Measurement and Evaluation of Fuels and Technologies for Passenger Rail Service in North Carolina

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16. Abstract
The purpose of this project is to measure a baseline for fuel use and emission rates on the rebuilt or replaced engines on each locomotive in the NCDOT Rail Division fleet, using ultra-low sulfur diesel (ULSD) fuel; measure real-world, in-use "over-the-rail" activity, fuel use, and emissions for service between Raleigh and Charlotte; assess the avoided fuel use and emissions from substitution of automobile trips with rail service based on real-world data obtained in this research for the train service and real-world highway vehicle data obtained in recent previous research; and conduct an evaluation of the emissions implications of B20 biodiesel versus ULSD using a life cycle inventory approach that takes into account the fuel cycle, as well as locomotive emissions. The methodology features the use of portable emissions measurement systems (PEMS).

The results of this project will enable the NCDOT Rail Division to accurately assess the fuel use and emissions benefits of the engine rebuilds and replacements, the use of alternative fuel, and the energy and emissions benefits of passenger rail service compared to the avoided highway vehicle usage. These data can be used to identify priorities for further emission reduction measures, if needed, and to claim credit for the energy and environmental benefits of rail transportation. These data and information will be useful to the NCDOT Rail Division as the basis for determining the energy and emissions benefits of B20 and of rail versus highway transportation and, thus, as an input to prioritizing future activity pertaining to asset management and community relations.

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INTRODUCTION

In 2008, the National Railroad Passenger Corporation, better known as AMTRAK, used nearly 300 locomotives to move over 29 million people on 21,000 miles of track in 46 states, 3 Canadian provinces, and the District of Columbia (AMTRAK, 2010). One of those states is North Carolina, where the state's Department of Transportation (NCDOT) financially sponsors the operation of the Piedmont – passenger rail service between Raleigh and Charlotte with four trains daily. An existing fleet of six in-service passenger locomotives operates the Piedmont. These locomotives have been remanufactured and, therefore, must meet new locomotive emission standards finalized by the U.S. Environmental Protection Agency (EPA) in 2008.

The purpose of this project is to measure a baseline for fuel use and emission rates on the rebuilt or replaced engines on each locomotive in the NCDOT Rail Division fleet, using ultra-low sulfur diesel (ULSD) fuel; measure real-world, in-use "over-the-rail" activity, fuel use, and emissions for service between Raleigh and Charlotte; assess the avoided fuel use and emissions from substitution of automobile trips with rail service based on real-world data obtained in this research for the train service and real-world highway vehicle data obtained in recent previous research; and conduct an evaluation of the emissions implications of B20 biodiesel versus ULSD using a life cycle inventory approach that takes into account the fuel cycle, as well as locomotive emissions. The methodology features the use of portable emissions measurement systems (PEMS).

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The fleet of locomotives currently includes two F59PHIs and four F59PHs. A GP40 locomotive previously was in service. All are configured for passenger rail service. Each locomotive has a main, prime mover engine used to provide direct current (DC) electric power for propulsion, and a second engine used to generate alternating current (AC) power for "hotel services" in passenger cars. The latter is referred to as a "head-end power" (HEP) engine. Each engine from each of six locomotives was measured in this project.

North Carolina State University (NCSU) has been a pioneer in the development and application of procedures for real-world data collection of in-use vehicles using a PEMS. Beginning in 1999, NCSU has conducted field studies of the activity, fuel use, and emissions of light duty vehicles (Frey *et al*., 2003). Beginning in 2004, NCSU conducted field studies on comparison of B20 versus petroleum diesel for heavy-duty diesel vehicles, including dump trucks, concrete mixer trucks, and nonroad equipment (Frey and Kim, 2006; Frey *et al.*, 2008b; Frey and Kim, 2009). Since 2005, NCSU has been conducting field studies on nonroad vehicles, including bulldozers, backhoes, front-end loaders, motor graders, excavators, off-road dump trucks, and skid steer loaders (Frey *et al*., 2008a&c). NCSU has provided technical assistance on several other projects, including assessment of actvity, fuel use, and emissions of vehicles on dirt versus paved roads, assessment of light-duty diesel vehicle emissions in England, and assessment of the effect of fuel additives on fuel use and emissions. These projects have been sponsored by the NCDOT, National Science Foundation (NSF), Texas Transportation Institute (TTI), and Imperial College (London, England) Consultants.

NCSU has completed several technical assistance projects for the NCDOT Rail Division that forms a foundation for this study. These include an assessment of locomotive emission standards and technological alternatives for compliance with the standards, and rail yard measurements (prior to the scheduled rebuild and replacements) of the fuel use and emission rates of the prime mover and HEP engines on ULSD for each of three locomotives using a PEMS (Frey and Choi, 2008). These measurements established emission rates for nitric oxide (NO), carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), and particulate matter (PM) on both a mass per time (g/sec) and mass per fuel consumed (g/gal) basis. Another project involved dynamometer measurements of the fuel use and emission rates of the prime mover engine for each of three locomotives using a PEMS during the engine rebuild process (Frey and Graver, 2010).

This report is divided into eight chapters. This chapter introduces the purpose and importance of the locomotive research. Chapter 2 provides background on locomotive exhaust emission measurement techniques, emission factors, and emission standards. Two methods of testing that were conducted, rail yard and over-the-rail, are discussed in Chapters 3 and 4, respectively, and include testing results for the NCDOT locomotive fleet. Emission factors and duty cycles from over-the-rail testing are used in Chapter 5 to quantify and compare the avoided emissions attributable to the reduction in personal automobile trips by rail passengers. Chapter 6 quantifies the fuel use and emission rates of passenger rail for diesel and biodiesel use, and quantifies fuel cycle emissions using a life cycle inventory approach. Key findings, conclusions, and recommendations from the research are included in Chapter 7. Additional information not contained in the report text, such as the checklists used in emissions measurements, equations used in the calculation of fuel use and emission rates, and observed over-the-rail duty cycles, are included in the Appendices.

1.0 BACKGROUND

This section provides background regarding: emissions measurement methods for heavy-duty vehicles such as locomotives; locomotive emission standards; duty cycles for locomotives; and existing emissions data for locomotives. Emission factors estimated in the rail yard and over-the-rail testing chapters are compared to the literature-cited locomotive emission factors and standards provided in this chapter.

1.1 Emission Measurement Methods

Commonly used methods for measuring nonroad vehicle emissions include engine dynamometers and on-board measurement. Available data regarding locomotive emissions is typically from engine dynamometer measurements (EPA, 1998). These data are reported in units of grams per brake horsepower-hour (g/bhp-hr). Engine dynamometer test cycles are based upon steady-state modal tests that may not be representative of real-world emissions. However, engine dynamometer tests are the basis for certifying compliance with applicable emission standards.

On-board emissions measurement systems offer the advantage of being able to capture real-world emission during an entire duty cycle (Frey *et al*., 2008a). In particular, PEMS are more easily installed in multiple vehicles than complex on-board systems, and are selected for use in this project.

To describe the advantages of the PEMS method, we compare it to the Federal Reference Method (FRM) approved by the U.S. Environmental Protection Agency (EPA). Standards for locomotive emissions testing are found in Part 1033 of CFR Title 40 (EPA, 2008). The FRM is intended to measure brake-specific mass emissions of nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), particulate matter (PM), and smoke sampled directly from the exhaust stream at each throttle position. Smoke is defined as the "matter in the engine exhaust which obscures the transmission of light." This method focuses primarily on emissions from diesel locomotive engines, but includes provisions for alternative fuels.

FRM engine testing is to be performed in a fixed setting, either with a dynamometer or alternator/generator configuration. The dynamometer or alternator/generator configuration must be able to control engine torque and speed simultaneously at steady-speed operation and during acceleration. The engine dynamometer is configured to absorb shaft power produced by the prime mover. A water brake dynamometer transfers power from the engine shaft through a turbine or propeller into the working fluid contained inside the housing, which is restrained by a torque meter. The torque meter measures power as the housing attempts to rotate due to the torque produced by the engine. Engine speed (RPM) is measured by a tachometer (Frey and Graver, 2010).

