxygenates on Regulated Emissions from Heavy-Duty Diesel Engines. *Environ. Sci. Technol.* **31**(4):1144-1150.

McKenna, D; Bhatia, KK; Hesketh, RP; Rowen, C; Vaughn, T; Marchese, AJ; Chipko, G; Guran, S (2008) Evaluation of Emissions and Performance of Diesel Locomotives with B20 Biodiesel Blends: Static Test Results. *Fall Tech. Conf. ASME Rail Transp. Div.*: 167-175.

Myers, J; Kelly, T; Dindal, A.; Willenberg, Z; Riggs, K (2003) "*Environmental Technology Verification Report: Clean Air Technologies International, Inc. REMOTE On-Board Emissions Monitor*." Prepared for U.S. Environmental Protection Agency: Research Triangle Park, NC.

NCRRP (2015) "Comparison of Passenger Rail Energy Consumption with Competing Modes." *Report No. 3*; Transportation Research Board, National Cooperative Rail Research Program: Washington, DC.

NS (2013) "Norfolk Southern 2013 Sustainability Report." Norfolk Southern: Norfolk, VA.

Osborne, DT; Fritz, SG; Glenn, D (2011) The Effects of Biodiesel Fuel Blends on Exhaust Emissions from a General Electric Tier 2 Line-Haul Locomotive. *J. Eng. Gas Turbines Power* **133**(10): 102803 1-7.

Osborne, DT; Fritz, SG; Iden, M; Newburry, D (2007) Exhaust Emissions from a 2,850 kW EMD SD60M Locomotive Equipped with a Diesel Oxidation Catalyst. *Spring Tech. Conf. ASME Intern. Combust. Engine Div.*: 441-449.

Pang, S; Frey, HC; Rasdorf, WJ (2009) Life Cycle Inventory Energy Consumption and Emission for Biodiesel versus Petroleum Diesel Fueled Construction Vehicles. *Environ. Sci. Technol.* **43**(16): 6398-6405.

Popp, PJ; Bishop, GA; Stedman, DH (1999) "Remote Sensing of Railroad Locomotive Emissions: A Feasability Study." Prepared by University of Denver for the Federal Highway Administration: Washington, DC.

Sandhu, GS; Frey, HC (2013) Effects of Errors on Vehicle Emission Rates from Portable Emissions Measurement Systems. *Transp. Res. Rec.* **2340**: 10-19.

Sandhu, GS; Frey, HC (2011) "Real-World Measurement and Evaluation of Heavy Duty Truck Duty Cycles, Fuels, and Emission Control Technologies." *Proceedings of the 91st Annual Meeting of the Transportation Research Board*. Transportation Research Board: Washington, DC.

Sawant, AA; Nigram, A; Miller, JW; Johnson, KC; Cocker, DR (2007) Regulated and Non-Regulated Emissions from In-Use Diesel-Electric Switching Locomotives. *Environ. Sci. Technol.* **41**(17): 6074-6083.

Seinfeld, JH; Pandis, SN (1998) *Atmospheric Chemistry and Physics*; Wiley: New York, NY.

Sheehan, J; Duffield, J; Graboski, M; Shapouri, H (1998) “Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus.” *NREL-SR-580-24089*; prepared by National Renewable Energy Laboratory for U.S. Department of Energy’s Office of Fuels Development and U.S. Department of Agriculture’s Office of Energy: Washington, DC.

Signer, M; Heinze, P; Mercogliano, R; Stein, HJ (1996) “European Programme on Emissions, Fuels and Engine Technologies (EPEFE) – Heavy-Duty Diesel Study.” *Technical Paper No. 961074*; Society of Automotive Engineers: Warrendale, PA.

Singer, BC; Harley, DA; Littlejohn, D; Ho, J; Vo, T (1998) Scaling of Infrared Remote Sensor Hydrocarbon Measurements for Motor Vehicle Emission Inventory Calculations. *Environ. Sci. Technol.* **32**(21), 3241-3248.

Stephens, RD; Cadle, SH; Qian, TZ (1996) Analysis of Remote Sensing Errors of Commission and Omission under FTP Conditions. *J. Air Waste Manage. Assoc.* **46**(6), 510-516.

Stephens, RD; Mulawa, PA; Giles, MT; Kennedy, KG; Groblicki, PJ; Cadle, SH; Knapp, KT (1996) An experimental evaluation of remote sensing-based hydrocarbon measurements: A comparison to FID measurements. *J. Air Waste Manage. Assoc.* **46**(2): 148-158.

Tang, NW; Apte, JS; Martien, PT; Kirchstetter, TW (2015) Measurement of black carbon emissions from in-use diesel-electric passenger locomotives in California. *Atmospheric Environment* **115**(2015): 295-303.

Tyson, KS (2001) “Biodiesel Handling and Use Guidelines.” *NREL-TP-580-30004*; Prepared by National Renewable Energy Laboratory for U.S. Department of Energy: Washington, DC.

Unal, A; Rouphail, NM; Frey, HC (2003) Effect of Arterial Signalization and Level of Service on Measured Vehicle Emissions. *Transp. Res. Rec.* **1842**: 47-56.

Vojtisek-Lom, M; Allsop, JE (2001) “Development of Heavy-Duty Diesel Portable, On-Board Mass Exhaust Emissions Monitoring System with NO_x, CO_2, and Qualitative PM Capabilities.” *Report 2001-01-3641*; Society of Automotive Engineers: Warrenton, PA.

Vojtisek-Lom, M; Cobb, JT (1997) Vehicle Mass Emissions Measurement using a Portable 5-Gas Exhaust Analyzer and Engine Computer Data. *Proc. EPA A&WMA Emiss. Inventory Conf.*: 656-669.

Wang, WG; Lyons, DW; Clark, NN; Gautam, M (2000) Emissions from Nine Heavy Trucks Fueled by Diesel and Biodiesel Blend without Engine Modification. *Environ. Sci. Technol.* **34**(6): 933-939.

Weaver, CS (2006) “Start-up and Idling Emissions from Two Locomotives.” *Technical Report SCAQMD No. 00112*; Prepared for the South Coast Air Quality Management District, Diamond Bar, CA.

WHO (2015) “Diesel Engine Exhaust Carcinogenic.” International Agency for Research on Cancer, World Health Organization: Lyon, France. http://www.iarc.fr/en/media-centre/pr/2012/pdfs/pr213_E.pdf (accessed November 2015).

Xue, J; Grift, TE; Hansen, AC (2011) Effect of biodiesel on engine performances and emissions. *Renew. Sustain. Energy Rev.* **15**(2): 1098-1116.

Yanowitz, J (2003) Particulate Matter Emissions during Transient Locomotive Operation: Preliminary Study. *J. Air & Waste Manage. Assoc.* **53**(10): 1241-1247.

You, S; Lee, G; Ritchie, SG; Saphores, JD; Sangkapichai, M; Ayala, R (2010) Air Pollution Impacts of Shifting Freight from Truck to Rail at California’s San Pedro Bay Ports. *Transp. Res. Rec.* **2162**: 25-34.

Zhang, K (2006) “Micro-Scale On-Road Vehicle-Specific Emissions Measurements and Modeling.” *PhD Dissertation*; Department of Civil, Construction, and Environmental Engineering, North Carolina State University: Raleigh, NC.

APPENDICES

Appendix A

Locomotive Specifications

Model Designation	**F59PH**
Number Currently in NCDOT Locomotive Fleet	**4**
Prime Mover Diesel Engine	**EMD**
Model	12N-710G3
Type	Turbocharged
Total Displacement	139.6 L (8,520 in^3)
Number of Cylinders	12
Cylinder Arrangement	45° “V”
Compression Ratio	16:1
Displacement per Cylinder	11,635 cm^3 (710 in^3)
Cylinder Bore	230.19 mm (9.06 in)
Cylinder Stroke	279.4 mm (11.0 in)
Operating Principle	2 Stroke Cycle
Rotation (Facing Flywheel End)	Counterclockwise
Full Speed	904 RPM
Normal Idle Speed	343 RPM
Low Idle Speed	200 RPM
Weight	13,700 kg (30,200 lbs)

Speed and Performance Data

Maximum Speed based on Rated Speed of Traction Motors	83 mph
Overspeed Alarm and Penalty Setting	80 mph
Tractive Effort (Stall)	29,300 kg (64,500 lbs)
Tractive Effort (Continuous)	19,100 kg (42,000 lbs)
Peak Dynamic Brake Effort	12,100 kg (26,750 lbs)

Major Dimensions

Maximum Length	17.72 m (58 ft, 2 in)
Maximum Width	3.20 m (10 ft, 6 in)
Maximum Height	4.81 m (15 ft, 8.19 in)
Loaded Weight on Rail	118,000 kg (260,000 lbs)
Fuel Tank Capacity	6,820 to 8,410 L (1,500 to 1,850 gal)

Model Designation	**F59PHI**
Number Currently in NCDOT Locomotive Fleet	**2**
Prime Mover Diesel Engine	**EMD**
Model	12N-710G3B-EC
Type	Turbocharged
Total Displacement	139.6 L (8,520 in^3)
Number of Cylinders	12
Cylinder Arrangement	45° "V"
Compression Ratio	16:1
Displacement per Cylinder	11,635 cm^3 (710 in^3)
Cylinder Bore	230.19 mm (9.06 in)
Cylinder Stroke	279.4 mm (11.0 in)
Operating Principle	2 Stroke Cycle
Rotation (Facing Flywheel End)	Counterclockwise
Full Speed	904 RPM
Normal Idle Speed	343 RPM
Low Idle Speed	200 RPM
Weight	13,700 kg (30,200 lbs)

Speed and Performance Data

Maximum Speed based on Rated Speed of Traction Motors	110 mph
Overspeed Alarm and Penalty Setting	83 mph
Tractive Effort (Stall)	29,300 kg (64,500 lbs)
Tractive Effort (Continuous)	19,100 kg (42,000 lbs)
Peak Dynamic Brake Effort	12,100 kg (26,750 lbs)

Major Dimensions

Maximum Length	17.9 m (58 ft, 7 in)
Maximum Width	3.2 m (10 ft, 7.5 in)
Maximum Height	4.9 m (15 ft, 11.75 in)
Loaded Weight on Rail	124,250 kg (270,000 lbs)
Fuel Tank Capacity	8,200 L (1,800 gal)

Model Designation	**GP40**
Number Currently in NCDOT Locomotive Fleet	**0** **(*Locomotive retired from fleet in May 2010)***
Prime Mover Diesel Engine	**EMD**
Model	16-645E3
Type	Turbocharged
Total Displacement	169.1 L (10,320 in^3)
Number of Cylinders	16
Cylinder Arrangement	45° “V”
Compression Ratio	14.5:1
Displacement per Cylinder	10,570 cm^3 (645 in^3)
Cylinder Bore	230.19 mm (9.06 in)
Cylinder Stroke	254.0 mm (10.0 in)
Operating Principle	2 Stroke Cycle
Rotation (Facing Flywheel End)	Counterclockwise
Full Speed	900 RPM
Low Idle Speed	235 RPM
Normal Idle Speed	318 RPM
Weight	14,700 kg (32,500 lbs)

Speed and Performance Data

Maximum Speed based on Rated Speed of Traction Motors	103 mph
Tractive Effort (Continuous)	20,700 kg (45,700 lbs)

Major Dimensions

Maximum Length	18.0 m (59 ft, 2 in)
Maximum Width	3.0 m (10 ft, 0 in)
Maximum Height	4.7 m (15 ft, 5 in)
Loaded Weight on Rail	127,000 kg (280,000 lbs)
Fuel Tank Capacity	8,500 L (2,250 gal)

Appendix B

PEMS Calibration Accuracy Check Procedure

1. Inspect all portable emissions measurement system (PEMS) pumps for proper vacuum.
2. Clean the non-dispersive infrared (NDIR) chambers for both PEMS benches.
3. Warm up the PEMS for a minimum of sixty (60) minutes.
4. Calibrate both PEMS benches using BAR-97 LOW calibration gas.
5. Once calibration is complete, allow PEMS to run for ten (10) minutes to allow complete purging of system.
6. Run BAR-97 LOW calibration gas through system for two (2) minutes.
7. Allow PEMS to run for ten (10) minutes to allow complete purging of system.
8. Run BAR-97 HIGH calibration gas through system for two (2) minutes.
9. Allow PEMS to run for ten (10) minutes to allow complete purging of system.
10. Calibrate both PEMS benches using BAR-97 HIGH calibration gas.
11. Once calibration is complete, allow PEMS to run for ten (10) minutes to allow complete purging of system.
12. Run BAR-97 HIGH calibration gas through system for two (2) minutes.
13. Allow PEMS to run for ten (10) minutes to allow complete purging of system.
14. Run BAR-97 LOW calibration gas through system for two (2) minutes.
15. Allow PEMS to run for ten (10) minutes to allow complete purging of system.
16. Download the PEMS data and calculate average concentrations of each gas compound during Steps 6, 8, 12, and 14. Calculate the difference in measured average concentrations from calibration gas certification concentrations.

Table B-1: PEMS Calibration Accuracy Check Results

(a) Calibration with BAR-97 Low, Bench Reading with BAR-97 Low

Compound	Low Gas Certification	Bench A Reading	Bench B Reading	Average of Benches A and B
HC (ppm)	**198**	182 (-8.1%)	191 (-3.5%)	187 (-5.6%)
CO (%)	**0.50**	0.48 (-4.0%)	0.50 (0.0%)	0.49 (-2.0%)
CO_2 (%)	**6.0**	5.86 (-2.3%)	5.99 (-0.2%)	5.93 (-1.2%)
NO (ppm)	**299**	298 (-0.3%)	300 (+0.3%)	299 (0.0%)

(b) Calibration with BAR-97 Low, Bench Reading with BAR-97 High

Compound	High Gas Certification	Bench A Reading	Bench B Reading	Average of Benches A and B
HC (ppm)	**3212**	3044 (-5.2%)	3114 (-3.1%)	3079 (-4.1%)
CO (%)	**7.96**	7.78 (-2.3%)	8.06 (+1.3%)	7.92 (-0.5%)
CO_2 (%)	**12.20**	12.33 (+1.1%)	12.07 (-1.1%)	12.20 (0.0%)
NO (ppm)	**3020**	3141 (+4.0%)	3164 (+4.8%)	3153 (+4.4%)

(c) Calibration with BAR-97 High, Bench Reading with BAR-97 High

Compound	High Gas Certification	Bench A Reading	Bench B Reading	Average of Benches A and B
HC (ppm)	**3212**	3180 (-1.0%)	3184 (-0.9%)	3182 (-0.9%)
CO (%)	**7.96**	7.85 (-1.4%)	8.00 (+0.5%)	7.93 (-0.4%)
CO_2 (%)	**12.20**	12.10 (-0.8%)	12.20 (0.0%)	12.15 (-0.4%)
NO (ppm)	**3020**	3024 (+0.1%)	3021 (0.0%)	3023 (+0.1%)

(d) Calibration with BAR-97 High, Bench Reading with BAR-97 Low

Compound	Low Gas Certification	Bench A Reading	Bench B Reading	Average of Benches A and B
HC (ppm)	**198**	191 (-3.5%)	196 (-1.0%)	194 (-2.0%)
CO (%)	**0.50**	0.48 (-4.0%)	0.50 (0.0%)	0.49 (-2.0%)
CO_2 (%)	**6.0**	5.76 (-4.0%)	6.04 (+0.7%)	5.90 (-1.7%)
NO (ppm)	**299**	287 (-4.0%)	286 (-4.3%)	287 (-4.0%)

Appendix C

Engine Parameters and Emission Rates from Rail Yard Measurements

Table C-1: Measured Notch Average Engine Performance Parameters from Rail Yard Measurements of Prime Mover Engines

(a) F59PH Locomotives – EMD 12-710 Prime Mover Engine

Locomotive	Notch Position	Engine Output (kW)	Engine Speed (RPM)	IAT (K)	MAP (kPa)
NC 1810 (3 replicates)	Low Idle	7	238 (*0.00*)	331 (*0.00*)	101 (*0.01*)
	High Idle	7	386 (*0.02*)	341 (*0.00*)	110 (*0.01*)
	1	142	382 (*0.00*)	333 (*0.00*)	110 (*0.00*)
	2	261	381 (*0.00*)	335 (*0.00*)	110 (*0.01*)
	3	503	491 (*0.00*)	338 (*0.01*)	121 (*0.00*)
	4	746	565 (*0.00*)	340 (*0.00*)	132 (*0.00*)
	5	969	652 (*0.00*)	339 (*0.00*)	146 (*0.00*)
	6	1,193	729 (*0.00*)	341 (*0.00*)	162 (*0.00*)
	7	1,790	820 (*0.00*)	344 (*0.00*)	208 (*0.03*)
	8	2,013	906 (*0.00*)	346 (*0.00*)	237 (*0.00*)
NC 1859 (3 replicates)	Low Idle	7	238 (*0.00*)	335 (*0.01*)	100 (*0.00*)
	High Idle	7	370 (*0.00*)	346 (*0.00*)	108 (*0.00*)
	1	142	370 (*0.00*)	340 (*0.00*)	108 (*0.00*)
	2	261	370 (*0.00*)	342 (*0.00*)	109 (*0.00*)
	3	503	492 (*0.00*)	345 (*0.00*)	120 (*0.00*)
	4	746	565 (*0.00*)	346 (*0.00*)	129 (*0.01*)
	5	969	653 (*0.00*)	345 (*0.00*)	143 (*0.01*)
	6	1,193	731 (*0.00*)	348 (*0.00*)	158 (*0.01*)
	7	1,790	822 (*0.00*)	349 (*0.00*)	181 (*0.02*)
	8	2,013	904 (*0.00*)	351 (*0.00*)	228 (*0.01*)
NC 1869 (3 replicates)	Low Idle	7	240 (*0.00*)	335 (*0.01*)	104 (*0.00*)
	High Idle	7	372 (*0.00*)	340 (*0.02*)	112 (*0.01*)
	1	142	372 (*0.00*)	336 (*0.01*)	112 (*0.01*)
	2	261	372 (*0.00*)	337 (*0.01*)	112 (*0.00*)
	3	503	494 (*0.00*)	339 (*0.02*)	124 (*0.01*)
	4	746	566 (*0.00*)	340 (*0.02*)	133 (*0.01*)
	5	969	653 (*0.00*)	340 (*0.02*)	147 (*0.01*)
	6	1,193	732 (*0.00*)	341 (*0.02*)	162 (*0.01*)
	7	1,790	823 (*0.00*)	345 (*0.03*)	194 (*0.02*)
	8	2,013	906 (*0.00*)	347 (*0.04*)	222 (*0.01*)
NC 1893 (3 replicates)	Low Idle	7	201 (*0.00*)	337 (*0.00*)	103 (*0.00*)
	High Idle	7	351 (*0.00*)	344 (*0.00*)	112 (*0.00*)
	1	142	351 (*0.00*)	337 (*0.00*)	112 (*0.00*)
	2	261	350 (*0.00*)	341 (*0.00*)	112 (*0.00*)
	3	503	492 (*0.00*)	344 (*0.00*)	126 (*0.00*)
	4	746	571 (*0.00*)	345 (*0.00*)	137 (*0.00*)
	5	969	654 (*0.00*)	341 (*0.00*)	150 (*0.00*)
	6	1,193	734 (*0.00*)	347 (*0.00*)	167 (*0.00*)
	7	1,790	829 (*0.00*)	351 (*0.00*)	229 (*0.01*)
	8	2,013	911 (*0.00*)	351 (*0.00*)	254 (*0.01*)