Under the FRM, fuel consumption is measured continuously on either a weight or volume per time flow rate basis. The fuel consumption value is the one-minute average taken during the last minute of the sampling period; however, the measured value for fuel consumption during idle notch position is the three-minute average taken during the last three minutes of a minimum sampling period.

In the FRM, mass emissions of each pollutant are measured continuously using the following detection methods:

- CO and CO_2 using a non-dispersive infrared (NDIR) analyzer.
- HC using a heated flame ionization detector (HFID) analyzer.
- NO_x using a chemiluminescence (CL) analyzer.
- PM using gravimetric analysis and flow meters. PM sample filters are removed at regular intervals and replaced; flow meters are placed in series, just before the filter.
- Smoke opacity using light scattering. Exhaust is passed between a light source and a sensor; opacity is found by measuring the light transmission loss through the exhaust smoke.

Water traps or other means of condensing water and removing it from the exhaust stream are required.

The FRM procedure includes several steps. After the engine has been sufficiently prepared for normal operation and all specified testing equipment has been connected and initialized, the engine is warmed up to the required operating temperature. Sample measurement and collection proceeds according to a specified test sequence. Engine measurements and emission samples are recorded on a minimum frequency of 10 seconds. Engine speed, power output, and emissions data is monitored and maintained within the established tolerance limits.

Compared to the FRM, PEMS have some similarities, differences, advantages, and disadvantages. PEMS are similar to the FRM for some of the detection methods. For example, similar to the FRM, NDIR is used for CO_2 and CO measurement, and light scattering is used to measure opacity. PEMS use different detection methods than the FRM for HC (NDIR instead of HFID) and for NO_x (electrochemical sensor instead of chemiluminescence), and are not currently capable of a gravimetric measurement of PM. PEMS have the advantage of being portable and deployable on-board the locomotive, enabling measurements at a rail yard or on-board during over-the-rail operations. Furthermore, PEMS equipment and measurements are far less expensive than FRM measurements. PEMS can provide useful quantification of relative differences in emissions. The measurements of emissions are accurate for CO_2. Although the PEMS measurements are accurate for CO, the detection limit of the repair grade gas analyzer used in the PEMS is typically greater than the low concentrations of CO that are emitted from diesel engines. The HC measurement is known to be biased low, because NDIR responds only partially to molecules other than straight-chain alkanes (Stephens *et al.*, 1996). A typical correction factor to adjust NDIR HC measurements to a “corrected” value is approximately 2. The nitric oxide (NO) measurement is accurate; however, NO is only one component of NO_x, which also includes nitrogen dioxide (NO_2). NO_x emissions are typically 90 to 95 percent NO, by volume (Seinfeld and Pandis, 1998). Therefore, the NO measurement of the PEMS is a good indicator of NO_x emissions.

The FRM methods have the advantage of providing the greatest degree of sensitivity, precision, and accuracy, but are more expensive than PEMS measurements. Furthermore, there are few

FRM facilities in the U.S. for measuring locomotive emissions. Therefore, there are costly logisitics to transport a locomotive engine to one of the small number of facilities, and opportunity costs due to the lack of availability of the engine for revenue generating operation, in addition to the direct costs of the FRM measurements themselves. With PEMS, the locomotive can be measured during scheduled rebuild activity, rail yard time, or while in service.

1.2 Emissions Standards for Locomotives

The EPA established emissions regulations for locomotives in 1997, and revised them in 2008 (EPA, 2009). The standards for line-haul and switching locomotives are shown in Table 2-1. Line-haul refers to freight and passenger transport. Switching refers to rail yard work.

In the 1997 EPA regulations, three sets of emission standards were adopted and are referred to as Tiers 0, 1, and 2. The applicability of the standards depends on the date by which a locomotive is manufactured (EPA, 1998). Tier 0 standards apply to locomotives and prime mover engines originally manufactured from 1973 to 2001. Tier 1 standards apply to locomotives and prime mover engines originally manufactured from 2002 to 2004. Newly produced locomotives in 2005 to 2011 are subject to Tier 2 standards. For Tiers 0 to 2, locomotives and their prime mover engines are required to meet the applicable standards at the time of original manufacture and each subsequent remanufacture.

The 2008 EPA regulations introduce more stringent emission standards for Tiers 0 to 2 (referred to as Tier 0+ to 2+) compared to the 1997 standard, and also create new Tiers 3 and 4 standards for locomotive and their prime mover engines produced after 2012 and 2015, respectively. Any locomotive engine that is manufactured or remanufactured must now achieve the 2008 EPA exhaust emission standards.

For the HEP engines, the EPA emission standards for nonroad compression-ignition engines apply (EPA, 2011). The emission standards regulating HEP engine emissions are discussed further in Section 2.3.

1.3 Locomotive Duty Cycles

The EPA locomotive emission standards are based on the average amount of time spent by the prime mover in a specific throttle position and the associated emission factors for each throttle position. The emission factors used by EPA are obtained from engine dynamometer test methods that measure shaft brake horsepower over time. A throttle that has a predetermined "notch" setting controls the prime mover engine load. Emissions measurements typically involve characterization of the emission factor for each notch setting for a particular engine. The measurements in a notch setting are typically a steady-state measurement. The steady-state emission factors for each notch setting are weighted to arrive at an average emission rate for a duty cycle. EPA developed locomotive emission standards based on the notch emission factors weighted by two typical duty cycles: line-haul and switching (EPA, 1998). Line-haul freight engines characteristically have large prime mover engines (e.g., 4,000 to 6,000 horsepower). Typically, switching locomotives have prime mover engines of 2,000 horsepower or less. The duty cycles for line-haul, passenger, and switching operation are summarized in Table 2-2. The passenger locomotive duty cycle is used for informational, and not regulatory, purposes. The

Table 2-1. EPA Emissions Standards for Locomotive Prime Mover Engines

(a) 1997 EPA Standards for Locomotives

Standards Apply to Year of Original Manufacture	NO_x (g/bhp-hr)	CO (g/bhp-hr)	HC (g/bhp-hr)	PM (g/bhp-hr)
Tier 0 (1973-2001)				
Line-Haul	9.5	5.0	1.00	0.60
Switch	14.0	8.0	2.10	0.72
Tier 1 (2002-2004)				
Line-Haul	7.4	2.2	0.55	0.45
Switch	11.0	2.5	1.2	0.54
Tier 2 (2005-2011)				
Line-Haul	5.5	1.5	0.30	0.20
Switch	8.1	2.4	0.60	0.24

(b) 2008 EPA Standards for Locomotives that are New or Remanufactured (40 CFR Part 1033, Subpart B, 2008)

Standards Apply to Year of Original Manufacture	NO_x (g/bhp-hr)	CO (g/bhp-hr)	HC (g/bhp-hr)	PM (g/bhp-hr)
Tier 0+				
Line-Haul (1973-1992) [a, d]	8.0	5.0	1.00	0.22
Switch (1973-2001)	11.8	8.0	2.10	0.26
Tier 1+				
Line-Haul (1993-2004) [a]	7.4	2.2	0.55	0.22
Switch (2002-2004) [b]	11.0	2.5	1.20	0.26
Tier 2+				
Line-Haul (2005-2011) [a]	5.5	1.5	0.30	0.10 [e]
Switch (2005-2010) [b]	8.1	2.4	0.60	0.13 [e]
Tier 3				
Line-Haul (2012-2014)[c]	5.5	1.5	0.30	0.10[f]
Switch (2011-2014)	5.0	2.4	0.60	0.10
Tier 4				
Line-Haul (2015 or later)	1.3	1.5	0.14[g]	0.03
Switch (2015 or later)	1.3	2.4	0.14[g]	0.03

[a] Tier 0-2 line-haul locomotives must also meet switch standards of the same tier.
[b] Tier 1-2 switch locomotives must also meet line-haul standards of the same tier.
[c] Tier 3 line-haul locomotives must also meet Tier 2 switch standards.
[d] 1993-2001 locomotives that were not equipped with an intake air coolant system are subject to Tier 0 rather than Tier 1 standards.
[e] 0.24 g/bhp-hr until January 1, 2013.
[f] 0.20 g/bhp-hr until January 1, 2013.
[g] Manufacturers may elect to meet a combined NOx+HC standard of 1.4 g/bhp-hr for line-haul and 1.3 g/bhp-hr for switcher.

Source: 40 CFR 1033.101

EPA believes that it is not necessary to use a passenger-specific duty cycle because it is similar to the average line-haul cycle, with some differences such as increased idling time (EPA, 1998). However, the actual basis of, and representativeness of, these cycles is not well known.

As stated in Section 2.2, HEP emissions are regulated under EPA's nonroad compression-ignition engines exhaust emission standards, shown in Table 2-2. These emission standards are based on engine model year. The HEP engines used in the F59PH locomotives must meet the Tier 2 standards due to their manufacture in 2009: a non-methane hydrocarbon (NMHC) + NO_x emission limit of 6.4 g/kW-hr, a PM emission limit of 0.20 g/kW-hr, and a CO emission limit of 3.5 g/kW-hr (EPA, 2011). Due to the date of manufacture, the HEP engines used in the F59PHI and GP40 locomotives are not required to meet an emission standard. Once the rebuild of the F59PHI locomotives are complete, the HEP engines must also meet the applicable Tier 2 emission standards.

Table 2-2. Nonroad Compression-Ignition Engines Exhaust Emission Standards

Rated Power	Tier	Model Year	NMHC[a] (g/kW-hr)	NMHC + NO_x (g/kW-hr)	NO_x (g/kW-hr)	PM (g/kW-hr)	CO (g/kW-hr)
225 ≤ kW < 450	1	1996-2000	1.3[d]	---	9.2	0.54	11.4
	2	2001-2005	---	6.4	---	0.20	3.5
	3	2006-2010	---	4.0	---	0.20	3.5
	4	2011-2013[b]	---	4.0	---	0.02	3.5
		2014+[c]	0.19	---	0.40	0.02	3.5
450 ≤ kW < 560	1	1996-2001	1.3[d]	---	9.2	0.54	11.4
	2	2002-2005	---	6.4	---	0.20	3.5
	3	2006-2010	---	4.0	---	0.20	3.5
	4	2011-2013[b]	---	4.0	---	0.02	3.5
		2014+[c]	0.19	---	0.40	0.02	3.5
560 ≤ kW < 900	1	2000-2005	1.3[d]	---	9.2	0.54	11.4
	2	2006-2010	---	6.4	---	0.20	3.5
	3	2011-2014	0.40	---	3.5	0.10	3.5
	4	2015+[c]	0.19	---	3.5[e]	0.04[f]	3.5

[a] Non-methane hydrocarbons

[b] These standards are phase-out standards. Not more than 50 percent of a manufacturer's engine production is allowed to meet these standards during each model year of the phase-out period. Engines not meeting these standards must meet the final Tier 4 standards.

[c] These standards are phased-in during the indicated years. At least 50 percent of a manufacturer's engine production must meet these standards during each year of the phase-in. Engines not meeting these standards must meet the applicable phase-out standards.

[d] For Tier 1 engines, the standard is for total hydrocarbons.

[e] The NO_x standard for generator sets is 0.67 g/kW-hr.

[f] The PM standard for generator sets is 0.03 g/kW-hr.

Source: (EPA, 2011)

1.4 Previously Reported Locomotive Emissions Data

The purpose of this section is to identify data that can be compared with the measurements made in this project, in order to assess the validity of the measurements. While many emissions are reported in terms of g/bhp-hr, some emissions are reported in terms of mass per second (g/sec). Where possible, emission rates are converted to units of mass emitted per gallon of fuel consumed (g/gal). In real-world measurements using PEMS, it is not possible to measure bhp-hr of engine output, unless the locomotive has an onboard readout of engine power output. However, it is possible to measure g/sec emission rates, which are influenced by the size of the engine. A fuel-based emission factor is less sensitive to engine size, and thus can be used to compare the magnitude of emission rates for different engines.

Fuel-based emission factors can be calculated based on a carbon balance, assuming that all of the carbon in the fuel is emitted as CO_2, CO, and HC. The composition of the exhaust gas in terms of these components is measured using the PEMS. Thus, it is possible to estimate the fraction of total carbon that is embodied in CO_2, CO, and HC at any given second. The carbon in the exhaust originates from the carbon in the fuel. Thus, it is possible to estimate the ratio of carbon as CO compared to the total carbon in the fuel, and arrive at an emission factor in terms of grams of CO per gallon of fuel consumed. Similarly, a fuel-based HC emission factor can be derived. A fuel-based emission factor for NO can be derived based on the molar ratio of NO to CO_2 in the exhaust, and the portion of carbon in the fuel that is emitted as CO_2.

Table 2-3. EPA Duty Cycles for Locomotives

Throttle Notch	Percent Time in Notch		
	Line-haul	Passenger	Switch
Idle	38.0	47.4	59.8
Dynamic Brake	12.5	6.2	0.0
1	6.5	7.0	12.4
2	6.5	5.1	12.3
3	5.2	5.7	5.8
4	4.4	4.7	3.6
5	3.8	4.0	3.6
6	3.9	2.9	1.5
7	3.0	1.4	0.2
8	16.2	15.6	0.8

Source: (EPA, 1998)

1.4.1 Duty-Cycle Based Average Emission Rates Reported by EPA

EPA (1998) reports cycle average emission rates for many locomotives. The locomotive emissions data for NO_x, CO, HC, and PM were provided to EPA by locomotive manufacturers. These manufacturers include Electro-Motive Diesel, Inc. (EMD) and General Electric (GE). These emission rates are shown in Table 2-4. The cycle weighted horsepower (hp) refers to the weighted sum of the brake horsepower taking into account all throttle notch settings. The average emission rates shown are for the line-haul duty cycle.

For purposes of developing a basis for benchmark comparison of the measured emission rates in this project to literature data, an average emission rate among all of the locomotives is estimated. The benchmark weighted average emission rate among the tested locomotives is estimated based on the weighted product of the number of locomotives in the fleet and the average horsepower for each type of locomotive.

$$BER_i^{avg} = \frac{\sum N_j \, P_j \, BER_i}{\sum N_j \, P_j} \qquad (1)$$

Where,

BER_i^{avg}	=	weighted average brake-specific emission rate (g/bhp-hr) for species *i*
BER_i	=	brake-specific emission rate (g/bhp-hr) for species *i*
N_j	=	number of locomotives of engine model *j*
P_j	=	duty cycle average engine horsepower (hp) of engine model *j*

Since EPA emission factor data do not include CO_2, it is not possible to estimate the fuel-based emission factors based on a carbon balance. Instead, the fuel consumption rate must be estimated and multiplied with the bhp-hr based emission factors in order to arrive at a g/gal emission factor. Fuel consumption for engines is often reported as “fuel specific engine output” (FSEO). FSEO can vary from one engine to another, and can differ by engine load for a given engine. However, often only a generic FSEO value is reported or used in regulatory work. EPA reports a typical FSEO of 20.8 bhp-hr/gal (EPA, 1997). This conversion factor was calculated from data provided by the Southwest Research Institute (SwRI). It represents the conversion factor for locomotives manufactured in the mid-1990s (EPA, 1998). To enable comparison of the EPA data in Table 2-4 to test results produced in this project, the brake-specific emission rates are converted to fuel-based emission rates using EPA’s reported FSEO value, and the results are shown in Table 2-5.