(b) F59PHI Locomotives – EMD 12-710 Prime Mover Engine

Locomotive	Notch Position	Engine Output (kW)	Engine Speed (RPM)	IAT (K)	MAP (kPa)
NC 1755 (2 replicates)	Idle	7	343 (*0.00*)	324 (*0.01*)	108 (*0.02*)
	1	142	343 (*0.00*)	323 (*0.00*)	108 (*0.02*)
	2	261	343 (*0.00*)	322 (*0.00*)	108 (*0.02*)
	3	503	490 (*0.00*)	322 (*0.00*)	122 (*0.02*)
	4	746	651 (*0.00*)	324 (*0.00*)	145 (*0.02*)
	5	969	750 (*0.00*)	329 (*0.00*)	166 (*0.02*)
	6	1,230	750 (*0.00*)	327 (*0.00*)	168 (*0.02*)
	7	1,899	820 (*0.00*)	329 (*0.01*)	215 (*0.02*)
	8	2,256	903 (*0.00*)	330 (*0.00*)	249 (*0.02*)
NC 1797 (4 replicates)	Idle	7	343 (*0.00*)	314 (*0.01*)	108 (*0.01*)
	1	142	343 (*0.00*)	314 (*0.00*)	108 (*0.01*)
	2	261	343 (*0.00*)	313 (*0.01*)	108 (*0.01*)
	3	503	490 (*0.00*)	314 (*0.01*)	122 (*0.01*)
	4	746	651 (*0.00*)	315 (*0.00*)	146 (*0.01*)
	5	969	750 (*0.00*)	319 (*0.00*)	167 (*0.01*)
	6	1,193	750 (*0.00*)	318 (*0.00*)	169 (*0.01*)
	7	1,790	820 (*0.00*)	319 (*0.01*)	207 (*0.00*)
	8	2,013	904 (*0.00*)	321 (*0.00*)	232 (*0.02*)

(c) GP40 Locomotive – EMD 16-645 Prime Mover Engine

Locomotive	Notch Position	Engine Output (kW)	Engine Speed (RPM)	IAT (K)	MAP (kPa)
NC 1792 (1 replicate)	Idle	15	252	291	106
	1	142	319	290	110
	2	257	383	290	114
	3	503	501	290	126
	4	746	566	290	135
	5	969	661	290	150
	6	1,193	728	290	164
	7	1,790	828	290	189
	8	2,013	901	290	209

Italicized values in parentheses are coefficients of variation on the mean emission rate.

Table C-2: Engine Output-Based Notch Average Emission Rates from Rail Yard Measurements of Prime Mover Engines

(a) F59PH Locomotives – EMD 12-710 Prime Mover Engine

Locomotive	Notch Position	NO as NO_2 (g/kW-hr)	HC (g/kW-hr)	CO (g/kW-hr)	Opacity-based PM (g/kW-hr)	CO_2 (g/kW-hr)
NC 1810 (3 replicates)	Low Idle	97.4 (*0.08*)	307 (*0.06*)	39.7 (*0.27*)	3.89 (*0.05*)	2805 (*0.07*)
	High Idle	129 (*0.05*)	429 (*0.03*)	44.4 (*0.21*)	4.53 (*0.11*)	5105 (0.05)
	1	13.8 (*0.05*)	15.0 (*0.08*)	1.62 (*0.35*)	0.34 (*0.02*)	611 (*0.01*)
	2	13.6 (*0.04*)	9.41 (*0.10*)	0.99 (*0.44*)	0.23 (*0.02*)	499 (*0.00*)
	3	13.3 (*0.01*)	6.42 (*0.17*)	0.50 (*0.35*)	0.18 (*0.02*)	459 (*0.01*)
	4	12.3 (*0.01*)	4.46 (*0.12*)	0.43 (*0.75*)	0.20 (*0.03*)	454 (*0.01*)
	5	11.7 (*0.02*)	2.73 (*0.11*)	0.31 (*0.68*)	0.23 (*0.03*)	452 (*0.00*)
	6	11.4 (*0.01*)	5.69 (*0.16*)	0.37 (*0.97*)	0.20 (*0.01*)	466 (*0.01*)
	7	9.32 (*0.04*)	2.71 (*0.46*)	1.43 (*0.33*)	0.31 (*0.10*)	470 (*0.00*)
	8	9.01 (*0.01*)	1.68 (*0.25*)	1.74 (*0.06*)	0.47 (*0.15*)	524 (*0.00*)
NC 1859 (3 replicates)	Low Idle	92.9 (*0.02*)	110 (*0.26*)	32.7 (*0.29*)	9.11 (*0.04*)	3411 (*0.02*)
	High Idle	111 (*0.00*)	685 (*0.37*)	352 (*0.46*)	8.48 (*0.02*)	5049 (*0.02*)
	1	13.2 (*0.02*)	12.1 (*0.15*)	2.57 (*0.31*)	0.69 (*0.02*)	685 (*0.01*)
	2	12.8 (*0.04*)	10.8 (*0.08*)	2.19 (*0.04*)	0.48 (*0.01*)	562 (*0.01*)
	3	12.0 (*0.03*)	8.97 (*0.08*)	1.90 (*0.09*)	0.37 (*0.02*)	504 (*0.00*)
	4	10.6 (*0.02*)	7.55 (*0.18*)	1.97 (*0.34*)	0.34 (*0.02*)	488 (*0.03*)
	5	9.92 (*0.03*)	3.36 (*0.87*)	0.87 (*0.91*)	0.35 (*0.02*)	478 (*0.01*)
	6	10.0 (*0.06*)	0.00 (*0.00*)	0.91 (*0.25*)	0.39 (*0.02*)	504 (*0.02*)
	7	8.92 (*0.09*)	4.85 (*1.12*)	3.26 (*0.85*)	0.49 (*0.05*)	523 (*0.03*)
	8	7.80 (*0.04*)	5.35 (*0.18*)	2.68 (*0.04*)	0.49 (*0.02*)	511 (*0.00*)
NC 1869 (3 replicates)	Low Idle	111 (*0.11*)	30.9 (0.56)	4.69 (*0.68*)	6.40 (*0.17*)	3706 (*0.03*)
	High Idle	206 (*0.22*)	77.4 (0.38)	8.18 (*1.06*)	10.0 (*0.17*)	7951 (*0.13*)
	1	18.7 (*0.05*)	2.22 (0.17)	0.55 (*0.26*)	0.73 (*0.08*)	713 (*0.04*)
	2	19.3 (*0.05*)	1.72 (0.67)	0.18 (*0.17*)	0.45 (*0.08*)	571 (*0.04*)
	3	17.4 (*0.04*)	0.98 (0.25)	0.09 (*0.34*)	0.31 (*0.07*)	497 (*0.05*)
	4	16.3 (*0.04*)	0.76 (0.27)	0.20 (*0.73*)	0.28 (*0.10*)	480 (*0.05*)
	5	15.1 (*0.06*)	0.47 (0.21)	0.24 (*0.62*)	0.29 (*0.10*)	483 (*0.05*)
	6	14.2 (*0.06*)	0.42 (0.87)	0.26 (*0.48*)	0.28 (*0.11*)	480 (*0.05*)
	7	11.0 (*0.06*)	0.45 (0.81)	1.05 (*0.18*)	0.42 (*0.14*)	476 (*0.04*)
	8	10.1 (*0.08*)	0.51 (0.33)	1.69 (*0.25*)	0.68 (*0.09*)	515 (*0.06*)
NC 1893 (3 replicates)	Low Idle	101 (*0.17*)	49.7 (*0.36*)	2.92 (*0.15*)	6.13 (*0.50*)	3227 (*0.08*)
	High Idle	128 (*0.01*)	117 (*0.12*)	2.20 (*0.56*)	10.4 (*0.23*)	6037 (*0.10*)
	1	17.6 (*0.03*)	2.67 (*0.29*)	0.62 (*0.37*)	0.63 (*0.71*)	747 (*0.03*)
	2	17.2 (*0.03*)	1.55 (*0.21*)	0.32 (*0.48*)	0.40 (*0.77*)	595 (*0.03*)
	3	15.8 (*0.02*)	1.05 (*0.28*)	0.15 (*0.30*)	0.27 (*0.69*)	515 (*0.01*)
	4	14.8 (*0.02*)	0.74 (*0.04*)	0.15 (*0.18*)	0.30 (*0.38*)	504 (*0.00*)
	5	14.1 (*0.03*)	0.57 (*0.19*)	0.25 (*0.09*)	0.33 (*0.04*)	519 (*0.02*)
	6	13.4 (*0.03*)	0.70 (*0.08*)	0.18 (*0.10*)	0.29 (*0.05*)	522 (*0.01*)
	7	10.8 (*0.02*)	0.61 (*0.11*)	0.44 (*0.14*)	0.28 (*0.13*)	496 (*0.02*)
	8	9.72 (*0.05*)	0.71 (*0.36*)	0.58 (*0.13*)	0.32 (*0.12*)	528 (*0.02*)

(b) F59PHI Locomotives – EMD 12-710 Prime Mover Engine

Locomotive	Notch Position	NO as NO_2 (g/kW-hr)	HC (g/kW-hr)	CO (g/kW-hr)	Opacity-based PM (g/kW-hr)	CO_2 (g/kW-hr)
NC 1755 (2 replicates)	Idle	231 (*0.00*)	129 (*0.32*)	1.89 (*0.86*)	n/a	4234 (*0.03*)
	1	30.6 (*0.02*)	14.1 (*0.10*)	0.09 (*0.99*)	n/a	615 (*0.01*)
	2	28.0 (*0.02*)	8.93 (*0.10*)	0.01 (*0.17*)	n/a	511 (*0.03*)
	3	16.9 (*0.03*)	6.82 (*0.31*)	0.05 (*1.34*)	n/a	450 (*0.01*)
	4	13.6 (*0.10*)	5.59 (*0.56*)	0.40 (*1.29*)	n/a	456 (*0.01*)
	5	15.2 (*0.08*)	2.85 (*1.04*)	0.04 (*0.52*)	n/a	448 (*0.03*)
	6	12.7 (*0.02*)	5.46 (*1.33*)	0.00 (*1.41*)	n/a	449 (*0.00*)
	7	10.1 (*0.02*)	5.17 (*1.29*)	0.54 (*0.32*)	n/a	460 (*0.00*)
	8	11.5 (*0.03*)	4.38 (*1.22*)	2.24 (*0.49*)	n/a	488 (*0.03*)
NC 1797 (3 replicates)	Idle	188 (*0.11*)	81.5 (*0.21*)	7.70 (*0.69*)	6.55 (*0.06*)	3141 (*0.14*)
	1	26.2 (*0.09*)	1.19 (*0.68*)	0.49 (*0.90*)	0.49 (*0.03*)	549 (*0.05*)
	2	24.8 (*0.04*)	1.91 (*0.77*)	0.33 (*0.56*)	0.25 (*0.04*)	452 (*0.05*)
	3	17.7 (*0.01*)	0.41 (*0.25*)	0.08 (*1.24*)	0.15 (*0.03*)	427 (*0.01*)
	4	14.3 (*0.01*)	0.47 (*0.36*)	0.03 (*1.48*)	0.12 (*0.04*)	444 (*0.00*)
	5	15.3 (*0.02*)	0.29 (*0.14*)	0.01 (*1.23*)	0.10 (*0.03*)	463 (*0.01*)
	6	14.5 (*0.06*)	1.39 (*0.77*)	0.01 (*1.63*)	0.09 (*0.02*)	447 (*0.06*)
	7	12.1 (*0.00*)	0.61 (*0.33*)	0.11 (*0.57*)	0.25 (*0.02*)	487 (*0.02*)
	8	12.8 (*0.01*)	0.90 (*0.93*)	1.19 (*0.17*)	0.25 (*0.06*)	504 (*0.01*)

(c) GP40 Locomotive – EMD 16-645 Prime Mover Engine

Locomotive	Notch Position	NO as NO_2 (g/kW-hr)	HC (g/kW-hr)	CO (g/kW-hr)	Opacity-based PM (g/kW-hr)	CO_2 (g/kW-hr)
NC 1792 (1 replicate)	Idle	47.6	33.5	32.6	6.28	2354
	1	10.4	10.0	5.91	0.93	472
	2	10.1	6.85	2.91	1.23	548
	3	9.24	3.64	1.38	1.02	473
	4	10.4	1.96	0.47	0.91	466
	5	10.9	1.64	1.07	0.86	513
	6	11.7	1.28	1.12	1.09	559
	7	10.2	0.87	0.73	1.25	531
	8	9.01	2.25	0.54	1.97	485

Italicized values in parentheses are coefficients of variation on the mean emission rate.

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

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

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

Appendix D

Piedmont Duty Cycles

Numerous factors can lead to variations in observed duty cycles and travel time, including: (1) differences in operating behavior among engineers; (2) slow orders because of weather or track repair; (3) allowing other rail traffic to pass by changing tracks or stopping on a siding; and (4) stopping due to malfunctioning rail crossing gates and signals, or locomotive mechanical difficulties. Multiple engineers operated the locomotives during OTR measurements. Some engineers downshifted to Notches 1 through 4, rather than using dynamic brake, to slow the train. Some engineers utilized Notch 6 more frequently during acceleration and deceleration, with proportionally less time in other notches, such as Notch 8. Planned slow orders, which affect all rail traffic passing over a specific rail segment for an extended period of time, were prevalent during most OTR measurements because of on-going rail improvement projects. Often, dispatchers instruct passenger trains to change tracks to bypass slow-moving freight traffic. To safely traverse rail switches, locomotives must reduce speed. While rare, locomotives may have to stop because of malfunctioning rail crossing safety equipment or mechanical breakdowns, which increase travel time and percentage of time spent in idle.

Table D-1: Piedmont Duty Cycles Based on Time in Each Notch Position During Over-the-Rail Measurements of the F59PH Locomotives in the NCDOT Fleet

Date:	June 26, 2012		June 26, 2012		June 28, 2012		June 28, 2012		June 29, 2012	
Train:	73		74		73		74		73	
Locomotive:	NC 1893		NC 1893		NC 1893		NC 1893		NC 1893	
	time (s)	%	time (s)	%	time (s)	%	time (s)	%	time (s)	%
DB	1557	13.8	1650	14.2	1019	8.9	1450	12.6	2034	16.6
Idle	3277	29.1	4029	34.8	1218	10.6	3213	28.0	3504	28.6
1	665	5.9	159	1.4	605	5.3	149	1.3	379	3.1
2	588	5.2	287	2.5	1017	8.8	204	1.8	483	3.9
3	209	1.9	295	2.5	946	8.2	292	2.5	389	3.2
4	165	1.5	270	2.3	660	5.7	212	1.8	475	3.9
5	122	1.1	166	1.4	104	0.9	193	1.7	257	2.1
6	81	0.7	112	1.0	93	0.8	18	0.2	179	1.5
7	12	0.1	11	0.1	10	0.1	16	0.1	86	0.7
8	4593	40.8	4601	39.7	5826	50.7	5746	50.0	4445	36.3

Date:	June 29, 2012		June 30, 2012		June 30, 2012		May 2, 2013		May 2, 2013	
Train:	74		73		74		73		74	
Locomotive:	NC 1893		NC 1893		NC 1893		NC 1893		NC 1893	
	time (s)	%	time (s)	%	time (s)	%	time (s)	%	time (s)	%
DB	1942	16.0	1462	12.9	447	3.8	975	6.3	1015	9.2
Idle	4354	35.8	2610	23.1	2577	21.9	6316	40.6	2360	21.4
1	456	3.7	557	4.9	947	8.0	437	2.8	414	3.8
2	558	4.6	378	3.3	981	8.3	1008	6.5	1182	10.7
3	312	2.6	188	1.7	520	4.4	1196	7.7	295	2.7
4	417	3.4	248	2.2	747	6.3	957	6.2	1254	11.4
5	118	1.0	115	1.0	101	0.9	256	1.6	433	3.9
6	103	0.8	54	0.5	111	0.9	222	1.4	1114	10.1
7	64	0.5	12	0.1	22	0.2	29	0.2	144	1.3
8	3840	31.6	5680	50.2	5314	45.2	4151	26.7	2800	25.4

Date:	May 3, 2013		May 3, 2013		May 4, 2013		May 4, 2013		July 1, 2013	
Train:	73		74		73		74		73	
Locomotive:	NC 1893		NC 1893		NC 1893		NC 1893		NC 1893	
	time (s)	%	time (s)	%	time (s)	%	time (s)	%	time (s)	%
DB	1823	16.4	1784	15.0	1543	13.7	933	7.9	2277	18.6
Idle	2795	25.2	3973	33.5	2729	24.2	2092	17.7	3812	31.2
1	225	2.0	130	1.1	459	4.1	592	5.0	374	3.1
2	366	3.3	286	2.4	451	4.0	930	7.9	444	3.6
3	614	5.5	500	4.2	214	1.9	918	7.8	527	4.3
4	431	3.9	396	3.3	220	2.0	914	7.7	422	3.5
5	495	4.5	431	3.6	138	1.2	269	2.3	446	3.6
6	317	2.9	211	1.8	88	0.8	104	0.9	623	5.1
7	121	1.1	62	0.5	54	0.5	33	0.3	100	0.8
8	3910	35.2	4091	34.5	5367	47.7	5024	42.5	3202	26.2

Date:	July 1, 2013		July 3, 2013		July 3, 2013		July 4, 2013		July 4, 2013	
Train:	74		73		74		73		74	
Locomotive:	NC 1893		NC 1893		NC 1893		NC 1893		NC 1893	
	time (s)	%	time (s)	%	time (s)	%	time (s)	%	time (s)	%
DB	1493	13.2	1853	16.5	1886	15.9	1502	13.4	1175	10.7
Idle	2953	26.1	2719	24.2	4216	35.5	1535	13.7	2398	21.8
1	672	5.9	532	4.7	143	1.2	332	3.0	512	4.7
2	532	4.7	469	4.2	380	3.2	1273	11.3	1048	9.5
3	373	3.3	439	3.9	571	4.8	1202	10.7	457	4.2
4	358	3.2	627	5.6	358	3.0	649	5.8	1095	10.0
5	365	3.2	440	3.9	384	3.2	266	2.4	426	3.9
6	384	3.4	632	5.6	364	3.1	125	1.1	1206	11.0
7	117	1.0	200	1.8	184	1.5	32	0.3	187	1.7
8	4081	36.0	3302	29.4	3394	28.6	4319	38.4	2497	22.7