Table 2-4. Baseline Engine Output-Based Line-Haul Duty Cycle Average Emission for Selected Locomotive Engines

Engine Model	Number in 1990 Fleet	Cycle Weighted Power (hp)	NO_x (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	PM (g/bhp-hr)
EMD16-645E3	1,562	853	13.64	0.48	1.85	0.29
EMD20-645E3	723	1,023	13.46	0.49	1.18	0.30
EMD16-645E3B	2,693	835	13.12	0.47	1.4	0.29
EMD16-645F3	232	988	15.54	0.49	1.33	0.30
EMD12-645F3B	6	769	11.52	0.35	1.17	0.25
EMD16-645F3B	400	1,073	15.23	0.33	0.63	0.25
EMD12-710G3	2	807	10.55	0.36	0.90	0.25
EMD16-710G3	537	1,084	11.55	0.38	0.52	0.26
EMD12-710G3A	17	846	10.75	0.15	1.09	0.25
EMD16-710G3A	250	1,086	11.04	0.21	2.30	0.25
GE12-2500	843	686	10.32	0.48	2.12	0.26
GE12-3000	145	819	10.56	0.45	1.73	0.24
GE12-3300	0	860	10.75	0.32	1.68	0.24
GE16-3000	801	839	11.35	0.73	2.44	0.41
GE16-3600	451	1,001	11.29	0.62	1.67	0.36
GE16-4100	1,029	1,127	11.23	0.58	1.44	0.34
Weighted Average			12.53	0.49	1.53	0.30

Source: (EPA, 1998)

Table 2-5. Estimated Baseline Fuel-Based Line-Haul Duty Cycle Average Emission Rates for Selected Locomotives

Engine Model	Number in 1990 Fleet	Cycle Weighted Power (hp)	NO_x (g/gal)[a]	HC (g/gal)[a]	CO (g/gal)[a]	PM (g/gal)[a]
EMD16-645E3	1562	853	284	10	38.5	6.0
EMD20-645E3	723	1,023	280	10	24.5	6.2
EMD16-645E3B	2693	835	273	10	29.1	6.0
EMD16-645F3	232	988	323	10	27.7	6.2
EMD12-645F3B	6	769	240	7.3	24.3	5.2
EMD16-645F3B	400	1,073	317	6.9	13.1	5.2
EMD12-710G3	2	807	219	7.5	18.7	5.2
EMD16-710G3	537	1,084	240	7.9	10.8	5.4
EMD12-710G3A	17	846	224	3.1	22.7	5.2
EMD16-710G3A	250	1,086	230	4.4	47.8	5.2
GE12-2500	843	686	215	10	44.1	5.4
GE12-3000	145	819	220	9.4	36.0	5.0
GE12-3300	0	860	224	6.7	34.9	5.0
GE16-3000	801	839	236	15	50.8	8.5
GE16-3600	451	1,001	235	13	34.7	7.5
GE16-4100	1029	1,127	234	12	30.0	7.1
Minimum		686	215	3.1	10.8	5.0
Maximum		1,127	323	15	50.8	8.5
Weighted Average		912	261	10	31.8	6.3

[a] The g/gal emission factors reported here are based on the corresponding g/bhp-hr emission factors for each engine model and pollutant as given in Table 2-3 and the fuel specific engine output (FSEO) value of 20.8 bhp-hr/gallon reported by EPA (1997).

Source: (EPA, 1998)

1.4.2 Other Reported Emission Rates

In addition to the data reported by EPA, data reported by other sources, such as Fritz (2000) and Weaver (2006), were identified and are summarized here. These data are not based on the EPA duty cycles, and are for a smaller number of locomotives than the EPA data.

Table 2-6 shows the emission rate results for a 16-cylinder, 4,000 horsepower EMD 16-710-G3 engine (Fritz, 2000). The reported data include a fuel use rate and the emission rates of NO_x, HC, CO, and PM, all on a mass per time basis. Although the CO_2 emission rate was not reported in the study, it can be estimated based on the fuel use rate. Assuming that the vast majority of carbon in the fuel is emitted as CO_2, the CO_2 emission rate is estimated as:

$$ER_{CO_2} = m_{fuel}\left(\frac{0.864\ g\ C}{g\ diesel}\right)\left(\frac{gmol\ C}{12\ g\ C}\right)\left(\frac{1\ gmol\ CO_2}{1\ gmol\ C}\right)\left(\frac{44\ g\ CO_2}{gmol\ CO_2}\right) \tag{2}$$

Where,

ER_{CO_2} = emission rate of CO_2 (g/sec)

m_{fuel} = fuel use rate (g/sec)

The carbon content per gallon of diesel fuel is obtained from EPA (2005).

Table 2-6(b) shows the estimated fuel-based emission rates for each notch position. The fuel-based emission rates shown here are comparable in magnitude to those estimated from the EPA data reported in Table 2-5.

Table 2-6. Fuel Use and Emission Rates for an SD70 Locomotive

(a) Time-based fuel use and emission rates

Engine Model	Notch Position	Horsepower (hp)	Fuel Use (g/sec)	CO_2[a] (g/sec)	NO_x (g/sec)	HC (g/sec)	CO (g/sec)	PM (g/sec)
EMD 16-710G3	Idle	19	5.9	19	0.31	0.04	0.09	0.01
	1	205	11.5	36	0.62	0.04	0.09	0.01
	2	437	21.6	68	1.25	0.06	0.12	0.03
	3	980	44.9	141	2.80	0.08	0.16	0.06
	4	1,519	68.3	215	4.56	0.11	0.42	0.10
	5	2,005	89.2	281	6.03	0.13	1.15	0.14
	6	2,881	126	397	8.44	0.18	4.12	0.26
	7	3,655	154	485	12.0	0.25	3.15	0.30
	8	4,210	176	555	12.9	0.31	2.80	0.59

[a] Estimated CO_2 emission rate of based on fuel use rate

(b) Fuel-based emission rates

Engine Model	Notch Position	Horsepower (hp)	NO_x (g/gal)	HC (g/gal)	CO (g/gal)	PM (g/gal)
EMD 16-710G3	Idle	19	167	23	49.4	6.4
	1	205	171	11	25.2	3.9
	2	437	184	8.1	17.9	3.9
	3	980	199	5.8	11.4	4.4
	4	1,519	212	4.9	19.6	4.7
	5	2,005	215	4.7	40.9	5.1
	6	2,881	213	4.6	104	6.7
	7	3,655	249	5.2	65.1	6.3
	8	4,210	234	5.6	50.6	11

Source: (Fritz, 2000)

Table 2-7. Time-Based Fuel Use and Emission Rates for CO_2, NO_x, HC, and PM

(a) Time-based fuel use and emission rates (g/sec)

Engine Model	Fuel Use (g/sec)	CO_2 (g/sec)	NO_x (g/sec)	HC (mg/sec)	PM (mg/sec)
EMD16-710G	12.8	41	0.97	47.2	33.3
EMD16-645E	8.95	28	0.55	57.8	14.1

Note: Test condition is an average of idle, Notch 2, and Notch 4

(b) Fuel-based emission rates (g/gal)

Engine Model	NO_x (g/gal)	HC (g/gal)	PM (g/gal)
EMD16-710G	242	12	8.3
EMD16-645E	196	21	5.0

Note: Test condition is an average of idle, Notch 2, and Notch 4

Source: (Weaver, 2006)

Weaver (2006) reports data based on the average of idle and notch settings 2 and 4 for two locomotive engines, as shown in Table 2-7. Thus, these are not directly comparable to either the EPA reported data, nor the data shown in Table 2-6. The time-based rate of fuel consumption and emissions of CO_2, NO_x, HC, and PM are reported. The emission rates are converted to a fuel basis as shown in Table 2-7(b). Although not directly comparable to the EPA cycle average emission rates, the magnitude of the fuel-based emission rates for NO_x, HC, and PM are similar to that from the EPA data.

1.5 Summary

In this chapter, the following items were discussed:

- Locomotive exhaust emission concentrations are typically measured using engine dynamometers.
- The EPA established locomotive emission standards in 1997, and revised them in 2008. Any locomotive engine that is manufactured or remanufactured must now achieve the 2008 EPA exhaust emission standards.
- Emission standards are based on duty cycle averaged emission factors.
- Emissions data are available for numerous locomotive engines and are used for developing a basis for benchmark comparison of measured emission rates.

2.0 RAIL YARD TESTING

The purpose of rail yard testing is to quantify fuel use and emission rates and compare to dynamometer measurements and literature cited values for validation of the measurement method. If dynamometer and rail yard fuel use and emission rates are similar, then rail yard testing can be used to assess the compliance of a locomotive with the emission standards, without removing the engine from the locomotive. This would save time by not having to remove a locomotive from service and sending it to a facility with a dynamometer. Rail yard tests are also less expensive than dynamometer testing.

The general technical approach for rail yard testing of the locomotives involved four major components: (1) the PEMS instrumentation; (2) preparation for field data collection; (3) field data collection; and (4) quality assurance and quality control. Each of these components of the technical approach is described. The results of data analysis are given and summarized.

2.1 Portable Emissions Measurement Systems

The PEMS used in this project are the OEM-2100 Montana and the OEM-2100AX Axion systems, both manufactured by Clean Air Technologies International, Inc. (CATI). The Montana and Axion systems are comprised of two parallel five-gas analyzers, a PM measurement system, an engine sensor array, and an on-board computer. The two parallel gas analyzers simultaneously measure the volume percentage of CO_2, CO, HC, NO, and oxygen (O_2) in the engine exhaust. The PM measurement capability includes a laser light scattering detector and a sample conditioning system. A temporarily mounted sensor array is used to measure manifold absolute pressure (MAP), intake air temperature (IAT), and engine speed (RPM) in order to estimate air and fuel use. A global positioning system (GPS) measures locomotive position. All rail yard measurements were conducted in the NCDOT Capital Yard Maintenance Facility in Raleigh, NC, and thus GPS position was not recorded. The on-board computer synchronizes the incoming emissions, engine, and GPS data.

The Montana and Axion systems are designed to measure emissions during the actual use of the locomotive in its regular daily operation. Each complete system comes in two weatherproof plastic cases; one of which contains the monitoring system itself, and the other contains sample inlet and exhaust lines, tie-down straps, AC adaptor, power and data cables, various electronic engine sensor connectors, and other parts. The monitoring system weighs approximately 35 pounds. The system typically runs off of the 12-volt DC motor vehicle electrical system, using a cigarette lighter or other power source. The power consumption is 5-8 Amps at 13.8 volts DC. During rail yard testing, the PEMS was connected to a shore-based or locomotive HEP-based power supply using a power converter.

2.1.1 Measured Gases and Pollutants

The gases and pollutants measured include CO_2, CO, HC, NO, O_2, and PM using the following detection methods:

- CO_2, CO, and HC using non-dispersive infrared (NDIR).

- NO and O_2 are measured using electrochemical cells. Typically, NO_x is comprised of approximately 90-95 volume percent NO; therefore, the NO measurement is a good indicator of NO_x emissions.
- PM is measured using light scattering, with measurements ranging from ambient levels to low double-digit opacity.

The NDIR accurately measures some HC compounds, but responds only partially to others (Stephens *et al.*, 1996). Actual HC emissions may be a factor of 2 to 2.5 greater than the values reported by the PEMS (Frey and Choi, 2008). A multiplicative correction factor of 2.5 is used to approximate total cycle average HC emissions.

The EPA emission standards focus on nitrogen oxides (NO_x), which includes NO and NO_2. The PEMS only measures NO. Typically, NO_x is comprised of 95 vol-% NO (Seinfeld and Pandis, 1998). In addition, NO_x is always reported as equivalent mass of NO_2. Therefore, a multiplicative correction factor of 1.053 is used to approximate total cycle average NO_x emissions.

The PM measurements are based on a light-scattering laser photometer that is analogous to opacity measurements. The measurement from the PM detector is factory calibrated to an equivalent mass per volume concentration, and is useful for relative comparisons. However, this method is not expected to be useful for accurate characterization of the magnitude of the PM emissions. The actual PM emission rate may be a factor of 5 to 20 greater than the values reported by the PEMS (Frey and Choi, 2008). A multiplicative correction factor of 5 is used to approximate total cycle average PM emissions.

Data from several laboratories using various vehicles and fuels suggests that when the PEMS is operated simultaneously with the laboratory system, the difference is typically less than 10% for aggregate mass NO_x and CO_2. The accuracy of HC measurements depends on the fuel used and on the emission levels (Vojtisek-Lom and Allsop, 2001).

Battelle completed an Environmental Technology Verification (ETV) study of the CATI Real-World Emissions Monitoring On-board Testing Equipment, comparing bias and precision of the PEMS to a reference method (Battelle, 2003). Overall, the second-by-second data had close agreement between the reference method and the PEMS, especially for NO_x, CO_2, and CO. The linear regression of the results shows that, except for one set of HC results (r^2 of 0.54), coefficients of determination were greater than 0.86 for all four emitted species. The slopes of the linear regressions were between 0.97 and 1.03 for CO_2 over a tested range of 300 to 620 g/mi. The slopes were between 0.95 and 1.05 for CO over a tested range of 0 to 13 g/mi and between 0.92 and 1.03 for NO_x over a tested range of 0 to 1.4 g/mi. However, the slopes of the linear regressions were between 0.62 and 0.79 for HC over a tested range of 0 to 1 g/mi. (Battelle, 2003).

2.1.2 Calibration

The PEMS gas analyzers utilize a two-point calibration system that includes “zero” and “span” calibrations.

Zero calibration is performed on each gas analyzer using ambient air every 10 minutes. Although zero air stored in bottles or generated using an external zero air generator can be used, it is believed that the ambient air pollutant levels are negligible compared to those found in undiluted exhaust; therefore, ambient air is viewed as sufficient for most conditions. For zero calibration purposes, it is assumed that ambient air contains 20.9 vol-% O_2, and no HC, CO, and NO. CO_2 levels in ambient air are approximately 400 parts per million (ppm), which are negligible compared to the typical levels of CO_2 in the engine exhaust (e.g., 5.0 vol-%).

Span calibration is performed using a BAR-97 low concentration calibration gas mixture, which has a known gas composition. The calibration gas includes a mixture of known concentrations of CO_2, CO, HC, and NO, with the balance being nitrogen (N_2). Span gas calibration is recommended once every three months. Span calibrations were conducted prior to every measurement campaign. The NDIR subsystem used in the gas analyzers is very stable and tends not to drift too significantly from their span calibrations.

2.1.3 Operating Software

Each PEMS includes an on-board computer that is used to collect and synchronize data obtained from the engine sensors, gas analyzers, and GPS system. Data from all three of these sources are reported on a second-by-second basis. The computer is controlled by plugging in a mouse and/or keyboard. Upon PEMS startup, the computer queries the user for information about the test locomotive, fuel used, test characteristics, weather conditions, and operating information. Most of this information is for identification purposes. However, the fuel type and composition, engine displacement, exhaust sample delivery delays, unit configuration, intake air sensor configuration, and volumetric efficiency are critical inputs that affect the accuracy of the reported emission rates. The details of the definition and significance of each of these are detailed in the PEMS operation manual (CATI, 2003; CATI, 2008). Engine air flow rate is estimated based on the "speed density" method based on RPM, MAP, IAT, engine displacement, engine compression ratio, number of strokes per cycle, and volumetric efficiency. RPM, MAP, and IAT are measured, as detailed below. Engine displacement, compression ratio, and number of strokes per cycle are based on manufacturer data. Volumetric efficiency is calibrated as explained in Section 3.4.6.

The software provides a continuous display of data during normal operation, including gas analyzer data, engine data, GPS data, and calculated quantities including the emission rate in units of mass per time. The emission rate is based on air flow estimated via the "speed density" method. Fuel flow is estimated based on exhaust composition and air flow, exhaust flow, and measured exhaust concentrations. The following parameters are typically displayed on the screen of the PEMS monitoring system unit on a second-by-second basis: RPM, MAP, IAT, concentrations of the measured pollutants, exhaust flow rate, air-to-fuel ratio, fuel use rate, and mass flow rates of the measured pollutants. The data are available in ASCII text, comma-delimited format, but can be supplied in any user-defined format on demand.