Date:	**August 30, 2013**		**August 30, 2013**		**August 31, 2013**		**August 31, 2013**		**September 2, 2013**	
Train:	**75**		**76**		**73**		**74**		**73**	
Locomotive:	**NC 1859**		**NC 1859**		**NC 1859**		**NC 1859**		**NC 1859**	
	time (s)	**%**	**time (s)**	**%**	**time (s)**	**%**	**time (s)**	**%**	**time (s)**	**%**
DB	1523	11.8	1798	14.0	1595	13.8	1104	9.5	1683	14.7
Idle	4267	33.0	4724	36.7	2542	22.0	1786	15.3	3308	28.9
1	198	1.5	79	0.6	458	4.0	766	6.6	85	0.7
2	309	2.4	219	1.7	345	3.0	954	8.2	255	2.2
3	535	4.1	366	2.8	206	1.8	831	7.1	289	2.5
4	524	4.1	302	2.3	161	1.4	263	2.3	524	4.6
5	308	2.4	269	2.1	184	1.6	209	1.8	371	3.2
6	274	2.1	385	3.0	52	0.4	82	0.7	431	3.8
7	61	0.5	152	1.2	9	0.1	34	0.3	182	1.6
8	4927	38.1	4594	35.6	6014	52.0	5650	48.4	4306	37.7

Date:	**September 2, 2013**		**September 6, 2013**		**September 6, 2013**		**September 7, 2013**		**September 7, 2013**	
Train:	**74**		**73**		**74**		**73**		**74**	
Locomotive:	**NC 1859**		**NC 1893**		**NC 1893**		**NC 1893**		**NC 1893**	
	time (s)	**%**	**time (s)**	**%**	**time (s)**	**%**	**time (s)**	**%**	**time (s)**	**%**
DB	1516	13.4	1922	17.3	1773	14.8	1506	13.4	1174	10.5
Idle	3218	28.5	2876	25.8	3955	33.0	2778	24.7	2059	18.4
1	371	3.3	121	1.1	257	2.1	397	3.5	808	7.2
2	315	2.8	321	2.9	299	2.5	465	4.1	804	7.2
3	177	1.6	398	3.6	137	1.1	241	2.1	708	6.3
4	182	1.6	292	2.6	93	0.8	151	1.3	339	3.0
5	102	0.9	360	3.2	64	0.5	233	2.1	177	1.6
6	81	0.7	295	2.6	50	0.4	122	1.1	126	1.1
7	14	0.1	184	1.7	23	0.2	32	0.3	8	0.1
8	5310	47.0	4373	39.2	5341	44.5	5338	47.4	5006	44.7

Date:	**September 9, 2013**		**September 9, 2013**		**March 20, 2014**		**March 20, 2014**		**March 21, 2014**	
Train:	**73**		**74**		**73**		**74**		**73**	
Locomotive:	**NC 1893**		**NC 1893**		**NC 1810**		**NC 1810**		**NC 1810**	
	time (s)	**%**	**time (s)**	**%**	**time (s)**	**%**	**time (s)**	**%**	**time (s)**	**%**
DB	1458	12.7	1991	13.4	1962	17.4	1126	10.0	1762	15.1
Idle	4134	36.1	6904	46.3	2738	24.3	2472	22.0	3245	27.9
1	343	3.0	219	1.5	198	1.8	1577	14.0	358	3.1
2	360	3.1	393	2.6	731	6.5	885	7.9	189	1.6
3	565	4.9	356	2.4	223	2.0	378	3.4	217	1.9
4	455	4.0	263	1.8	280	2.5	801	7.1	334	2.9
5	419	3.7	584	3.9	42	0.4	359	3.2	250	2.1
6	377	3.3	296	2.0	118	1.0	801	7.1	258	2.2
7	108	0.9	196	1.3	4	0.0	278	2.5	92	0.8
8	3222	28.2	3695	24.8	4994	44.2	2571	22.9	4941	42.4

Date:	**March 21, 2014**		**March 22, 2014**		**March 22, 2014**	
Train:	**74**		**73**		**74**	
Locomotive:	**NC 1810**		**NC 1810**		**NC 1810**	
	time (s)	**%**	**time (s)**	**%**	**time (s)**	**%**
DB	2002	15.7	1489	13.6	1115	9.8
Idle	4297	33.8	3110	28.3	2220	19.6
1	225	1.8	266	2.4	1117	9.8
2	414	3.3	285	2.6	960	8.5
3	584	4.6	153	1.4	728	6.4
4	604	4.7	185	1.7	502	4.4
5	310	2.4	43	0.4	291	2.6
6	367	2.9	77	0.7	145	1.3
7	85	0.7	36	0.3	25	0.2
8	3839	30.2	5328	48.6	4248	37.4

Table D-2: Piedmont Duty Cycles Based on Time in Each Notch Position During Over-the-Rail Measurements of the F59PHI Locomotives in the NCDOT Fleet

Date:	**October 10, 2012**		**October 10, 2012**		**October 11, 2012**		**October 11, 2012**		**October 9, 2013**	
Train:	**73**		**74**		**73**		**74**		**75**	
Locomotive:	**NC 1797**		**NC 1797**		**NC 1755**		**NC 1755**		**NC 1797**	
	time (s)	**%**	**time (s)**	**%**	**time (s)**	**%**	**time (s)**	**%**	**time (s)**	**%**
DB	417	3.62	112	0.92	0	0	176	1.48	325	2.83
Idle	4669	40.58	6291	51.76	2837	23.92	3692	31.03	4497	39.22
1	297	2.58	270	2.22	905	7.63	409	3.44	253	2.21
2	358	3.11	310	2.55	904	7.62	963	8.09	222	1.94
3	509	4.42	486	4	1219	10.28	272	2.29	290	2.53
4	520	4.52	400	3.29	537	4.53	1267	10.65	273	2.38
5	528	4.59	179	1.47	272	2.29	200	1.68	295	2.57
6	318	2.76	208	1.71	62	0.52	1209	10.16	238	2.08
7	79	0.69	41	0.34	307	2.59	256	2.15	124	1.08
8	3811	33.12	3858	31.74	4818	40.62	3453	29.02	4948	43.16

Date:	**October 9, 2013**		**October 10, 2013**		**October 10, 2013**		**October 11, 2013**		**October 11, 2013**	
Train:	**76**		**75**		**76**		**75**		**76**	
Locomotive:	**NC 1797**		**NC 1797**		**NC 1797**		**NC 1797**		**NC 1797**	
	time (s)	**%**	**time (s)**	**%**	**time (s)**	**%**	**time (s)**	**%**	**time (s)**	**%**
DB	563	4.52	345	3.01	401	3.39	383	3.12	855	6.96
Idle	5057	40.61	3489	30.43	2744	23.22	4755	38.71	4640	37.79
1	408	3.28	112	0.98	936	7.92	236	1.92	212	1.73
2	247	1.98	1063	9.27	1172	9.92	237	1.93	311	2.53
3	237	1.9	346	3.02	607	5.14	86	0.7	328	2.67
4	373	3	644	5.62	521	4.41	191	1.55	149	1.21
5	388	3.12	206	1.8	247	2.09	206	1.68	128	1.04
6	396	3.18	224	1.95	189	1.6	188	1.53	259	2.11
7	461	3.7	15	0.13	22	0.19	106	0.86	171	1.39
8	4323	34.71	5020	43.79	4978	42.13	5896	48	5225	42.56

Table D-3: Piedmont Duty Cycles Based on Time in each Notch Position During Over-the-Rail Measurements of the GP40 Locomotive in the NCDOT Fleet

Date:	**April 29, 2010**		**April 29, 2010**		**April 30, 2010**		**April 30, 2010**	
Train:	**73**		**76**		**73**		**76**	
Locomotive:	**NC 1792**		**NC 1792**		**NC 1792**		**NC 1792**	
	time (s)	**%**	**time (s)**	**%**	**time (s)**	**%**	**time (s)**	**%**
DB	1420	11.6	1681	13.4	1565	12.7	2188	17.7
Idle	2570	20.9	2950	23.5	3454	28.1	3268	26.4
1	627	5.1	549	4.4	939	7.6	1082	8.7
2	465	3.8	609	4.8	548	4.5	594	4.8
3	259	2.1	371	2.9	239	1.9	190	1.5
4	461	3.8	735	5.8	109	0.9	287	2.3
5	361	2.9	271	2.2	104	0.8	213	1.7
6	288	2.3	323	2.6	143	1.2	205	1.7
7	261	2.1	107	0.9	35	0.3	81	0.7
8	5576	45.4	4981	39.6	5149	41.9	4281	34.6

Date:	**May 1, 2010**		**May 1, 2010**	
Train:	**73**		**76**	
Locomotive:	**NC 1792**		**NC 1792**	
	time (s)	**%**	**time (s)**	**%**
DB	1830	14.8	2018	17.2
Idle	3184	25.8	2898	24.7
1	210	1.7	325	2.8
2	451	3.7	489	4.2
3	323	2.6	447	3.8
4	287	2.3	336	2.9
5	441	3.6	273	2.3
6	323	2.6	188	1.6
7	195	1.6	161	1.4
8	5083	41.2	4614	39.3

Appendix E

Engine Parameters and Emission Rates from Over-the-Rail Measurements

Table E-1: Measured Notch Average Engine Performance Parameters from Over-the-Rail Measurements of Prime Mover Engines

(a) F59PH Locomotives – EMD 12-710 Prime Mover Engine

Locomotive	Notch Position	Output (kW)	Speed (RPM)	IAT (K)	MAP (kPa)
NC 1810 (6 trips)	Low Idle	7	238 (*0.00*)	339 (*0.01*)	98 (*0.01*)
	High Idle	7	384 (*0.01*)	342 (*0.01*)	108 (*0.01*)
	DB	7	389 (*0.05*)	341 (*0.01*)	108 (*0.01*)
	1	142	379 (*0.01*)	341 (*0.01*)	109 (*0.00*)
	2	261	380 (*0.00*)	342 (*0.01*)	109 (*0.01*)
	3	503	484 (*0.01*)	342 (*0.01*)	119 (*0.00*)
	4	746	557 (*0.00*)	343 (*0.01*)	129 (*0.00*)
	5	969	651 (*0.00*)	344 (*0.01*)	146 (*0.00*)
	6	1,193	725 (*0.01*)	344 (*0.01*)	158 (*0.00*)
	7	2,013	823 (*0.00*)	346 (*0.01*)	194 (*0.03*)
	8	2,237	905 (*0.00*)	346 (*0.01*)	241 (*0.00*)
NC 1859 (6 trips)	Low Idle	7	237 (*0.00*)	343 (*0.01*)	100 (*0.00*)
	High Idle	7	369 (*0.00*)	348 (*0.01*)	108 (*0.00*)
	DB	7	386 (*0.04*)	348 (*0.01*)	109 (*0.00*)
	1	142	369 (*0.00*)	349 (*0.00*)	110 (*0.00*)
	2	261	369 (*0.00*)	347 (*0.01*)	110 (*0.00*)
	3	503	491 (*0.00*)	348 (*0.01*)	122 (*0.00*)
	4	746	564 (*0.00*)	349 (*0.01*)	132 (*0.01*)
	5	969	651 (*0.00*)	350 (*0.01*)	146 (*0.01*)
	6	1,193	728 (*0.00*)	350 (*0.01*)	160 (*0.01*)
	7	2,013	819 (*0.00*)	350 (*0.01*)	179 (*0.02*)
	8	2,237	902 (*0.00*)	352 (*0.01*)	227 (*0.01*)
NC 1869 (2 trips)	Idle	7	370 (*0.00*)	308 (*0.00*)	109 (*0.00*)
	1	142	370 (*0.00*)	307 (*0.00*)	110 (*0.01*)
	2	261	369 (*0.00*)	307 (*0.00*)	110 (*0.00*)
	3	503	492 (*0.00*)	308 (*0.00*)	121 (*0.00*)
	4	746	564 (*0.00*)	308 (*0.00*)	129 (*0.01*)
	5	969	653 (*0.00*)	308 (*0.00*)	143 (*0.00*)
	6	1,193	731 (*0.00*)	308 (*0.00*)	157 (*0.01*)
	7	2,013	821 (*0.00*)	308 (*0.00*)	176 (*0.02*)
	8	2,237	904 (*0.00*)	308 (*0.00*)	218 (*0.02*)

NC 1893 (14 trips)	Low Idle	7	198 (*0.00*)	338 (*0.03*)	102 (*0.01*)
	High Idle	7	349 (*0.00*)	342 (*0.03*)	110 (*0.01*)
	DB	7	368 (*0.07*)	341 (*0.03*)	111 (*0.02*)
	1	142	349 (*0.00*)	341 (*0.03*)	110 (*0.01*)
	2	261	347 (*0.00*)	342 (*0.03*)	111 (*0.01*)
	3	503	489 (*0.00*)	342 (*0.03*)	123 (*0.01*)
	4	746	568 (*0.00*)	343 (*0.03*)	135 (*0.01*)
	5	969	651 (*0.00*)	344 (*0.03*)	147 (*0.01*)
	6	1,193	731 (*0.00*)	344 (*0.03*)	163 (*0.01*)
	7	2,013	825 (*0.00*)	351 (*0.01*)	199 (*0.09*)
	8	2,237	907 (*0.00*)	346 (*0.03*)	239 (*0.02*)

(b) F59PHI Locomotives – EMD 12-710 Prime Mover Engine

Locomotive	Notch Position	Output (kW)	Speed (RPM)	IAT (K)	MAP (kPa)
NC 1755 (1 trip)	Idle	7	343	319	109
	DB	7	343	319	109
	1	142	342	319	109
	2	261	342	320	110
	3	503	489	320	124
	4	746	651	321	149
	5	969	748	319	170
	6	1,193	749	322	172
	7	2,013	818	322	197
	8	2,237	903	324	234
NC 1797 (6 trips)	Idle	7	343 (*0.00*)	320 (*0.00*)	106 (*0.01*)
	DB	7	343 (*0.00*)	320 (*0.01*)	106 (*0.01*)
	1	142	343 (*0.00*)	321 (*0.00*)	106 (*0.00*)
	2	261	343 (*0.00*)	321 (*0.00*)	106 (*0.01*)
	3	503	490 (*0.00*)	321 (*0.01*)	120 (*0.01*)
	4	746	651 (*0.00*)	321 (*0.00*)	144 (*0.01*)
	5	969	750 (*0.00*)	321 (*0.01*)	164 (*0.01*)
	6	1,193	750 (*0.00*)	321 (*0.00*)	165 (*0.01*)
	7	2,013	819 (*0.00*)	322 (*0.00*)	185 (*0.01*)
	8	2,237	903 (*0.00*)	322 (*0.00*)	216 (*0.01*)

(c) GP40 Locomotive – EMD 16-645 Prime Mover Engine

Locomotive	Notch Position	Output (kW)	Speed (RPM)	IAT (K)	MAP (kPa)
NC 1792 (6 trips)	Idle	15	297	284	104
	DB	15	536	286	128
	1	142	323	284	106
	2	261	381	284	110
	3	503	500	284	125
	4	746	566	283	132
	5	969	657	282	147
	6	1,193	725	282	161
	7	2,013	826	288	188
	8	2,237	899	286	213

Italicized values in parentheses are coefficients of variation on the mean emission rate.
DB: Dynamic Brake

Table E-2: Engine Output-Based Notch Average Emission Rates from Over-the-Rail Measurements of Prime Mover Engines