2.1.4 Manifold Air Boost Pressure Sensor

In order to measure MAP, a pressure sensor is installed on the engine. The sensor is attached to the engine via a port that allows the pressure of the air entering the engine to be measured.

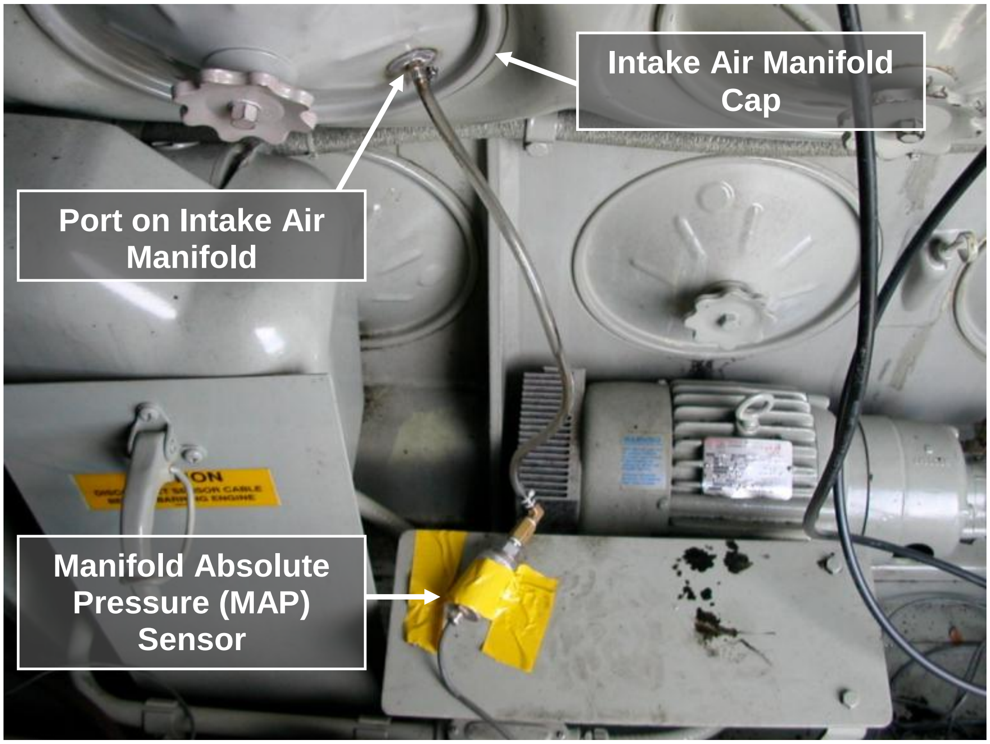


Figure 3-1. Placement of Manifold Absolute Pressure Sensor on the EMD 12-710G3 Engine of an F59PHI Locomotive

While there is a port on the engine after the turbocharger for most heavy-duty diesel engines, the locomotive prime mover engine does not have an existing port that could be used for this purpose. Thus, ports were created by a locomotive mechanic for each tested prime mover engine. For all locomotives, a mechanic drilled a hole and welded a fitting for the port in the intake air manifold. As an example, Figure 3-1 depicts the location of a fabricated port on the intake air manifold of the EMD 12-710G3 engine for an F59PHI locomotive. A barb fitting is screwed into the port. Plastic tubing is used to connect the MAP sensor to the barb fitting. The MAP sensor is attached to a location in the engine compartment, away from a hot surface of the engine. The MAP sensor provides MAP data for the computer of the main unit of the PEMS through a cable that connects the sensor to the back of the PEMS unit.

For the HEP engines, different techniques were used to measure MAP for each locomotive. On the GP40 engine, a mechanic drilled a hold and welded a fitting for the port on the intake air manifold. A new intake air pipe was fabricated with a port and replaced the existing pipe downstream of the turbocharger on the HEP engines of the F59PHI. It was not possible to measure the MAP for the HEP engines of the F59PH locomotives. Altering the engine through drilling and welding will void the warranty on the engines. The use of proprietary electronic software from the engine manufacturer was cost prohibitive for this study.

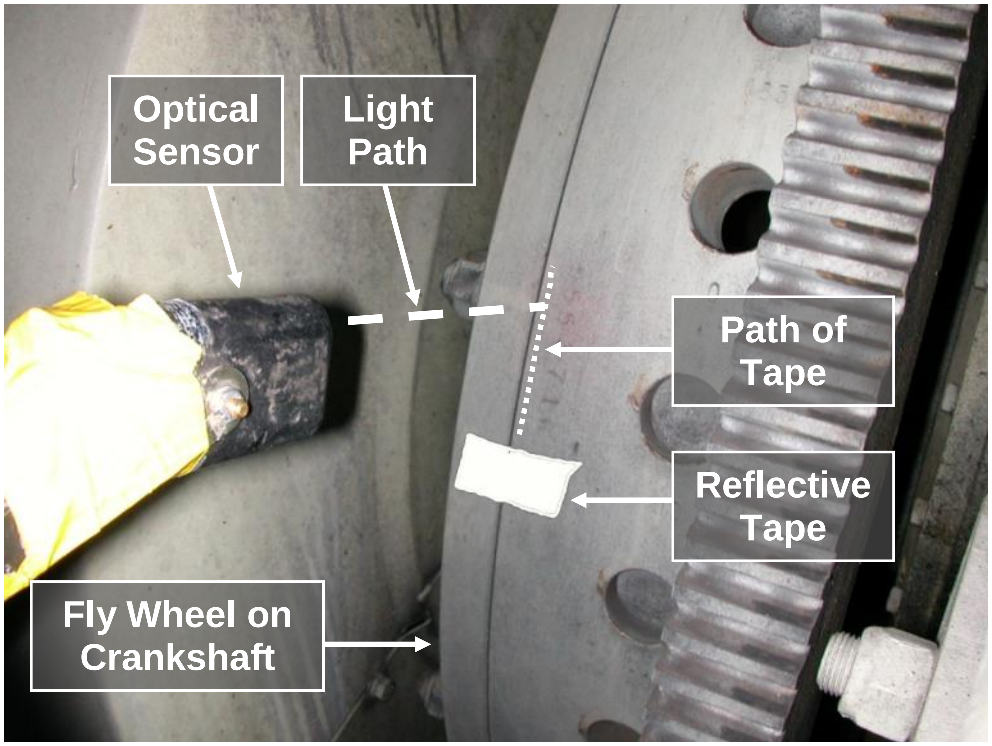


Figure 3-2. Placement of Optical Engine Speed Sensor and Reflective Tape on the EMD 12-710G3 Engine of an F59PHI Locomotive

2.1.5 Engine Speed Sensor

The engine speed, or RPM, sensor is an optical sensor used in combination with reflective tape to measure the time interval of revolutions of a pulley or wheel that rotates at the same speed as the engine crankshaft. The RPM sensor has a strong magnet to attach easily on metal surfaces. The reflective tape must be installed on a surface that rotates at the same rate as the crankshaft.

As an example, the placement of the reflective tape and the optical sensor for the EMD 12-710G3 engine of an F59PHI locomotive is shown in Figure 3-2. Some of the key factors considered in the placement of the sensor include: (1) avoid proximity to the engine cooling fan and other moving components; (2) place the sensor in a location where the magnet can securely affix the sensor to a surface; and (3) place the sensor so that its cable can reach the sensor array box, which is also located in the engine compartment. The signal from the RPM sensor is transmitted by cable to the sensor array box, which in turn transmits a signal by a second cable to the PEMS unit.

2.1.6 Intake Air Temperature Sensor

The engine intake air temperature (IAT) sensor needs to be installed in the intake air flow path of the prime mover engine. The sensor has a thermistor that can detect temperature. Installation of the IAT sensor is somewhat easy compared to the RPM and MAP sensors. Using duct tape or a plastic tie, one can affix the IAT sensor near the intake air flow where the MAP port is located.

To measure IAT for the HEP engines in the F59PHI and GP40 locomotives, an existing bolt in the intake air manifold was removed, revealing an opening that could be used as a sampling port. The thermocouple was located in the air intake path via the port. The port was sealed by duct tape. It was not possible to measure the IAT for the HEP engines of the F59PH locomotives. Altering the engine through drilling and welding will void the warranty on the engines. The use of proprietary electronic software from the engine manufacturer was cost prohibitive for this study.

2.1.7 Sensor Array Unit

The sensor array unit is the device which connects the RPM and IAT sensors to the PEMS unit. The sensor array unit is placed inside of the prime mover engine compartment.

2.1.8 System Installation and Operation

The time to preinstall the PEMS components in a typical locomotive was approximately one to four hours per engine, including time associated with fabricating parts to allow for sampling of engine parameters and of exhaust gases from the prime mover engine duct.

Another one-of-a-kind effort in this work was to configure the exhaust sampling system. This included fabricating a replaceable fitting with a sampling port that could be installed on the exhaust duct of the prime mover engine. Since the exhaust gas and the duct operate at very high temperatures, especially at high engine load, it was not possible to directly insert the exhaust sample hoses for the PEMS directly to the sampling port on the exhaust duct. The sample hoses are made of a rubber material that will melt at high temperatures. Thus, a set of 1.5-meter long metal pipes were connected to the sampling port, and the exhaust sample hoses were connected to the end of the pipes farthest form the exhaust duct.

During the static rail yard tests, the prime mover engines were tested under load. The electrical power generated by the prime mover engines was sent to an electrical resistor grid located at the top of the locomotive, where the electrical power was dissipated as heat. The HEP engines were tested under load by connecting passenger cars to the locomotive and turning on the lighting and heating/air conditioning in each passenger car.

Because this testing was stationary, it was not necessary to install the PEMS on the locomotive, such as for over-the-rail measurements. During rail yard tests, the PEMS was placed either outside or inside of the locomotive cab. Photographs of the installation of the PEMS on the locomotives are provided in Figures 3-3 through 3-14. The photographs are organized by type of locomotive. Figures 3-3 through 3-6 are for the F59PH locomotives. Figures 3-7 through 3-10 are for the F59PHI locomotives. Figures 3-11 through 3-14 are for the GP40 locomotive.

After completing all installation steps, the PEMS was warmed up for approximately 45 minutes. This time period is recommended in order to ensure consistency of measurements made by the monitoring system unit (CATI, 2003; CATI, 2008).

Figure 3-3. Placement of PEMS for Testing of an F59PH Locomotive Prime Mover Engine
(a) inside of the locomotive cab; (b) inside an air conditioned vehicle during extreme heat

Figure 3-4. 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

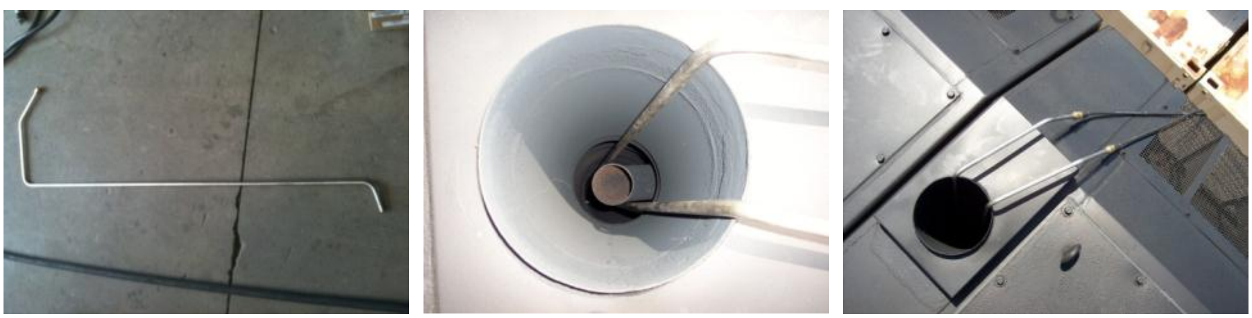


Figure 3-5. Installation of Probes for Testing of an F59PH Head End Power Engine
(a) fabricated stainless steel exhaust probe; (b) probes in HEP exhaust stack; (c) sampling lines connected to probes in HEP exhaust stack

Figure 3-6. Engine Activity Data Sources During Testing of an F59PH Locomotive
(a) prime mover engine activity digital display in locomotive cab; (b) head end power engine activity digital display on head end power engine

Figure 3-7. 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 3-8. Installation of Sensors on an F59PHI Locomotive Prime Mover Engine
(a) engine RPM sensor; (b) manifold absolute pressure (MAP) sensor; (c) intake air temperature (IAT) sensor

Figure 3-9. Installation of Sensors on an F59PHI Locomotive Head End Power Engine
(a) engine RPM sensor; (b) manifold absolute pressure (MAP) sensor; (c) intake air temperature (IAT) sensor

Figure 3-10. 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 3-11. 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 3-12. Installation of Sensors on a GP40 Locomotive Prime Mover Engine
(a) engine RPM sensor; (b) manifold absolute pressure (MAP) sensor; (c) side-view of locomotive

Figure 3-13. Installation of Sensors on a GP40 Locomotive Head End Power Engine
(a) engine RPM sensor (front view), (b) engine RPM sensor (side view); (c) intake air temperature (IAT) sensor

Figure 3-14. Installation of PEMS Exhaust Sample Lines in a GP40 Locomotive
(a) MAP sampling hose on the HEP engine; (b) sampling hose on HEP engine exhaust; (c) PEMS main unit on forklift next to locomotive

During testing, periodic checks of the system status were conducted. For example, the security of all connections with the engine was evaluated. This was done by determining whether the engine data is updated on the display of the PEMS unit in an appropriate matter, whether the gas concentrations are reasonable, and whether the instrument is receiving power. If the engine data were "frozen" or missing, which occurred a few times prior to rail yard testing, it was then necessary to reinstall the engine diagnostic data cable and reboot the engine sensor array. If the CO_2 gas concentrations were very low, then there might be a leakage in the sampling line and, therefore, inspection and repositioning of the sampling line is necessary. Low CO_2 gas concentrations were observed during one set of rail yard tests. The exhaust sampling lines were blown out to remove any carbon that was blocking exhaust flow. When that did not work, new exhaust sampling lines were used, and normal CO_2 gas concentrations were observed.

2.2 Preparation for Field Data Collection

Preparations for field data collection include four major steps: (1) verification of the status of the PEMS and that all necessary parts and consumables are available; (2) laboratory calibration of the PEMS; (3) completion of a field study design; and (4) coordination with the locomotive owner/operator regarding scheduling of the test and access to the locomotive.

As part of the preparation, NCSU ensured that the PEMS had functioning electrochemical sensors for NO and O_2, and that all consumables were replaced, such as filters in the exhaust sampling line. A calibration of the PEMS using a standard calibration gas was conducted before any testing.

Field study design includes specifying which locomotives are to be tested, which engine is to be tested, when they are to be tested, and what fuel will be used. As part of this project, NCDOT allowed NCSU access to its fleet of locomotives for testing. Each engine of six locomotives was tested at least once in the NCDOT rail yard.

2.3 Field Data Collection Procedure

Field data collection includes the following main steps: (1) installation; (2) data collection; and (3) decommissioning. Appendix A provides checklists that are used during all four steps of the field data collection procedure.