(a) F59PH Locomotives – EMD 12-710 Prime Mover Engine

Locomotive	Notch Position	NO as NO_2 (g/kW-hr)	HC (g/kW-hr)	CO (g/kW-hr)	Opacity-based PM (g/kW-hr)	CO_2 (g/kW-hr)
NC 1810 (6 trips)	Low Idle	95.8 (*0.09*)	204 (*0.34*)	31.1 (*0.30*)	3.98 (*0.09*)	3043 (*0.08*)
	High Idle	156 (*0.07*)	333 (*0.33*)	46.0 (*0.29*)	5.03 (*0.05*)	5834 (*0.10*)
	DB	149 (*0.09*)	342 (*0.26*)	52.2 (*0.48*)	4.39 (*0.04*)	6045 (*0.11*)
	1	14.1 (*0.08*)	17.7 (*0.44*)	2.73 (*0.41*)	0.35 (*0.04*)	578 (*0.08*)
	2	12.3 (*0.11*)	8.21 (*0.25*)	1.31 (*0.18*)	0.26 (*0.07*)	468 (*0.07*)
	3	11.7 (*0.09*)	6.68 (*0.41*)	0.88 (*0.28*)	0.24 (*0.10*)	458 (*0.05*)
	4	10.9 (*0.04*)	4.35 (*0.40*)	0.80 (*0.36*)	0.28 (*0.08*)	449 (*0.04*)
	5	11.0 (*0.03*)	9.19 (*1.37*)	0.97 (*0.56*)	0.26 (*0.19*)	449 (*0.06*)
	6	10.4 (*0.06*)	4.53 (*0.35*)	1.02 (*0.47*)	0.26 (*0.16*)	485 (*0.04*)
	7	7.34 (*0.15*)	3.64 (*0.41*)	1.41 (*0.56*)	0.35 (*0.19*)	401 (*0.05*)
	8	7.63 (*0.03*)	2.08 (*0.37*)	2.08 (*0.25*)	0.40 (*0.11*)	488 (*0.02*)
NC 1859 (6 trips)	Low Idle	86.6 (*0.11*)	105 (*1.97*)	10.4 (*1.13*)	10.2 (*0.08*)	2784 (*0.24*)
	High Idle	121 (*0.10*)	309 (*0.76*)	43.9 (*0.82*)	10.5 (*0.11*)	4837 (*0.18*)
	DB	132 (*0.08*)	304 (*0.85*)	36.9 (*1.03*)	11.0 (*0.09*)	5562 (*0.15*)
	1	12.9 (*0.10*)	18.5 (*0.97*)	2.35 (*0.60*)	0.80 (*0.08*)	525 (*0.18*)
	2	11.3 (*0.04*)	5.24 (*0.77*)	1.37 (*0.63*)	0.58 (*0.09*)	429 (*0.09*)
	3	10.7 (*0.04*)	7.17 (*0.82*)	1.56 (*1.64*)	0.46 (*0.10*)	434 (*0.08*)
	4	10.1 (*0.06*)	5.13 (*0.81*)	0.60 (*0.73*)	0.45 (*0.17*)	395 (*0.07*)
	5	9.77 (*0.04*)	5.32 (*0.82*)	0.53 (*0.98*)	0.46 (*0.13*)	448 (*0.05*)
	6	9.52 (*0.07*)	4.84 (*0.74*)	0.57 (*0.68*)	0.52 (*0.29*)	451 (*0.08*)
	7	6.73 (*0.08*)	3.17 (*1.10*)	0.37 (*0.97*)	0.44 (*0.25*)	395 (*0.09*)
	8	6.72 (*0.03*)	3.16 (*0.51*)	1.06 (*0.11*)	0.53 (*0.13*)	438 (*0.01*)
NC 1869 (2 trips)	Idle	189 (*0.15*)	156 (*0.07*)	15.7 (*0.00*)	9.32 (*0.20*)	8997 (*0.29*)
	1	17.6 (*0.07*)	6.40 (*0.56*)	1.42 (*0.29*)	1.06 (*0.41*)	720 (*0.08*)
	2	14.0 (*0.10*)	5.02 (*0.18*)	0.68 (*0.14*)	0.58 (*0.05*)	520 (*0.04*)
	3	14.4 (*0.02*)	2.78 (*0.79*)	0.57 (*0.04*)	0.48 (*0.12*)	515 (*0.03*)
	4	13.3 (*0.01*)	1.52 (*0.55*)	0.58 (*0.23*)	0.53 (*0.22*)	474 (*0.00*)
	5	13.4 (*0.02*)	1.01 (*0.93*)	0.73 (*0.38*)	0.66 (*0.35*)	497 (*0.02*)
	6	12.3 (*0.00*)	0.52 (*0.38*)	1.13 (*0.53*)	0.78 (*0.35*)	514 (*0.05*)
	7	8.89 (*0.02*)	0.52 (*0.52*)	1.30 (*0.05*)	0.63 (*0.20*)	432 (*0.01*)
	8	8.28 (*0.01*)	0.15 (*0.01*)	2.06 (*0.04*)	0.60 (*0.00*)	504 (*0.03*)
NC 1893 (14 trips)	Low Idle	96.7 (*0.12*)	63.5 (*0.86*)	9.61 (*1.48*)	6.25 (*0.60*)	2777 (*0.19*)
	High Idle	166 (*0.15*)	102 (*0.99*)	21.4 (*0.90*)	7.93 (*0.52*)	6708 (*0.24*)
	DB	139 (*0.16*)	145 (*0.98*)	23.6 (*1.41*)	8.90 (*0.53*)	6341 (*0.24*)
	1	15.9 (*0.14*)	5.56 (*0.94*)	1.00 (*1.22*)	0.59 (*0.47*)	606 (*0.13*)
	2	13.2 (*0.14*)	3.08 (*0.95*)	0.41 (*0.83*)	0.40 (*0.47*)	459 (*0.16*)
	3	12.7 (*0.17*)	1.60 (*1.04*)	0.31 (*1.05*)	0.28 (*0.42*)	427 (*0.14*)
	4	12.3 (*0.15*)	0.91 (*1.26*)	0.38 (*1.27*)	0.27 (*0.45*)	418 (*0.18*)
	5	12.3 (*0.10*)	0.88 (*1.35*)	0.40 (*1.34*)	0.29 (*0.54*)	433 (*0.12*)
	6	11.7 (*0.08*)	1.00 (*1.32*)	0.29 (*0.87*)	0.27 (*0.55*)	467 (*0.12*)
	7	8.26 (*0.12*)	0.14 (*1.42*)	0.42 (*0.68*)	0.33 (*0.76*)	382 (*0.13*)
	8	7.86 (*0.13*)	0.64 (*1.52*)	0.72 (*0.49*)	0.27 (*0.41*)	447 (*0.10*)

(b) F59PHI Locomotives – EMD 12-710 Prime Mover Engine

Locomotive	**Notch Position**	**NO as NO_2 (g/kW-hr)**	**HC (g/kW-hr)**	**CO (g/kW-hr)**	**Opacity-based PM (g/kW-hr)**	**CO_2 (g/kW-hr)**
NC 1755 (1 trip)	Idle	173	73.1	13.0	11.6	4702
	DB	258	124	7.28	11.0	4871
	1	13.3	3.54	0.46	0.59	330
	2	13.5	2.85	0.40	0.31	402
	3	14.9	1.50	0.08	0.23	346
	4	14.2	1.40	0.27	0.16	412
	5	17.4	0.91	0.35	0.15	408
	6	13.5	1.03	0.34	0.12	392
	7	9.30	0.50	0.30	0.13	325
	8	8.75	0.41	0.91	0.20	407
NC 1797 (6 trips)	Idle	266 (*0.10*)	303 (*0.54*)	45.8 (*0.59*)	6.29 (*0.08*)	4605 (*0.19*)
	DB	267 (*0.13*)	298 (*0.76*)	60.3 (*1.00*)	6.95 (*0.17*)	4779 (*0.14*)
	1	29.5 (*0.15*)	12.4 (*0.60*)	1.59 (*0.58*)	0.46 (*0.11*)	508 (*0.21*)
	2	25.6 (*0.21*)	8.38 (*0.44*)	1.00 (*0.54*)	0.30 (*0.05*)	427 (*0.27*)
	3	29.1 (*0.06*)	5.04 (*0.63*)	0.61 (*0.65*)	0.15 (*0.14*)	404 (*0.15*)
	4	27.7 (*0.06*)	6.01 (*0.37*)	0.69 (*0.43*)	0.11 (*0.13*)	439 (*0.10*)
	5	25.7 (*0.07*)	5.02 (*0.36*)	0.58 (*0.31*)	0.11 (*0.26*)	448 (*0.08*)
	6	18.9 (*0.07*)	3.24 (*0.54*)	0.57 (*0.84*)	0.10 (*0.15*)	429 (*0.09*)
	7	12.5 (*0.17*)	2.20 (*0.64*)	0.55 (*0.79*)	0.17 (*0.31*)	335 (*0.28*)
	8	13.3 (*0.03*)	1.68 (*0.37*)	0.87 (*0.21*)	0.19 (*0.10*)	431 (*0.07*)

(c) GP40 Locomotive – EMD 16-645 Prime Mover Engine

Locomotive	**Notch Position**	**NO as NO_2 (g/kW-hr)**	**HC (g/kW-hr)**	**CO (g/kW-hr)**	**Opacity-based PM (g/kW-hr)**	**CO_2 (g/kW-hr)**
NC 1792 (6 trips)	Idle	67.2	65.4	10.2	n/a	2596
	DB	164	181	18.2	n/a	7303
	1	12.7	6.57	1.17	n/a	465
	2	12.4	3.02	0.74	n/a	521
	3	13.6	2.60	0.51	n/a	536
	4	13.3	0.79	0.26	n/a	562
	5	13.6	0.83	0.72	n/a	608
	6	14.0	1.29	0.90	n/a	631
	7	13.5	0.49	0.82	n/a	636
	8	14.0	1.03	0.34	n/a	555

Italicized values in parentheses are coefficients of variation on the mean emission rate.

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

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

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

Appendix F

Sample Real-World Emissions Time Traces

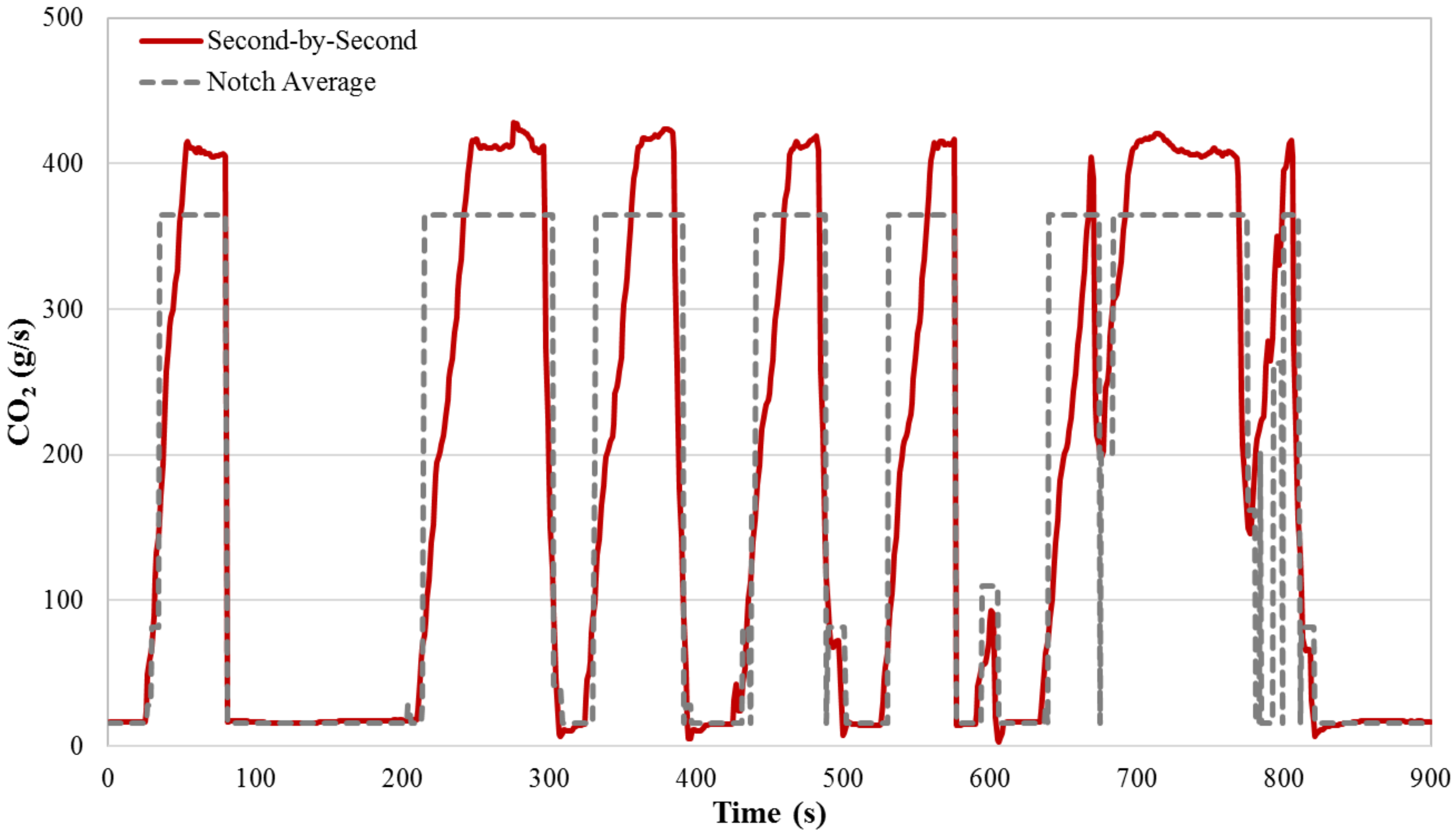


Figure F-1: Time Trace of PEMS-Measured Time-Based CO_2 Emission Rate for a 900-Second Segment of a One-Way Piedmont Trip by Locomotive NC 1859 on Ultra-Low Sulfur Diesel

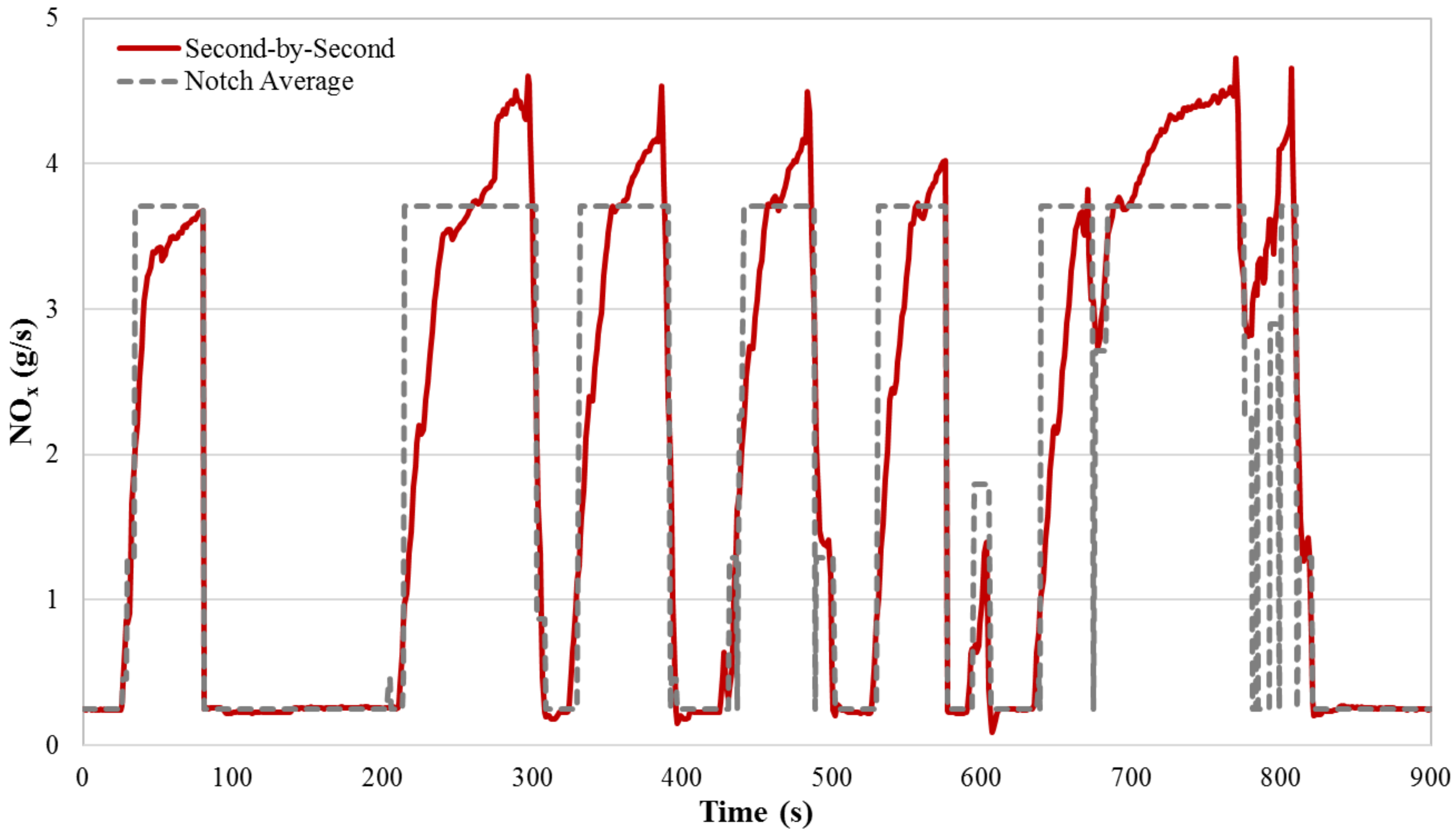


Figure F-2: Time Trace of PEMS-Measured Time-Based NO_x Emission Rate for a 900-Second Segment of a One-Way Piedmont Trip by Locomotive NC 1859 on Ultra-Low Sulfur Diesel

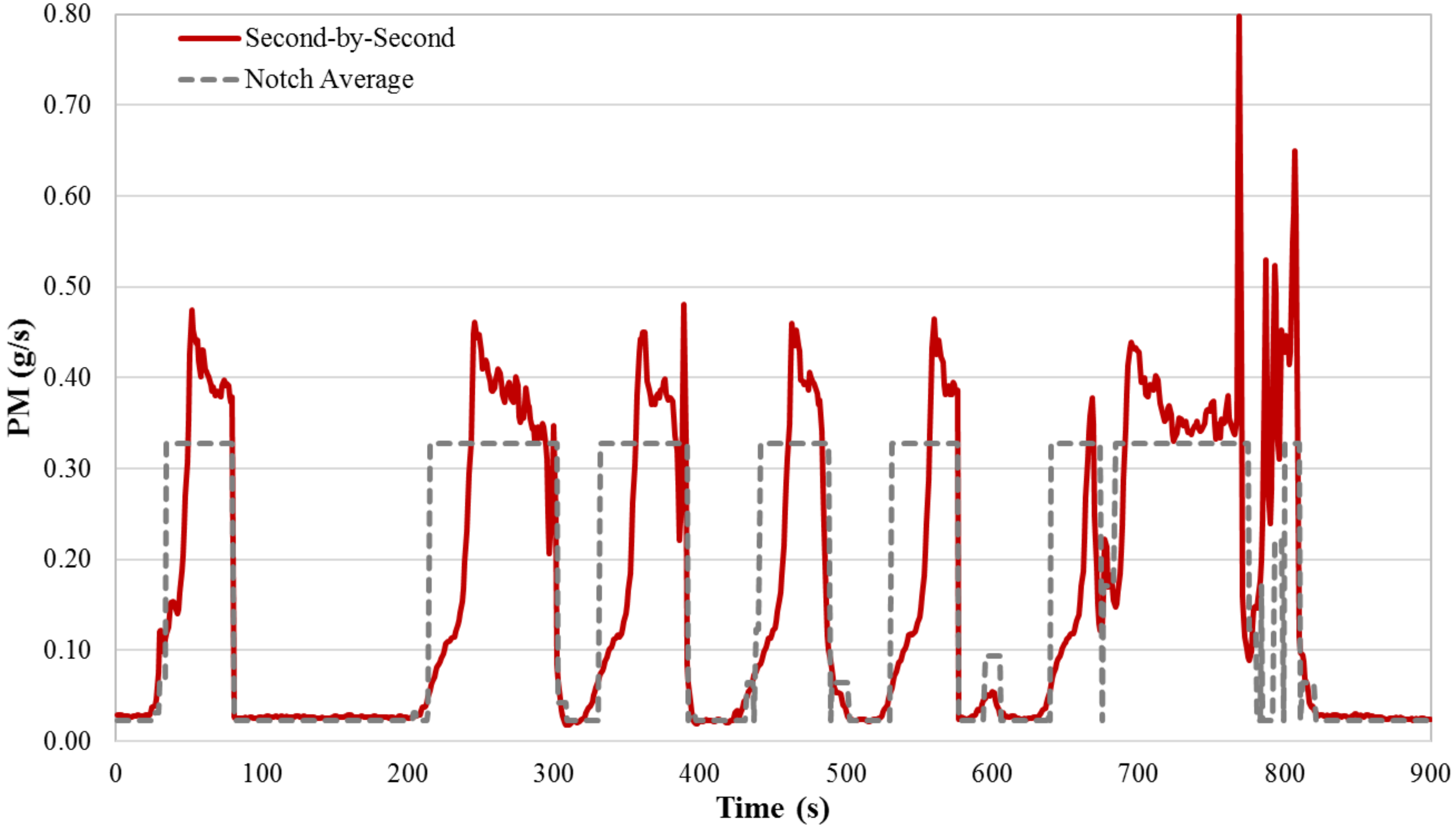


Figure F-3: Time Trace of PEMS-Measured Time-Based PM Emission Rate for a 900-Second Segment of a One-Way Piedmont Trip by Locomotive NC 1859 on Ultra-Low Sulfur Diesel

Appendix G

NO$_x$ and HC Bias Correction Factors

Table G-1: NO$_x$ Bias Correction Factors Based on SEMTECH Measurements

(a) ULSD

Notch Position	NC 1797	NC 1810	NC 1859
Idle	1.105	1.033	1.082
Dynamic Brake*	1.105	1.033	1.082
1	1.098	1.069	1.072
2	1.078	1.050	1.042
3	1.071	1.045	1.033
4	1.076	1.040	1.030
5	1.077	1.041	1.033
6	1.063	1.038	1.031
7	1.059	1.051	1.039
8	1.072	1.070	1.065

(b) B10

Notch Position	NC 1797	NC 1810	NC 1859
Idle	1.082	No SEMTECH Measurements Using NC 1859 Correction Factors	1.116
Dynamic Brake*	1.082		1.116
1	1.086		1.101
2	1.074		1.072
3	1.067		1.065
4	1.070		1.060
5	1.072		1.060
6	1.064		1.057
7	1.056		1.061
8	1.067		1.083

(c) B20

Notch Position	NC 1797	NC 1810	NC 1859
Idle	No SEMTECH Measurements Using NC 1859 Correction Factors		1.093
Dynamic Brake*			1.093
1			1.095
2			1.066
3			1.059
4			1.054
5			1.054
6			1.051
7			1.056
8			1.077

(d) B40

Notch Position	NC 1797	NC 1810	NC 1859
Idle	1.177	No SEMTECH Measurements Using NC 1859 Correction Factors	1.090
Dynamic Brake*	1.177		1.090
1	1.134		1.085
2	1.097		1.059
3	1.094		1.054
4	1.102		1.051
5	1.098		1.051
6	1.081		1.049
7	1.081		1.050
8	1.094		1.067

(e) B60

Notch Position	**NC 1810**
Idle	1.102
Dynamic Brake*	1.102
1	1.096
2	1.071
3	1.066
4	1.060
5	1.059
6	1.057
7	1.062
8	1.077

(f) B80

Notch Position	**NC 1810**
Idle	1.093
Dynamic Brake*	1.093
1	1.083
2	1.058
3	1.048
4	1.043
5	1.043
6	1.038
7	1.041
8	1.068

(g) B100

Notch Position	**NC 1810**
Idle	1.090
Dynamic Brake*	1.090
1	1.082
2	1.064
3	1.059
4	1.055
5	1.053
6	1.052
7	1.056
8	1.075

Table G-2: NO_x Bias Correction Factors Based on Ambient Temperature and Humidity

(a) NC 1797

Fuel	RY	OTR
ULSD	0.7550	0.7941
B10	0.7535	0.7326
B20	0.8464	0.7104
B40	0.8322	0.8747

(b) NC 1810

Fuel	RY	OTR
ULSD	0.6534	0.7624
B10	0.8452	0.8707
B20	0.8407	0.7970
B40	0.7363	0.6957
B60	0.7601	0.8004
B80	0.8421	0.7388
B100	0.6134	0.6672

(c) NC 1859

Fuel	RY	OTR
ULSD	0.8589	0.8660
B10	0.6492	0.6090
B20	0.6576	0.6873
B40	0.7446	0.7718

NO_x correction factors were estimated for each day of OTR measurements using the following equations from Lindhjem *et al.* (*46*):

$$KNO_x = 1 / (K_H K_T)$$

$$K_H = 1989.6 / (85.444 + 2219.426 \exp(-0.0143 H))$$

$$K_T = 1 / (1 - 0.017 (30 - T))$$

Where H = ambient humidity, gH2O/kg of dry air

T = ambient temperature, °C

NO_x emission rates for each OTR measurement were adjusted using the NO_x correction factor for the day in which the OTR measurement was made. OTR correction factors in the table above are the average NO_x correction factors for all OTR measurements of a particular locomotive and fuel blend.

Table G-3: HC Bias Correction Factors Based on Rail Yard SEMTECH and Axion Measurements

(a) ULSD

Notch Position	NC 1797	NC 1810	NC 1859
Idle	2.617	5.130	5.914
Dynamic Brake*	2.617	5.130	5.914
1	3.379	5.110	6.046
2	2.636	3.691	3.850
3	2.818	3.418	3.402
4	2.147	2.982	3.290
5	3.473	2.846	3.027
6	3.802	2.662	2.885
7	2.853	4.983	3.130
8	5.077	6.626	7.129

(b) B10

Notch Position	NC 1797	NC 1810	NC 1859
Idle	5.338	No SEMTECH Measurements Using NC 1859 Correction Factors	5.428
Dynamic Brake*	5.338		5.428
1	2.148		2.970
2	1.919		2.904
3	1.666		2.882
4	1.640		2.801
5	1.992		2.804
6	1.907		3.073
7	3.688		4.462
8	5.542		7.039

(c) B20

Notch Position	NC 1797	NC 1810	NC 1859
Idle	No SEMTECH Measurements Using NC 1859 Correction Factors		2.761
Dynamic Brake*			2.761
1			1.511
2			1.496
3			1.423
4			1.440
5			1.415
6			1.397
7			1.846
8			3.939

(d) B40

Notch Position	NC 1797	NC 1810	NC 1859
Idle	2.605	No SEMTECH Measurements Using NC 1859 Correction Factors	3.221
Dynamic Brake*	2.605		3.221
1	1.331		2.297
2	1.307		2.203
3	1.312		2.184
4	1.475		2.083
5	1.627		1.950
6	1.861		2.005
7	3.246		2.898
8	4.941		5.607

(e) B60

Notch Position	NC 1810
Idle	2.462
Dynamic Brake*	2.462
1	1.227
2	1.121
3	2.158
4	1.185
5	1.205
6	1.225
7	1.955
8	4.225

(f) B80

Notch Position	NC 1810
Idle	3.868
Dynamic Brake*	3.868
1	2.049
2	1.860
3	1.865
4	1.929
5	1.818
6	2.431
7	3.809
8	8.234

(g) B100

Notch Position	NC 1810
Idle	6.216
Dynamic Brake*	6.216
1	6.987
2	5.524
3	3.605
4	3.814
5	4.062
6	3.601
7	5.068
8	10.326

Appendix H

Rail Yard Biodiesel Measurement Emission Rates

Table H-1: Time-Based Notch Average Emission Rates from Rail Yard Biodiesel Measurements of Prime Mover Engines

(a) NC 1797 – F59PHI Locomotive

Fuel	Notch Position	NO as NO$_2$ (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO$_2$ (g/s)
ULSD (3 replicates)	Idle	0.31 (*0.11*)	0.18 (*0.21*)	0.02 (*0.69*)	0.01 (*0.06*)	8.73 (*0.14*)
	1	0.81 (*0.09*)	0.06 (*0.68*)	0.02 (*0.90*)	0.02 (*0.03*)	29.0 (*0.05*)
	2	1.39 (*0.04*)	0.07 (*0.77*)	0.02 (*0.56*)	0.02 (*0.04*)	43.9 (*0.05*)
	3	1.90 (*0.01*)	0.06 (*0.25*)	0.01 (*1.24*)	0.02 (*0.03*)	79.4 (*0.01*)
	4	2.28 (*0.01*)	0.08 (*0.36*)	0.01 (*1.48*)	0.02 (*0.04*)	123 (*0.00*)
	5	3.18 (*0.02*)	0.11 (*0.14*)	0.00 (*1.23*)	0.03 (*0.03*)	167 (*0.01*)
	6	3.67 (*0.06*)	0.70 (*0.77*)	0.00 (*1.63*)	0.03 (*0.02*)	198 (*0.06*)
	7	4.57 (*0.00*)	0.35 (*0.33*)	0.06 (*0.57*)	0.12 (*0.02*)	324 (*0.02*)
	8	6.13 (*0.01*)	1.14 (*0.93*)	0.74 (*0.17*)	0.15 (*0.06*)	420 (*0.01*)
B10 (3 replicates)	Idle	0.43 (*0.01*)	0.86 (*0.62*)	0.06 (*0.44*)	0.01 (*0.09*)	13.5 (*0.01*)
	1	1.10 (*0.02*)	0.27 (*0.54*)	0.05 (*0.16*)	0.01 (*0.04*)	35.4 (*0.01*)
	2	1.91 (*0.03*)	0.40 (*0.37*)	0.07 (*0.41*)	0.01 (*0.03*)	53.9 (*0.01*)
	3	2.43 (*0.02*)	0.45 (*0.16*)	0.09 (*0.22*)	0.02 (*0.01*)	92.5 (*0.01*)
	4	2.86 (*0.03*)	0.62 (*0.35*)	0.16 (*0.57*)	0.03 (*0.03*)	140 (*0.00*)
	5	3.89 (*0.04*)	0.59 (*0.46*)	0.10 (*0.09*)	0.03 (*0.02*)	180 (*0.01*)
	6	4.55 (*0.01*)	0.75 (*0.36*)	0.11 (*0.92*)	0.03 (*0.01*)	219 (*0.02*)
	7	5.31 (*0.02*)	1.63 (*0.15*)	0.14 (*0.94*)	0.13 (*0.05*)	356 (*0.01*)
	8	7.36 (*0.02*)	3.55 (*0.16*)	0.55 (*0.19*)	0.18 (*0.12*)	433 (*0.00*)
B20 (3 replicates)	Idle	0.42 (*0.25*)	0.78 (*0.19*)	0.07 (*0.70*)	0.01 (*0.02*)	11.4 (*0.21*)
	1	0.95 (*0.04*)	0.30 (*0.13*)	0.01 (*1.36*)	0.01 (*0.04*)	26.0 (*0.09*)
	2	1.73 (*0.03*)	0.38 (*0.21*)	0.01 (*0.87*)	0.01 (*0.01*)	41.5 (*0.08*)
	3	2.20 (*0.03*)	0.54 (*0.21*)	0.01 (*0.98*)	0.02 (*0.02*)	71.1 (*0.06*)
	4	2.54 (*0.02*)	0.84 (*0.07*)	0.01 (*1.73*)	0.02 (*0.02*)	115 (*0.06*)
	5	3.55 (*0.01*)	0.49 (*0.58*)	0.00 (*n/a*)	0.02 (*0.02*)	146 (*0.00*)
	6	4.15 (*0.02*)	0.88 (*0.32*)	0.04 (*0.96*)	0.02 (*0.01*)	193 (*0.02*)
	7	5.09 (*0.04*)	0.87 (*0.92*)	0.13 (*0.97*)	0.10 (*0.06*)	311 (*0.01*)
	8	7.34 (*0.03*)	4.85 (*0.32*)	0.60 (*0.25*)	0.11 (*0.07*)	398 (*0.09*)

Fuel	**Notch Position**	**NO as NO_2 (g/s)**	**HC (g/s)**	**CO (g/s)**	**Opacity-based PM (g/s)**	**CO_2 (g/s)**
B40 (3 replicates)	Idle	0.50 (*0.02*)	0.26 (*0.99*)	0.06 (*0.79*)	0.01 (*0.07*)	15.8 (*0.02*)
	1	1.13 (*0.00*)	0.03 (*1.63*)	0.03 (*0.92*)	0.01 (*0.06*)	38.1 (*0.02*)
	2	1.94 (*0.01*)	0.07 (*1.38*)	0.04 (*1.60*)	0.01 (*0.07*)	56.4 (*0.01*)
	3	2.37 (*0.01*)	0.09 (*1.44*)	0.06 (*1.60*)	0.01 (*0.02*)	96.4 (*0.00*)
	4	2.68 (*0.01*)	0.14 (*1.45*)	0.09 (*1.73*)	0.02 (*0.01*)	144 (*0.01*)
	5	3.73 (*0.01*)	0.06 (*1.24*)	0.04 (*1.73*)	0.03 (*0.01*)	187 (*0.01*)
	6	4.41 (*0.02*)	0.70 (*0.52*)	0.06 (*1.35*)	0.03 (*0.01*)	237 (*0.01*)
	7	5.00 (*0.00*)	1.33 (*0.28*)	0.34 (*0.80*)	0.15 (*0.05*)	375 (*0.01*)
	8	7.02 (*0.01*)	1.28 (*0.72*)	0.60 (*0.25*)	0.19 (*0.28*)	446 (*0.01*)

(b) NC 1810 – F59PH Locomotive

Fuel	**Notch Position**	**NO as NO_2 (g/s)**	**HC (g/s)**	**CO (g/s)**	**Opacity-based PM (g/s)**	**CO_2 (g/s)**
ULSD (3 replicates)	Low Idle	Low Idle	0.13 (*0.08*)	1.30 (*0.06*)	0.08 (*0.24*)	0.01 (*0.06*)
	High Idle	High Idle	0.17 (*0.05*)	1.82 (*0.03*)	0.09 (*0.24*)	0.01 (*0.11*)
	1	1	0.36 (*0.05*)	1.21 (*0.08*)	0.06 (*0.37*)	0.01 (*0.01*)
	2	2	0.64 (*0.04*)	1.01 (*0.10*)	0.07 (*0.44*)	0.02 (*0.02*)
	3	3	1.21 (*0.01*)	1.23 (*0.16*)	0.07 (*0.33*)	0.03 (*0.01*)
	4	4	1.64 (*0.01*)	1.10 (*0.12*)	0.09 (*0.70*)	0.05 (*0.03*)
	5	5	2.03 (*0.02*)	0.84 (*0.10*)	0.08 (*0.67*)	0.06 (*0.03*)
	6	6	2.43 (*0.01*)	2.00 (*0.16*)	0.12 (*0.91*)	0.07 (*0.00*)
	7	7	3.02 (*0.04*)	2.66 (*0.46*)	0.72 (*0.33*)	0.22 (*0.11*)
	8	8	3.35 (*0.01*)	2.50 (*0.26*)	0.98 (*0.06*)	0.28 (*0.15*)
B10 (1 replicate)	Low Idle	0.16	0.16	0.01	0.01	7.98
	High Idle	0.24	0.12	0.01	0.01	14.8
	1	0.51	0.11	0.04	0.02	31.6
	2	0.88	0.12	0.04	0.03	48.6
	3	1.59	0.13	0.04	0.04	85.3
	4	2.17	0.04	0.11	0.06	127
	5	2.54	0.00	0.13	0.09	170
	6	3.04	0.01	0.12	0.11	204
	7	3.75	0.23	0.88	0.17	316
	8	3.78	0.09	1.40	0.26	416

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
B20 (1 replicate)	Low Idle	0.14	0.01	0.01	0.01	6.73
	High Idle	0.24	0.10	0.01	0.00	32.1
	1	0.45	0.00	0.02	0.01	20.6
	2	0.79	0.00	0.01	0.01	37.6
	3	1.56	0.01	0.02	0.02	63.9
	4	2.06	0.00	0.05	0.03	101
	5	2.65	0.00	0.09	0.04	109
	6	3.05	0.03	0.02	0.04	149
	7	3.69	0.17	0.50	0.07	282
	8	3.66	0.55	0.76	0.11	421
B40 (1 replicates)	Low Idle	0.16	0.07	0.03	0.01	5.69
	High Idle	n/a	n/a	n/a	n/a	n/a
	1	0.52	0.07	0.00	0.01	24.7
	2	0.91	0.08	0.00	0.02	43.2
	3	1.65	0.15	0.01	0.03	69.7
	4	2.13	0.20	0.05	0.04	112
	5	2.85	0.04	0.00	0.06	144
	6	3.17	0.06	0.04	0.06	191
	7	3.86	0.49	0.06	0.13	284
	8	3.96	0.07	0.74	0.43	358
B60 (5 replicates)	Low Idle	0.16 (*0.08*)	0.09 (*0.80*)	0.07 (*0.61*)	0.01 (*0.09*)	8.28 (*0.12*)
	High Idle	0.21 (*0.07*)	0.10 (*0.91*)	0.07 (*0.88*)	0.00 (*0.22*)	13.4 (*0.07*)
	1	0.51 (*0.10*)	0.06 (*1.17*)	0.08 (*0.59*)	0.01 (*0.07*)	36.0 (*0.05*)
	2	0.85 (*0.12*)	0.06 (*1.07*)	0.08 (*0.67*)	0.02 (*0.03*)	52.2 (*0.05*)
	3	1.55 (*0.12*)	0.11 (*1.24*)	0.08 (*0.90*)	0.02 (*0.07*)	94.3 (*0.02*)
	4	2.04 (*0.11*)	0.05 (*1.41*)	0.10 (*1.00*)	0.04 (*0.07*)	134 (*0.01*)
	5	2.52 (*0.10*)	0.03 (*1.58*)	0.07 (*1.09*)	0.05 (*0.12*)	181 (*0.00*)
	6	2.99 (*0.09*)	0.11 (*0.99*)	0.15 (*1.35*)	0.06 (*0.14*)	226 (*0.02*)
	7	3.68 (*0.11*)	0.11 (*0.96*)	0.40 (*0.60*)	0.12 (*0.19*)	325 (*0.06*)
	8	4.13 (*0.06*)	0.63 (*1.13*)	0.63 (*0.55*)	0.18 (*0.18*)	407 (*0.03*)

Fuel	**Notch Position**	**NO as NO_2 (g/s)**	**HC (g/s)**	**CO (g/s)**	**Opacity-based PM (g/s)**	**CO_2 (g/s)**
B80 (3 replicates)	Low Idle	0.12 (*0.06*)	0.04 (*0.29*)	0.01 (*0.68*)	0.02 (*0.06*)	6.41 (*0.09*)
	High Idle	0.16 (*0.01*)	0.08 (*0.61*)	0.02 (*0.06*)	0.02 (*0.16*)	9.63 (*0.01*)
	1	0.41 (*0.01*)	0.03 (*0.21*)	0.01 (*0.61*)	0.03 (*0.02*)	27.6 (*0.01*)
	2	0.61 (*0.00*)	0.06 (*0.18*)	0.01 (*0.71*)	0.04 (*0.00*)	36.1 (*0.01*)
	3	1.32 (*0.01*)	0.03 (*0.27*)	0.00 (*0.82*)	0.05 (*0.04*)	77.0 (*0.00*)
	4	1.67 (*0.01*)	0.05 (*0.35*)	0.01 (*0.77*)	0.07 (*0.04*)	107 (*0.01*)
	5	2.28 (*0.00*)	0.05 (*0.10*)	0.03 (*0.31*)	0.10 (*0.05*)	161 (*0.01*)
	6	2.88 (*0.00*)	0.04 (*0.25*)	0.08 (*0.24*)	0.15 (*0.03*)	223 (*0.01*)
	7	3.48 (*0.02*)	0.08 (*1.35*)	0.37 (*0.12*)	0.25 (*0.08*)	312 (*0.01*)
	8	4.16 (*0.01*)	0.39 (*1.26*)	1.80 (*0.11*)	0.46 (*0.20*)	417 (*0.00*)
B100 (3 replicates)	Low Idle	0.13 (*0.01*)	0.99 (*0.42*)	0.07 (*0.23*)	0.01 (*0.05*)	8.37 (*0.05*)
	High Idle	0.22 (*0.11*)	1.72 (*0.53*)	0.12 (*0.59*)	0.01 (*0.34*)	14.6 (*0.05*)
	1	0.45 (*0.01*)	0.87 (*0.53*)	0.04 (*0.75*)	0.01 (*0.02*)	36.8 (*0.01*)
	2	0.74 (*0.03*)	1.01 (*0.53*)	0.07 (*0.77*)	0.02 (*0.01*)	53.3 (*0.01*)
	3	1.41 (*0.01*)	0.65 (*0.52*)	0.03 (*0.90*)	0.02 (*0.02*)	99.9 (*0.01*)
	4	1.84 (*0.02*)	0.67 (*0.58*)	0.04 (*1.18*)	0.03 (*0.02*)	140 (*0.00*)
	5	2.27 (*0.02*)	0.68 (*0.69*)	0.05 (*1.26*)	0.04 (*0.01*)	190 (*0.01*)
	6	2.74 (*0.02*)	0.68 (*0.95*)	0.05 (*1.22*)	0.05 (*0.03*)	236 (*0.00*)
	7	3.59 (*0.03*)	0.91 (*0.95*)	0.06 (*0.36*)	0.17 (*0.10*)	337 (*0.00*)
	8	3.83 (*0.02*)	0.69 (*0.34*)	0.20 (*0.50*)	0.30 (*0.43*)	419 (*0.01*)

(c) NC 1859 – F59PH Locomotive

Fuel	**Notch Position**	**NO as NO_2 (g/s)**	**HC (g/s)**	**CO (g/s)**	**Opacity-based PM (g/s)**	**CO_2 (g/s)**
ULSD (3 replicates)	Low Idle	0.17 (*0.02*)	0.23 (*0.26*)	0.07 (*0.29*)	0.02 (*0.04*)	9.20 (*0.02*)
	High Idle	0.20 (*0.00*)	1.42 (*0.37*)	0.73 (*0.46*)	0.02 (*0.02*)	13.8 (*0.02*)
	1	0.45 (*0.02*)	0.47 (*0.15*)	0.10 (*0.31*)	0.03 (*0.02*)	35.5 (*0.01*)
	2	0.79 (*0.04*)	0.78 (*0.08*)	0.16 (*0.04*)	0.03 (*0.01*)	53.7 (*0.01*)
	3	1.42 (*0.03*)	1.25 (*0.08*)	0.27 (*0.09*)	0.05 (*0.02*)	93.7 (*0.00*)
	4	1.84 (*0.02*)	1.56 (*0.18*)	0.41 (*0.34*)	0.07 (*0.02*)	126 (*0.03*)
	5	2.25 (*0.03*)	0.91 (*0.87*)	0.23 (*0.91*)	0.09 (*0.02*)	171 (*0.01*)
	6	2.78 (*0.06*)	0.00 (*n/a*)	0.30 (*0.25*)	0.13 (*0.02*)	226 (*0.02*)
	7	3.23 (*0.09*)	2.01 (*1.12*)	1.36 (*0.85*)	0.21 (*0.05*)	304 (*0.03*)
	8	3.79 (*0.04*)	2.99 (*0.13*)	1.50 (*0.04*)	0.28 (*0.02*)	392 (*0.00*)

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
B10 (3 replicates)	Low Idle	0.15 (*0.04*)	0.22 (*0.55*)	0.05 (*0.56*)	0.01 (*0.05*)	9.07 (*0.03*)
	High Idle	0.19 (*0.05*)	0.36 (*0.14*)	0.09 (*0.25*)	0.02 (*0.10*)	14.7 (*0.01*)
	1	0.44 (*0.06*)	0.11 (*0.54*)	0.04 (*0.46*)	0.01 (*0.02*)	35.8 (*0.01*)
	2	0.77 (*0.06*)	0.09 (*0.40*)	0.03 (*0.66*)	0.02 (*0.01*)	53.2 (*0.01*)
	3	1.40 (*0.05*)	0.09 (*0.67*)	0.02 (*0.00*)	0.02 (*0.01*)	91.8 (*0.00*)
	4	1.89 (*0.06*)	0.07 (*0.40*)	0.01 (*0.87*)	0.03 (*0.07*)	130 (*0.00*)
	5	2.38 (*0.04*)	0.09 (*0.47*)	0.02 (*0.00*)	0.04 (*0.03*)	173 (*0.00*)
	6	2.82 (*0.04*)	0.16 (*0.07*)	0.03 (*0.00*)	0.04 (*0.05*)	212 (*0.00*)
	7	3.64 (*0.04*)	0.19 (*0.34*)	0.15 (*0.27*)	0.10 (*0.06*)	310 (*0.00*)
	8	3.93 (*0.03*)	0.09 (*0.33*)	0.22 (*0.51*)	0.18 (*0.22*)	372 (*0.00*)
B20 (3 replicates)	Low Idle	0.13 (*0.05*)	0.32 (*0.46*)	0.07 (*0.46*)	0.01 (*0.04*)	7.55 (*0.13*)
	High Idle	0.17 (*0.06*)	0.47 (*0.14*)	0.09 (*0.21*)	0.01 (*0.09*)	12.9 (*0.14*)
	1	0.40 (*0.03*)	0.33 (*0.37*)	0.08 (*0.43*)	0.02 (*0.03*)	30.8 (*0.02*)
	2	0.71 (*0.02*)	0.41 (*0.30*)	0.09 (*0.28*)	0.02 (*0.04*)	46.7 (*0.04*)
	3	1.30 (*0.02*)	0.53 (*0.30*)	0.09 (*0.43*)	0.03 (*0.03*)	80.8 (*0.03*)
	4	1.76 (*0.02*)	0.57 (*0.40*)	0.09 (*0.44*)	0.04 (*0.02*)	118 (*0.02*)
	5	2.23 (*0.02*)	0.36 (*0.40*)	0.02 (*0.87*)	0.05 (*0.03*)	158 (*0.01*)
	6	2.65 (*0.03*)	0.96 (*0.38*)	0.09 (*0.88*)	0.06 (*0.01*)	194 (*0.01*)
	7	3.46 (*0.03*)	2.12 (*0.40*)	0.27 (*0.77*)	0.12 (*0.02*)	286 (*0.01*)
	8	3.66 (*0.04*)	0.27 (*0.63*)	0.22 (*0.20*)	0.16 (*0.15*)	374 (*0.03*)
B40 (3 replicates)	Low Idle	0.19 (*0.05*)	0.23 (*0.19*)	0.08 (*0.07*)	0.01 (*0.09*)	7.79 (*0.06*)
	High Idle	0.23 (*0.02*)	0.31 (*0.29*)	0.15 (*0.47*)	0.01 (*0.16*)	12.6 (*0.09*)
	1	0.56 (*0.03*)	0.07 (*0.47*)	0.11 (*0.35*)	0.02 (*0.04*)	34.1 (*0.01*)
	2	0.98 (*0.02*)	0.06 (*0.33*)	0.10 (*0.30*)	0.02 (*0.02*)	49.9 (*0.02*)
	3	1.78 (*0.03*)	0.07 (*0.30*)	0.11 (*0.33*)	0.03 (*0.02*)	88.0 (*0.01*)
	4	2.28 (*0.01*)	0.06 (*0.23*)	0.11 (*0.49*)	0.04 (*0.06*)	119 (*0.03*)
	5	2.91 (*0.02*)	0.06 (*0.89*)	0.09 (*0.18*)	0.05 (*0.06*)	163 (*0.02*)
	6	3.45 (*0.06*)	0.59 (*1.12*)	0.18 (*0.27*)	0.06 (*0.01*)	199 (*0.04*)
	7	4.35 (*0.03*)	0.48 (*0.66*)	0.35 (*0.15*)	0.11 (*0.05*)	294 (*0.03*)
	8	4.89 (*0.04*)	0.22 (*0.34*)	0.45 (*0.25*)	0.15 (*0.08*)	386 (*0.02*)

Italicized values in parentheses are coefficients of variation (standard deviation divided by the mean) on the mean emission rate.

NO_x includes NO and NO_2. Only NO was measured. Results include multiplicative correction factors based on NO and NO_2 measurements of the prime mover engines in the rail yard with a SEMTECH-DS PEMS, temperature, and humidity.

HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factors based on FID measurements of the prime mover engines in the rail yard with a SEMTECH-DS PEMS.

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

Table H-2: Time-Based Cycle Average Emission Rates from Rail Yard Biodiesel Measurements of Prime Mover Engines

Locomotive	Fuel	Cycle Average Emission Rate (g/s)				
		NO_x[a]	HC[b]	CO	PM[c]	CO_2
NC 1797 (F59PHI)	ULSD	1.85 (*0.01*)	0.31 (*0.49*)	0.13 (*0.19*)	0.04 (*0.09*)	106 (*0.06*)
	B10	2.29 (*0.02*)	1.10 (*0.30*)	0.14 (*0.05*)	0.04 (*0.08*)	118 (*0.01*)
	B20	2.20 (*0.03*)	1.27 (*0.15*)	0.13 (*0.17*)	0.03 (*0.10*)	101 (*0.04*)
	B40	2.23 (*0.00*)	0.39 (*0.28*)	0.14 (*0.42*)	0.04 (*0.20*)	116 (*0.05*)
NC 1810 (F59PH)	ULSD	1.21 (*0.02*)	2.57 (*0.15*)	0.24 (*0.06*)	0.07 (*0.10*)	107 (*0.00*)
	B10	1.19	0.40	0.28	0.07	111
	B20	1.17	0.28	0.14	0.03	97.1
	B40	1.59	0.25	0.13	0.08	86.1
	B60	1.32 (*0.07*)	0.16 (*1.00*)	0.16 (*0.55*)	0.04 (*0.15*)	110 (*0.05*)
	B80	1.24 (*0.01*)	0.10 (*0.89*)	0.15 (*0.04*)	0.11 (*0.11*)	105 (*0.05*)
	B100	1.22 (*0.02*)	0.89 (*0.47*)	0.08 (*0.08*)	0.06 (*0.34*)	116 (*0.00*)
NC 1859 (F59PH)	ULSD	1.21 (*0.02*)	2.57 (*0.15*)	0.50 (*0.18*)	0.07 (*0.06*)	105 (*0.05*)
	B10	1.24 (*0.04*)	0.28 (*0.41*)	0.08 (*0.37*)	0.05 (*0.16*)	105 (*0.00*)
	B20	1.16 (*0.03*)	0.35 (*0.41*)	0.10 (*0.09*)	0.05 (*0.09*)	101 (*0.02*)
	B40	1.54 (*0.04*)	0.25 (*0.21*)	0.16 (*0.30*)	0.04 (*0.09*)	101 (*0.04*)
Average of All Locomotives	ULSD	1.37 (*0.27*)	1.41 (*0.71*)	0.29 (*0.59*)	0.06 (*0.27*)	106 (*0.04*)
	B10	1.69 (*0.33*)	0.60 (*0.84*)	0.13 (*0.56*)	0.05 (*0.21*)	112 (*0.06*)
	B20	1.61 (*0.34*)	0.71 (*0.77*)	0.12 (*0.19*)	0.04 (*0.28*)	101 (*0.03*)
	B40	1.80 (*0.23*)	0.29 (*0.46*)	0.15 (*0.31*)	0.05 (*0.35*)	105 (*0.11*)

Italicized values in parentheses are coefficients of variation (standard deviation divided by the mean) on the mean emission rate.

[a] NO_x includes NO and NO_2. Only NO was measured. Results include multiplicative correction factors based on NO and NO_2 measurements of the prime mover engines in the rail yard with a SEMTECH-DS PEMS, temperature, and humidity.

[b] HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factors based on FID measurements of the prime mover engines in the rail yard with a SEMTECH-DS PEMS.

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

Appendix I

Over-the-Rail Biodiesel Measurement Emission Rates

Table I-1: Time-Based Notch Average Emission Rates from Over-the-Rail Biodiesel Measurements of Prime Mover Engines

(a) NC 1797 – F59PHI Locomotive

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
ULSD (6 replicates)	Idle	0.46 (*0.10*)	0.10 (*0.59*)	0.09 (*0.59*)	0.01 (*0.08*)	12.8 (*0.19*)
	Dynamic Brake	0.46 (*0.14*)	0.13 (*1.00*)	0.12 (*1.00*)	0.01 (*0.17*)	13.3 (*0.14*)
	1	0.96 (*0.14*)	0.08 (*0.58*)	0.06 (*0.58*)	0.02 (*0.11*)	26.8 (*0.21*)
	2	1.51 (*0.20*)	0.08 (*0.54*)	0.07 (*0.54*)	0.02 (*0.05*)	41.5 (*0.27*)
	3	3.29 (*0.08*)	0.10 (*0.65*)	0.09 (*0.65*)	0.02 (*0.14*)	75.8 (*0.15*)
	4	4.66 (*0.08*)	0.12 (*0.43*)	0.14 (*0.43*)	0.02 (*0.13*)	122 (*0.10*)
	5	5.63 (*0.09*)	0.22 (*0.31*)	0.16 (*0.31*)	0.03 (*0.26*)	162 (*0.08*)
	6	5.02 (*0.06*)	0.29 (*0.84*)	0.19 (*0.84*)	0.03 (*0.15*)	191 (*0.09*)
	7	5.62 (*0.16*)	0.35 (*0.79*)	0.31 (*0.79*)	0.09 (*0.31*)	251 (*0.28*)
	8	6.68 (*0.04*)	1.10 (*0.21*)	0.54 (*0.21*)	0.12 (*0.10*)	359 (*0.07*)
B10 (6 replicates)	Idle	0.43 (*0.17*)	0.14 (*0.29*)	0.06 (*0.29*)	0.01 (*0.04*)	14.6 (*0.11*)
	Dynamic Brake	0.44 (*0.18*)	0.16 (*0.21*)	0.08 (*0.21*)	0.01 (*0.05*)	14.8 (*0.08*)
	1	0.99 (*0.24*)	0.04 (*0.52*)	0.05 (*0.52*)	0.01 (*0.04*)	33.2 (*0.13*)
	2	1.39 (*0.23*)	0.04 (*0.72*)	0.05 (*0.72*)	0.02 (*0.08*)	44.8 (*0.15*)
	3	3.16 (*0.17*)	0.03 (*0.46*)	0.04 (*0.46*)	0.02 (*0.04*)	89.2 (*0.08*)
	4	4.30 (*0.21*)	0.04 (*0.73*)	0.06 (*0.73*)	0.03 (*0.12*)	134 (*0.06*)
	5	5.22 (*0.12*)	0.07 (*0.74*)	0.09 (*0.74*)	0.03 (*0.07*)	175 (*0.08*)
	6	5.46 (*0.11*)	0.05 (*0.85*)	0.07 (*0.85*)	0.03 (*0.09*)	194 (*0.14*)
	7	5.95 (*0.11*)	0.28 (*0.81*)	0.19 (*0.81*)	0.09 (*0.38*)	280 (*0.20*)
	8	6.66 (*0.11*)	0.59 (*0.59*)	0.26 (*0.59*)	0.14 (*0.13*)	385 (*0.02*)

Fuel	Notch Position	NO as NO$_2$ (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO$_2$ (g/s)
B20 (5 replicates)	Idle	0.38 (*0.06*)	0.02 (*0.98*)	0.02 (*0.98*)	0.01 (*0.09*)	12.4 (*0.11*)
	Dynamic Brake	0.35 (*0.13*)	0.02 (*1.78*)	0.02 (*1.78*)	0.01 (*0.08*)	11.8 (*0.14*)
	1	0.80 (*0.10*)	0.01 (*1.50*)	0.01 (*1.50*)	0.01 (*0.07*)	25.8 (*0.18*)
	2	1.35 (*0.09*)	0.01 (*1.09*)	0.01 (*1.09*)	0.01 (*0.07*)	41.6 (*0.16*)
	3	2.65 (*0.09*)	0.01 (*1.76*)	0.01 (*1.76*)	0.02 (*0.07*)	77.6 (*0.14*)
	4	3.79 (*0.07*)	0.01 (*1.44*)	0.02 (*1.44*)	0.02 (*0.05*)	112 (*0.10*)
	5	4.90 (*0.09*)	0.01 (*1.20*)	0.01 (*1.20*)	0.02 (*0.10*)	153 (*0.12*)
	6	4.91 (*0.05*)	0.01 (*1.70*)	0.01 (*1.70*)	0.02 (*0.06*)	174 (*0.11*)
	7	5.85 (*0.07*)	0.01 (*0.88*)	0.02 (*0.88*)	0.09 (*0.16*)	285 (*0.15*)
	8	6.28 (*0.03*)	0.20 (*0.30*)	0.13 (*0.30*)	0.10 (*0.21*)	347 (*0.05*)
B40 (6 replicates)	Idle	0.69 (*0.13*)	0.17 (*0.76*)	0.16 (*0.76*)	0.01 (*0.37*)	16.2 (*0.03*)
	Dynamic Brake	0.63 (*0.09*)	0.27 (*0.58*)	0.26 (*0.58*)	0.01 (*0.33*)	16.0 (*0.05*)
	1	1.41 (*0.15*)	0.05 (*0.62*)	0.09 (*0.62*)	0.01 (*0.19*)	35.4 (*0.11*)
	2	2.05 (*0.15*)	0.06 (*0.60*)	0.11 (*0.60*)	0.01 (*0.25*)	49.1 (*0.12*)
	3	4.24 (*0.05*)	0.07 (*0.72*)	0.12 (*0.72*)	0.02 (*0.26*)	93.6 (*0.03*)
	4	5.86 (*0.11*)	0.09 (*0.76*)	0.16 (*0.76*)	0.03 (*0.38*)	137 (*0.06*)
	5	7.12 (*0.11*)	0.09 (*0.68*)	0.15 (*0.68*)	0.05 (*0.51*)	182 (*0.06*)
	6	7.42 (*0.14*)	0.08 (*1.03*)	0.11 (*1.03*)	0.05 (*0.51*)	208 (*0.07*)
	7	8.24 (*0.04*)	0.18 (*0.60*)	0.14 (*0.60*)	0.25 (*1.05*)	254 (*0.06*)
	8	8.29 (*0.05*)	0.91 (*0.24*)	0.46 (*0.24*)	0.22 (*0.23*)	389 (*0.02*)

(b) NC 1810 – F59PH Locomotive

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
ULSD (6 replicates)	Low Idle	0.15 (*0.14*)	0.13 (*0.31*)	0.06 (*0.31*)	0.01 (*0.10*)	8.45 (*0.08*)
	High Idle	0.24 (*0.13*)	0.19 (*0.29*)	0.09 (*0.29*)	0.01 (*0.04*)	16.2 (*0.10*)
	Dynamic Brake	0.24 (*0.14*)	0.22 (*0.49*)	0.11 (*0.49*)	0.01 (*0.05*)	16.8 (*0.11*)
	1	0.44 (*0.11*)	0.21 (*0.39*)	0.10 (*0.39*)	0.01 (*0.04*)	30.5 (*0.08*)
	2	0.70 (*0.13*)	0.13 (*0.19*)	0.09 (*0.19*)	0.02 (*0.06*)	45.5 (*0.07*)
	3	1.34 (*0.10*)	0.16 (*0.35*)	0.12 (*0.35*)	0.03 (*0.08*)	85.8 (*0.05*)
	4	1.81 (*0.09*)	0.18 (*0.40*)	0.15 (*0.40*)	0.06 (*0.09*)	125 (*0.04*)
	5	2.29 (*0.07*)	0.30 (*0.52*)	0.26 (*0.52*)	0.07 (*0.19*)	168 (*0.06*)
	6	2.69 (*0.06*)	0.36 (*0.50*)	0.33 (*0.50*)	0.09 (*0.15*)	215 (*0.04*)
	7	3.18 (*0.17*)	1.64 (*0.53*)	0.82 (*0.53*)	0.20 (*0.22*)	301 (*0.05*)
	8	3.72 (*0.05*)	3.46 (*0.26*)	1.30 (*0.26*)	0.25 (*0.11*)	407 (*0.02*)
B10 (6 replicate)	Low Idle	0.16 (*0.21*)	0.01 (*1.44*)	0.01 (*1.45*)	0.01 (*0.14*)	6.83 (*0.41*)
	High Idle	0.25 (*0.09*)	0.07 (*0.25*)	0.03 (*0.25*)	0.01 (*0.16*)	15.1 (*0.16*)
	Dynamic Brake	0.22 (*0.10*)	0.07 (*0.50*)	0.03 (*0.50*)	0.01 (*0.20*)	14.3 (*0.07*)
	1	0.39 (*0.19*)	0.06 (*0.49*)	0.05 (*0.49*)	0.02 (*0.12*)	26.6 (*0.21*)
	2	0.63 (*0.21*)	0.06 (*0.41*)	0.05 (*0.41*)	0.03 (*0.08*)	40.7 (*0.19*)
	3	1.15 (*0.13*)	0.09 (*0.32*)	0.08 (*0.32*)	0.05 (*0.11*)	74.4 (*0.17*)
	4	1.52 (*0.15*)	0.16 (*0.31*)	0.14 (*0.31*)	0.09 (*0.19*)	108 (*0.15*)
	5	1.99 (*0.07*)	0.26 (*0.40*)	0.23 (*0.40*)	0.14 (*0.16*)	153 (*0.13*)
	6	2.42 (*0.04*)	0.39 (*0.17*)	0.32 (*0.18*)	0.18 (*0.13*)	204 (*0.04*)
	7	2.80 (*0.04*)	1.82 (*0.43*)	1.02 (*0.43*)	0.30 (*0.31*)	287 (*0.08*)
	8	3.17 (*0.05*)	6.33 (*0.17*)	2.25 (*0.17*)	0.38 (*0.05*)	387 (*0.04*)

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
B20 (6 replicate)	0.13 (*0.11*)	0.01 (*0.64*)	0.01 (*0.64*)	0.01 (*0.30*)	6.71 (*0.18*)	0.13 (*0.11*)
	0.24 (*0.08*)	0.03 (*0.24*)	0.03 (*0.24*)	0.01 (*0.20*)	14.8 (*0.10*)	0.24 (*0.08*)
	0.22 (*0.12*)	0.03 (*0.22*)	0.03 (*0.22*)	0.01 (*0.19*)	15.8 (*0.15*)	0.22 (*0.12*)
	0.47 (*0.12*)	0.02 (*0.37*)	0.04 (*0.37*)	0.02 (*0.10*)	28.0 (*0.14*)	0.47 (*0.12*)
	0.61 (*0.15*)	0.02 (*0.19*)	0.04 (*0.19*)	0.03 (*0.15*)	37.1 (*0.19*)	0.61 (*0.15*)
	1.06 (*0.17*)	0.04 (*0.36*)	0.07 (*0.36*)	0.04 (*0.11*)	67.4 (*0.23*)	1.06 (*0.17*)
	1.50 (*0.12*)	0.05 (*0.66*)	0.09 (*0.66*)	0.07 (*0.10*)	97.3 (*0.17*)	1.50 (*0.12*)
	2.04 (*0.07*)	0.09 (*0.43*)	0.16 (*0.43*)	0.09 (*0.08*)	146 (*0.10*)	2.04 (*0.07*)
	2.45 (*0.07*)	0.15 (*0.63*)	0.28 (*0.63*)	0.11 (*0.19*)	181 (*0.08*)	2.45 (*0.07*)
	3.22 (*0.13*)	0.38 (*0.16*)	0.51 (*0.52*)	0.18 (*0.55*)	282 (*0.08*)	3.22 (*0.13*)
	3.52 (*0.08*)	1.93 (*0.21*)	1.22 (*0.21*)	0.21 (*0.20*)	370 (*0.06*)	3.52 (*0.08*)
B40 (5 replicates)	0.17 (*0.15*)	0.02 (*0.60*)	0.01 (*0.60*)	0.01 (*0.30*)	8.64 (*0.32*)	0.17 (*0.15*)
	0.29 (*0.20*)	0.03 (*0.25*)	0.03 (*0.25*)	0.02 (*0.25*)	20.4 (*0.23*)	0.29 (*0.20*)
	0.24 (*0.16*)	0.03 (*0.53*)	0.02 (*0.53*)	0.03 (*0.24*)	18.6 (*0.24*)	0.24 (*0.16*)
	0.38 (*0.08*)	0.03 (*0.47*)	0.04 (*0.47*)	0.03 (*0.09*)	28.7 (*0.29*)	0.38 (*0.08*)
	0.46 (*0.13*)	0.03 (*0.23*)	0.03 (*0.23*)	0.02 (*0.27*)	36.7 (*0.18*)	0.46 (*0.13*)
	0.92 (*0.11*)	0.05 (*0.51*)	0.06 (*0.51*)	0.04 (*0.21*)	65.2 (*0.19*)	0.92 (*0.11*)
	1.35 (*0.21*)	0.06 (*0.33*)	0.08 (*0.33*)	0.05 (*0.09*)	90.0 (*0.19*)	1.35 (*0.21*)
	1.90 (*0.13*)	0.10 (*0.24*)	0.13 (*0.24*)	0.08 (*0.12*)	134 (*0.18*)	1.90 (*0.13*)
	2.38 (*0.09*)	0.10 (*0.42*)	0.13 (*0.42*)	0.10 (*0.13*)	166 (*0.27*)	2.38 (*0.09*)
	2.99 (*0.05*)	0.23 (*0.67*)	0.19 (*0.92*)	0.11 (*0.65*)	256 (*0.09*)	2.99 (*0.05*)
	3.09 (*0.13*)	1.70 (*0.16*)	0.76 (*0.16*)	0.23 (*0.06*)	364 (*0.12*)	3.09 (*0.13*)

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
B60 (6 replicates)	Low Idle	0.15 (*0.27*)	0.21 (*1.27*)	0.22 (*1.23*)	0.01 (*0.38*)	6.74 (*0.19*)
	High Idle	0.24 (*0.20*)	0.21 (*0.88*)	0.22 (*0.85*)	0.02 (*0.42*)	12.5 (*0.10*)
	Dynamic Brake	0.26 (*0.14*)	0.23 (*1.14*)	0.24 (*1.11*)	0.02 (*0.44*)	14.6 (*0.12*)
	1	0.51 (*0.22*)	0.07 (*0.59*)	0.14 (*0.59*)	0.03 (*0.36*)	26.8 (*0.12*)
	2	0.82 (*0.18*)	0.06 (*0.73*)	0.13 (*0.73*)	0.04 (*0.32*)	39.1 (*0.10*)
	3	1.62 (*0.18*)	0.11 (*0.82*)	0.12 (*0.82*)	0.06 (*0.41*)	79.3 (*0.09*)
	4	2.05 (*0.14*)	0.20 (*0.91*)	0.42 (*0.91*)	0.09 (*0.37*)	116 (*0.08*)
	5	2.71 (*0.15*)	0.30 (*1.54*)	0.62 (*1.55*)	0.13 (*0.42*)	157 (*0.11*)
	6	3.10 (*0.21*)	0.27 (*1.62*)	0.55 (*1.62*)	0.16 (*0.48*)	198 (*0.17*)
	7	3.73 (*0.17*)	0.32 (*1.32*)	0.41 (*1.32*)	0.20 (*0.63*)	273 (*0.27*)
	8	4.33 (*0.15*)	1.47 (*0.47*)	0.87 (*0.47*)	0.39 (*0.46*)	373 (*0.06*)
B80 (6 replicates)	Low Idle	0.09 (*0.58*)	0.04 (*0.58*)	0.02 (*0.58*)	0.01 (*0.17*)	5.02 (*0.55*)
	High Idle	0.19 (*0.16*)	0.07 (*0.34*)	0.05 (*0.34*)	0.01 (*0.09*)	12.4 (*0.14*)
	Dynamic Brake	0.21 (*0.29*)	0.07 (*0.40*)	0.05 (*0.40*)	0.01 (*0.13*)	14.4 (*0.29*)
	1	0.35 (*0.36*)	0.03 (*0.49*)	0.04 (*0.49*)	0.01 (*0.13*)	21.4 (*0.35*)
	2	0.54 (*0.34*)	0.03 (*0.28*)	0.04 (*0.28*)	0.02 (*0.18*)	34.7 (*0.28*)
	3	1.14 (*0.32*)	0.04 (*0.52*)	0.05 (*0.52*)	0.03 (*0.10*)	72.4 (*0.27*)
	4	1.54 (*0.30*)	0.06 (*0.21*)	0.07 (*0.21*)	0.04 (*0.06*)	108 (*0.21*)
	5	2.12 (*0.25*)	0.06 (*0.72*)	0.08 (*0.72*)	0.05 (*0.08*)	157 (*0.20*)
	6	2.56 (*0.22*)	0.16 (*0.55*)	0.17 (*0.55*)	0.08 (*0.23*)	205 (*0.19*)
	7	3.26 (*0.17*)	0.43 (*0.11*)	0.28 (*0.11*)	0.22 (*0.16*)	304 (*0.11*)
	8	3.87 (*0.09*)	1.28 (*0.34*)	0.39 (*0.34*)	0.25 (*0.10*)	391 (*0.04*)

Fuel	Notch Position	NO as NO$_2$ (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO$_2$ (g/s)
B100 (4 replicates)	Low Idle	0.15 (*0.14*)	0.12 (*0.27*)	0.05 (*0.27*)	0.01 (*0.08*)	8.53 (*0.09*)
	High Idle	0.25 (*0.11*)	0.21 (*0.20*)	0.08 (*0.20*)	0.01 (*0.13*)	15.9 (*0.07*)
	Dynamic Brake	0.26 (*0.16*)	0.26 (*0.33*)	0.10 (*0.33*)	0.01 (*0.19*)	16.8 (*0.17*)
	1	0.47 (*0.15*)	0.28 (*0.32*)	0.10 (*0.32*)	0.01 (*0.17*)	32.5 (*0.12*)
	2	0.62 (*0.24*)	0.20 (*0.42*)	0.09 (*0.42*)	0.02 (*0.20*)	42.8 (*0.20*)
	3	1.36 (*0.12*)	0.13 (*0.30*)	0.09 (*0.30*)	0.03 (*0.27*)	92.2 (*0.07*)
	4	1.79 (*0.04*)	0.17 (*0.40*)	0.11 (*0.40*)	0.04 (*0.18*)	130 (*0.01*)
	5	2.30 (*0.04*)	0.21 (*0.64*)	0.13 (*0.64*)	0.05 (*0.05*)	179 (*0.01*)
	6	2.79 (*0.03*)	0.20 (*0.31*)	0.14 (*0.31*)	0.07 (*0.08*)	227 (*0.02*)
	7	3.32 (*0.10*)	0.48 (*0.37*)	0.24 (*0.37*)	0.15 (*0.06*)	299 (*0.10*)
	8	3.88 (*0.06*)	1.50 (*0.32*)	0.36 (*0.32*)	0.27 (*0.15*)	404 (*0.01*)

(c) NC 1859 – F59PH Locomotive

Fuel	Notch Position	NO as NO$_2$ (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO$_2$ (g/s)
ULSD (6 replicates)	Low Idle	0.16 (*0.11*)	0.05 (*1.13*)	0.02 (*1.13*)	0.02 (*0.08*)	7.73 (*0.24*)
	High Idle	0.22 (*0.11*)	0.22 (*0.82*)	0.09 (*0.82*)	0.02 (*0.11*)	13.4 (*0.18*)
	Dynamic Brake	0.24 (*0.08*)	0.18 (*1.03*)	0.08 (*1.03*)	0.02 (*0.09*)	15.5 (*0.15*)
	1	0.45 (*0.10*)	0.22 (*0.60*)	0.09 (*0.60*)	0.03 (*0.08*)	27.7 (*0.18*)
	2	0.70 (*0.03*)	0.15 (*0.63*)	0.10 (*0.63*)	0.04 (*0.09*)	41.7 (*0.09*)
	3	1.27 (*0.03*)	0.30 (*1.64*)	0.22 (*1.64*)	0.06 (*0.10*)	81.4 (*0.08*)
	4	1.77 (*0.06*)	0.16 (*0.73*)	0.12 (*0.73*)	0.09 (*0.17*)	110 (*0.07*)
	5	2.24 (*0.03*)	0.17 (*0.98*)	0.14 (*0.98*)	0.12 (*0.13*)	162 (*0.05*)
	6	2.68 (*0.08*)	0.22 (*0.68*)	0.19 (*0.68*)	0.17 (*0.29*)	201 (*0.08*)
	7	2.87 (*0.07*)	0.23 (*0.97*)	0.19 (*0.97*)	0.22 (*0.25*)	263 (*0.09*)
	8	3.66 (*0.04*)	1.87 (*0.11*)	0.66 (*0.11*)	0.33 (*0.13*)	365 (*0.01*)

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
B10 (6 replicates)	Low Idle	Low Idle	0.14 (*0.24*)	0.15 (*0.47*)	0.07 (*0.47*)	0.01 (*0.20*)
	High Idle	High Idle	0.21 (*0.19*)	0.20 (*0.37*)	0.09 (*0.37*)	0.01 (*0.18*)
	Dynamic Brake	Dynamic Brake	0.23 (*0.22*)	0.22 (*0.36*)	0.10 (*0.36*)	0.01 (*0.19*)
	1	1	0.41 (*0.21*)	0.09 (*0.63*)	0.08 (*0.63*)	0.01 (*0.20*)
	2	2	0.61 (*0.23*)	0.09 (*0.71*)	0.08 (*0.71*)	0.02 (*0.19*)
	3	3	1.23 (*0.23*)	0.11 (*0.50*)	0.09 (*0.50*)	0.02 (*0.17*)
	4	4	1.66 (*0.24*)	0.11 (*0.66*)	0.10 (*0.66*)	0.03 (*0.21*)
	5	5	2.13 (*0.24*)	0.15 (*0.61*)	0.13 (*0.61*)	0.04 (*0.17*)
	6	6	2.61 (*0.22*)	0.16 (*0.55*)	0.13 (*0.55*)	0.05 (*0.14*)
	7	7	3.28 (*0.20*)	0.23 (*0.85*)	0.13 (*0.83*)	0.12 (*0.19*)
	8	8	3.62 (*0.20*)	0.64 (*0.50*)	0.23 (*0.50*)	0.19 (*0.20*)
B20 (15 replicates)	Low Idle	Low Idle	0.13 (*0.78*)	0.10 (*0.76*)	0.09 (*0.45*)	0.02 (*0.47*)
	High Idle	High Idle	0.33 (*0.26*)	0.16 (*0.90*)	0.15 (*0.35*)	0.02 (*0.53*)
	Dynamic Brake	Dynamic Brake	0.21 (*0.30*)	0.16 (*0.77*)	0.14 (*0.36*)	0.02 (*0.53*)
	1	1	0.40 (*0.41*)	0.07 (*0.75*)	0.12 (*0.35*)	0.02 (*0.52*)
	2	2	0.60 (*0.52*)	0.07 (*0.96*)	0.11 (*0.58*)	0.03 (*0.49*)
	3	3	1.17 (*0.54*)	0.08 (*0.89*)	0.14 (*0.64*)	0.03 (*0.44*)
	4	4	1.60 (*0.57*)	0.07 (*0.69*)	0.12 (*0.57*)	0.05 (*0.38*)
	5	5	2.09 (*0.55*)	0.10 (*0.88*)	0.18 (*0.85*)	0.06 (*0.43*)
	6	6	2.49 (*0.40*)	0.10 (*1.05*)	0.17 (*0.63*)	0.06 (*0.39*)
	7	7	3.27 (*0.30*)	0.19 (*0.91*)	0.26 (*0.65*)	0.14 (*0.36*)
	8	8	3.60 (*0.31*)	0.54 (*1.36*)	0.34 (*0.42*)	0.18 (*0.18*)

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
B40 (6 replicates)	Low Idle	0.15 (*0.12*)	0.07 (*0.26*)	0.05 (*0.26*)	0.02 (*0.07*)	7.10 (*0.06*)
	High Idle	0.24 (*0.08*)	0.09 (*0.29*)	0.07 (*0.26*)	0.01 (*0.20*)	13.9 (*0.30*)
	Dynamic Brake	0.25 (*0.12*)	0.11 (*0.27*)	0.08 (*0.27*)	0.01 (*0.08*)	14.8 (*0.11*)
	1	0.45 (*0.14*)	0.06 (*0.41*)	0.07 (*0.40*)	0.02 (*0.11*)	25.6 (*0.10*)
	2	0.61 (*0.16*)	0.05 (*0.38*)	0.05 (*0.45*)	0.02 (*0.14*)	35.3 (*0.14*)
	3	1.39 (*0.09*)	0.07 (*0.48*)	0.08 (*0.48*)	0.03 (*0.05*)	77.7 (*0.06*)
	4	1.90 (*0.07*)	0.07 (*0.27*)	0.09 (*0.27*)	0.05 (*0.08*)	110 (*0.05*)
	5	2.53 (*0.04*)	0.08 (*0.51*)	0.11 (*0.51*)	0.06 (*0.09*)	152 (*0.06*)
	6	3.05 (*0.05*)	0.09 (*0.41*)	0.11 (*0.41*)	0.06 (*0.06*)	195 (*0.05*)
	7	3.81 (*0.07*)	0.26 (*0.37*)	0.23 (*0.35*)	0.10 (*0.12*)	271 (*0.07*)
	8	4.43 (*0.07*)	0.72 (*0.26*)	0.32 (*0.26*)	0.15 (*0.10*)	362 (*0.04*)

Italicized values in parentheses are coefficients of variation (standard deviation divided by the mean) on the mean emission rate.

NO_x includes NO and NO_2. Only NO was measured. Results include multiplicative correction factors based on NO and NO_2 measurements of the prime mover engines in the rail yard with a SEMTECH-DS PEMS, temperature, and humidity.

HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factors based on FID measurements of the prime mover engines in the rail yard with a SEMTECH-DS PEMS.

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

Table I-2: Time-Based Cycle Average Emission Rates from Over-the-Rail Biodiesel Measurements of Prime Mover Engines

Locomotive	Fuel	Cycle Average Emission Rate (g/s)				
		NO_x[a]	HC[b]	CO	PM[c]	CO_2
NC 1797 (F59PHI)	ULSD	3.61 (*0.05*)	0.53 (*0.21*)	0.77 (*0.46*)	0.04 (*0.09*)	98.3 (*0.09*)
	B10	3.22 (*0.13*)	0.26 (*0.45*)	0.61 (*0.32*)	0.04 (*0.10*)	108 (*0.05*)
	B20	3.25 (*0.15*)	0.09 (*0.36*)	0.45 (*0.34*)	0.03 (*0.13*)	93.4 (*0.09*)
	B40	4.34 (*0.13*)	0.45 (*0.32*)	0.92 (*0.31*)	0.05 (*0.30*)	105 (*0.04*)
NC 1810 (F59PH)	ULSD	1.80 (*0.15*)	1.38 (*0.22*)	0.83 (*0.32*)	0.06 (*0.09*)	110 (*0.05*)
	B10	1.63 (*0.10*)	2.42 (*0.22*)	0.25 (*1.33*)	0.10 (*0.07*)	104 (*0.05*)
	B20	1.81 (*0.12*)	0.81 (*0.20*)	0.18 (*0.30*)	0.06 (*0.17*)	97.7 (*0.10*)
	B40	1.26 (*0.20*)	0.52 (*0.29*)	0.03 (*0.36*)	0.06 (*0.09*)	96.1 (*0.08*)
	B60	2.18 (*0.14*)	0.75 (*0.37*)	0.32 (*0.60*)	0.10 (*0.42*)	100 (*0.10*)
	B80	1.84 (*0.26*)	0.54 (*0.49*)	0.46 (*0.37*)	0.06 (*0.12*)	101 (*0.09*)
	B100	1.91 (*0.13*)	0.72 (*0.35*)	0.57 (*0.26*)	0.06 (*0.14*)	110 (*0.05*)
NC 1859 (F59PH)	ULSD	1.90 (*0.09*)	0.90 (*0.21*)	0.88 (*0.71*)	0.09 (*0.14*)	179 (*0.11*)
	B10	1.70 (*0.24*)	0.32 (*0.48*)	0.71 (*0.31*)	0.05 (*0.16*)	155 (*0.14*)
	B20	1.65 (*0.11*)	0.26 (*0.79*)	0.62 (*0.78*)	0.05 (*0.22*)	151 (*0.11*)
	B40	2.05 (*0.12*)	0.32 (*0.33*)	0.38 (*0.35*)	0.04 (*0.07*)	157 (*0.11*)
Average of All Locomotives	ULSD	2.44 (*0.36*)	0.94 (*0.44*)	0.83 (*0.50*)	0.06 (*0.39*)	179 (*0.11*)
	B10	2.18 (*0.38*)	1.00 (*1.08*)	0.52 (*0.60*)	0.06 (*0.47*)	166 (*0.12*)
	B20	2.00 (*0.34*)	0.35 (*0.88*)	0.48 (*0.85*)	0.05 (*0.33*)	159 (*0.14*)
	B40	2.63 (*0.53*)	0.42 (*0.36*)	0.47 (*0.87*)	0.05 (*0.23*)	159 (*0.18*)

Italicized values in parentheses are coefficients of variation (standard deviation divided by the mean) on the mean emission rate.

[a] NO_x includes NO and NO_2. Only NO was measured. Results include multiplicative correction factors based on NO and NO_2 measurements of the prime mover engines in the rail yard with a SEMTECH-DS PEMS, temperature, and humidity.

[b] HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds but responds only partially to others. Results include multiplicative correction factors based on FID measurements of the prime mover engines in the rail yard with a SEMTECH-DS PEMS.

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

Appendix J

Lube Oil Analysis Results

As a part of the 90-day inspection of each locomotive in the NCDOT fleet, oil samples are taken from the prime mover engines and sent to a fluid analysis laboratory. These fluid analyses characterize wear metals present in the oil, as well as oil condition. Each set of lubricating oil analyses is given one of three color-coded conclusions: (1) Green: No Action Required; (2) Yellow: Monitor; and (3) Red: Action Required.

According to a member of the fluid analysis laboratory, these color-coded conclusions are based on trends among wear metals over previous samples. There are not any specific criteria that determine the conclusions made; the conclusions are based on the discretion of the laboratory analyst. In general, there are ranges in metal concentrations that the laboratory analyst looks for to determine whether engine wear may be present. However, these concentration ranges are proprietary and not available to the public.

It is apparent that, over time, most of the locomotives in the NCDOT fleet have had oil analyses come back with recommendations from the laboratory to monitor (yellow) or take action on (red) the lubricating oil. Based on the comments given on the oil analysis reports, the four wear metals that lead to results being coded yellow or red are copper (Cu), iron (Fe), tin (Sn), and Lead (Pb). In order to assess the trends of these four wear metals over time for each engine, reported concentrations were graphed. For the oil analysis that return coded yellow or red, an increasing trend in the concentration of one or more of these wear metals is observed.

Table J-1: Summary of Oil Analyses of Prime Mover Engines in the NCDOT Locomotive Fleet

(a) NC 1797 (F59PHI)

Date	Summary	Fuel
9/1/2010	No Action Required	ULSD
12/8/2010	No Action Required	ULSD
3/14/2011	No Action Required	ULSD
8/6/2012	Monitor: Wear metals and oil additives have changed a great deal; silicon levels may indicate some dirt entry or may be residue from a recent repair; iron, tin, and lead have increase and may indicate some crank and bearing wear	ULSD
8/15/2012	Action Required: Copper, iron, tin, and lead have increased and may indicate some crank and bearing wear	ULSD
2/14/2013	Action Required: Copper, lead and tin remains elevated. Possible bearing wear.	ULSD
5/7/2013	Action Required: Copper, lead and tin are increasing. Possible bearing wear.	ULSD

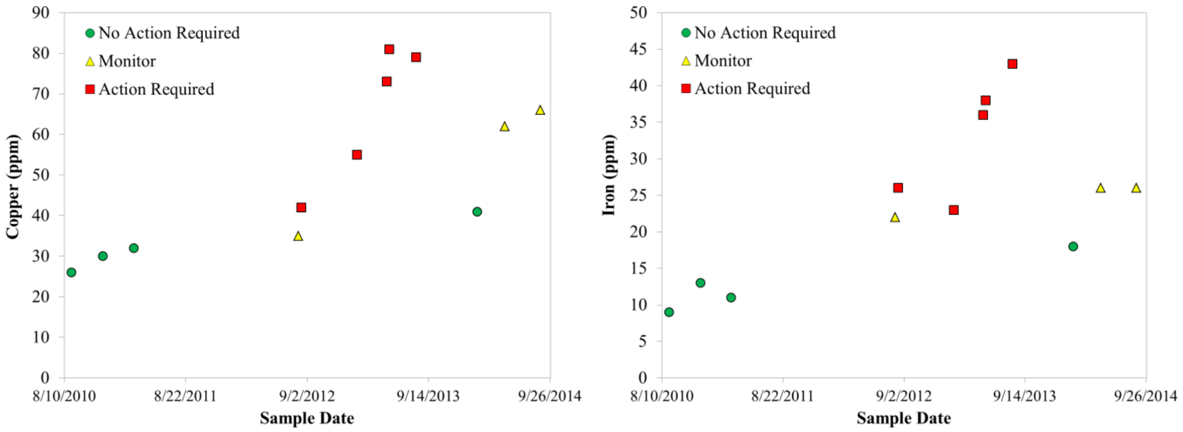
5/15/2013	Action Required: Copper, lead and tin are increasing. Possible bearing wear.	ULSD
8/6/2013	Action Required: Copper, lead and tin remain elevated. Possible bearing wear.	ULSD
11/8/2013	No Action Required	ULSD
2/12/2014	No Action Required	ULSD
5/9/2014	Monitor: Lead and tin are elevated. Possible bearing wear.	B40
8/28/2014	Monitor: Copper, lead, and tin are elevated. Possible bearing wear.	B10/B20

(b) NC 1810 (F59PH)

Date	**Summary**	**Fuel**
12/21/2010	No Action Required	ULSD
8/21/2011	No Action Required	ULSD
3/8/2012	No Action Required	ULSD
6/4/2012	No Action Required	ULSD
8/15/2012	Monitor: Iron and lead continue to increase and may indicate some crank and bearing wear	B10
2/22/2013	No Action Required	B10/B20/B40
9/8/2013	No Action Required	B20/B60
1/14/2014	No Action Required	B60/B80
3/10/2014	No Action Required	B100/ULSD
6/12/2014	No Action Required	ULSD

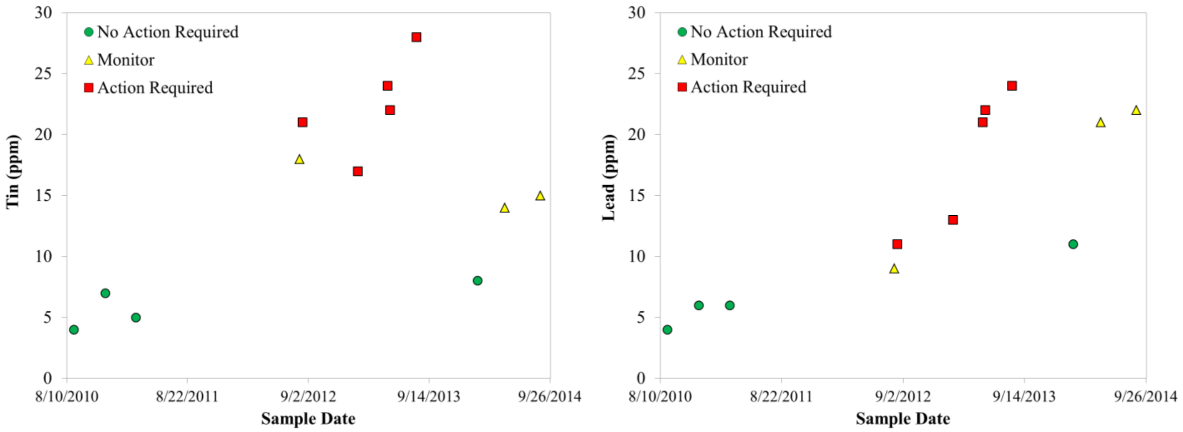
(c) NC 1859 (F59PH)

Date	**Summary**	**Fuel**
12/20/2011	Monitor: Copper, tin, and lead are higher than normal and may indicate some bearing wear	ULSD
3/18/2012	Monitor: No significant increase in wear detected	ULSD
6/19/2012	No Action Required	ULSD
9/14/2012	No Action Required	ULSD
12/25/2012	No Action Required	ULSD
3/27/2013	No Action Required	ULSD
6/29/2013	No Action Required	ULSD
9/21/2013	No Action Required	ULSD/B40
12/31/2013	No Action Required	B20/B40
3/24/2014	No Action Required	ULSD
6/25/2014	No Action Required	ULSD



(a) Copper (Cu)

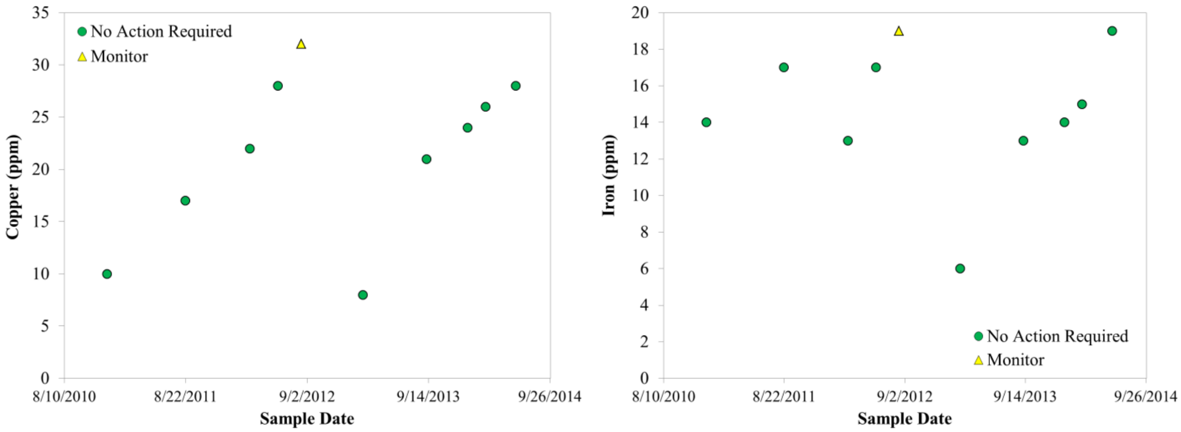
(b) Iron (Fe)



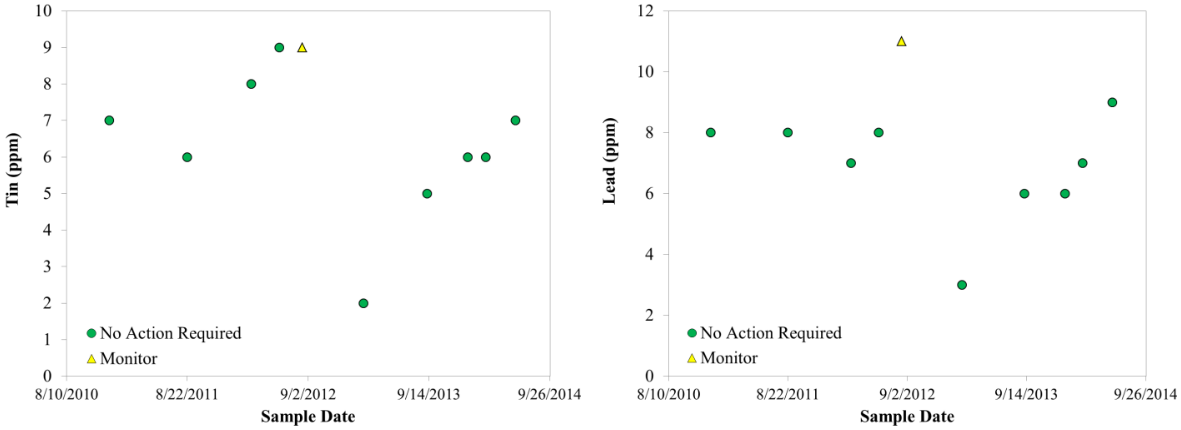
(c) Tin (Sn)

(d) Lead (Pb)

Figure J-1: Wear Metal Concentrations in Oil Samples from the NC 1797 Prime Mover Engine

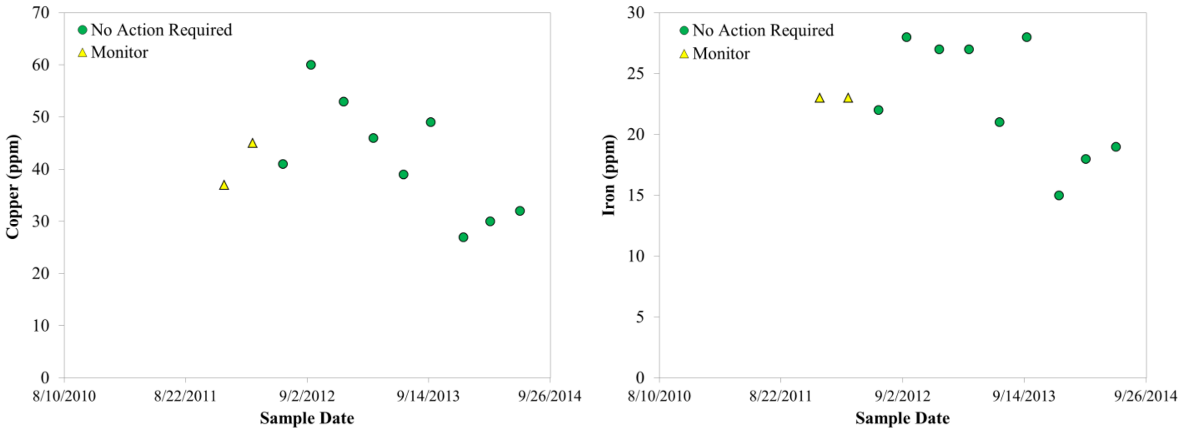


(a) Copper (Cu) (b) Iron (Fe)

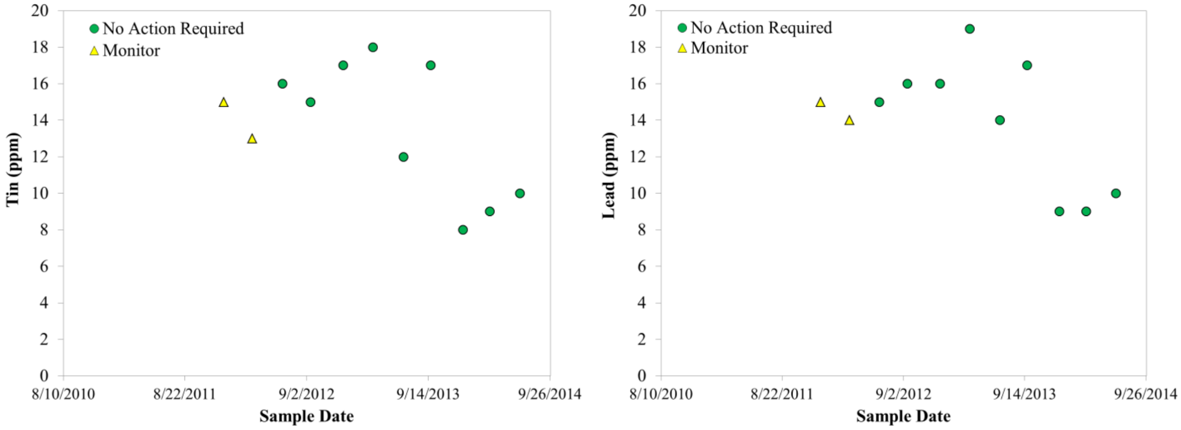


(c) Tin (Sn) (d) Lead (Pb)

Figure J-2: Wear Metal Concentrations in Oil Samples from the NC 1810 Prime Mover Engine



(a) Copper (Cu) (b) Iron (Fe)



(c) Tin (Sn) (d) Lead (Pb)

Figure J-3: Wear Metal Concentrations in Oil Samples from the NC 1859 Prime Mover Engine