2.3.1 Installation

Installation of the PEMS and its various components was performed the day before or the day of a scheduled test. This step involves installing the exhaust sampling lines to the locomotive engine being tested, power cables, the engine sensor array and its sensors, and the PEMS unit. For the prime mover engines, sampling lines are directly connected from the PEMS to the sampling port on the exhaust gas duct in the engine room. For the HEP engines, exhaust gas sampling lines have a probe that is inserted into the exhaust pipe. For the F59PH locomotives, an exhaust pipe probe was fabricated, as shown in Figure 3-5. Installation time was approximately two to four hours based on the availability of locomotive mechanics to assist in the fabrication and placement of sample fittings. During this installation time, the PEMS unit was warmed up for at least 45 minutes. The researcher entered the data into the PEMS regarding engine characteristics and fuel type.

2.3.2 Data Collection

Data collection involved continuously recording, on a second-by-second basis, exhaust gas concentrations and engine data. The status of the PEMS was periodically checked during the test, in order to determine quickly if any problems arose during data collection that could be corrected. For example, sometimes there can be a loss of signal that can be corrected by checking connections in a cable. Sometimes the gas analyzers "freeze" (exhaust gas concentrations fail to continuously update), and can be corrected by restarting the gas analyzers.

2.3.3 Decommissioning

Decommissioning occurs after the end of the test period. After data collection was complete, collected data were copied, the PEMS was powered down, and all sample lines, cables, sensors, and the engine sensor array were removed.

2.4 Quality Assurance and Quality Control

For quality assurance purposes, the combined data set for a locomotive test is screened to check for errors or possible problems. If errors are identified, the affected data are either corrected or not used for data analysis. The types of errors typically encountered are described in this section, including a discussion of methods for making corrections.

NCSU has developed a PEMS Quality Assurance System (PQAS) that takes raw data from the PEMS and processes it to identify data quality problems. Where possible, such problems are corrected. If correction is not possible, then the errant data are omitted from the final database used for analysis. PQAS also takes the exhaust concentrations and engine data obtained from the PEMS to calculate fuel use and emission rates.

2.4.1 Engine Data Errors

On occasion, communication between the PEMS and the engine sensor array, which the RPM sensor is connected to, may be lost. Sometimes the loss of connection is because of a physical loss of electrical contact. This occurred a few times during rail yard. However, when it happens, this error can be solved easily by restarting the PEMS in the field. After restarting, the on-board computer of the PEMS begins logging a new data file automatically. Thus, when this is noticed in the field, this error can be addressed. Loss of engine data is also obvious from the data file, since the missing data are evident and any calculations of emission rates are invalid. There are two types of engine errors that are included in the quality assurance procedure: unusual engine RPM and engine RPM freezing.

The engine speed for the prime mover engine typically varies from not less than 190 RPM during idling to about 950 RPM at Notch 8. The bounds for possible engine RPM were set as greater than or equal to 190 RPM and less than or equal to 950 RPM. Thus, if prime mover engine measured engine speeds fall outside of the bounds for possible engine RPM, those data are removed prior to further data analysis. The engine speed for the HEP engine typically varies from not less than 1600 RPM to about 1900 RPM during idle. Thus, if HEP engine measured engine speeds fall outside the bounds for possible engine RPM, those data are removed prior to further data analysis.

Engine RPM "freezing" refers to situation in which an engine speed value that is expected to change dynamically on a second-by-second basis remains constant over an unacceptably or implausibly long period of time. Engine RPM tends to fluctuate on a second-by-second basis, even if the engine is running at approximately constant RPM. Therefore, a check is performed to identify situations in which engine speed remained constant for more than three seconds. This type of error is rare, and did not occur in this project.

2.4.2 Gas Analyzer Errors

Each PEMS has two gas analyzers, which are referred to as "benches." Most of the time, both benches are in use. Occasionally, one bench is taken offline for zeroing. Therefore, most of the time, the emissions concentrations from each of the two benches can be compared to evaluate the consistency between benches. If both benches are producing consistent concentrations, then the measurements from both are averaged to arrive at a single estimate on a second-by-second basis of the emissions of each pollutant.

When the relative error in the emissions measurement between both benches is within five percent, and if no other errors are detected, then an average value is calculated based upon both benches.

However, if the relative error exceeds five percent, then further assessment of data quality is indicated. A discrepancy in measurements might be due to any of the following: (1) a leakage in the sample exhaust line leading to a bench; (2) overheating of abench; or (3) problems with the sampling pump of a bench, leading to inadequate flow. If one of these problems is identified, then only data obtained from the other bench was used for emissions estimation. When problems are identified, then attempts are made to resolve the problem in the field. For example, if a leak or overheating problem is detected during data collection, then the problem is fixed and testing resumes. Data recorded during the period when a leak or overheating event occurred are not included in any further analyses.

Another gas analyzer error experienced was the malfunction of the O_2 sensors. It is assumed that ambient air contains 20.9 vol-% O_2. Engine exhaust contains pollutants, so the concentration of O_2 in the engine exhaust must be less than ambient levels. If both benches are producing O_2 measurements of greater than 20.9 vol-%, then concentrations must be corrected. If O_2 measurements are not valid, then the volume percent of O_2 in the exhaust can be calculated based on the concentration of CO_2 in the exhaust. The exhaust CO_2 concentration is an indicator of the air-to-fuel ratio in the engine. Appendix B describes the equations used in the calculation exhaust concentrations of O_2 based on exhaust concentrations of CO_2.

2.4.3 Zeroing Procedure

For data quality control and assurance purposes, each gas analyzer bench alternates being zeroed every ten minutes. While zeroing, the gas analyzer intakes ambient air instead of engine exhaust. After zeroing is finished, a solenoid valve changes the gas analyzer intake from ambient air to the engine exhaust. There is a period of transition when this occurs. In particular, the O_2 sensor needs several seconds to respond to the switching of gases, since there is a large change in O_2 concentration when the switch occurs. To allow adequate time for a complete purging of the previous gas source from the system, a time delay of ten seconds is assumed. Thus, for 10 seconds before zeroing begins, the time period of zeroing (approximately 45 seconds), and 10 seconds after zeroing ends, data for the bench involved in zeroing are excluded from calculations of emission rates, and the emission rates are estimated based only upon the other bench.

2.4.4 Negative Emissions Values

Random measurement errors occur and, on occasion, some of the measured concentrations will have negative values that are not statistically different from zero or a small positive value. Diesel engines typically produce less HC emission concentrations than gasoline engines (Durbin *et al.*, 2000). Thus, it is frequently the case that HC emission measurements are very low and not substantially different from zero. Negative values of emissions estimates were assumed to be zero and were replaced with a numerical value of zero.

2.4.5 Loss of Power to Instrument

A loss of power to the PEMS results in a complete loss of data collection during the time period when power was not available. However, the system saves data up to the point at which the power loss occurs. After a loss of power, the instrument needs to be restarted, which takes approximately five to ten minutes. During the power loss and instrument restart, no data can be collected.

2.4.6 Calculation of Fuel Use and Emissions

The locomotive prime mover engines operate on a 2-stroke cycle. However, internal calculations of fuel use and emission rates by the PEMS are based on a 4-stroke cycle. Intake air molar flow rate is used to derive emission rates. Since the intake air molar flow rate is a function of the engine cycle, engine compression ratio, and engine volumetric efficiency, recalculation is needed to derive correct fuel use and emission rates. Appendix B describes the equations used in the recalculation of fuel use and emission rates for both 2- and 4-stroke engines.

Intake air flow, exhaust flow, and mass emissions are estimated using a method reported by Vojtisek-Lom and Cobb (1997).

Engine compression ratios are based on published specifications and dynamometer tests, where available. Engine volumetric efficiency is based on measured fuel flow rate, engine RPM, MAP, and IAT from dynamometer testing, and varies depending on throttle notch position. The engine volumetric efficiency is assumed to be 0.95 for every notch position, unless prior dynamometer testing was completed, in which case the engine volumetric efficiency was calibrated to measured fuel flow.

Time-based fuel use and emission rates (g/sec) are dependent on various engine parameters, including number of strokes per cycle, compression ratio, speed, displacement, and volumetric efficiency. The number of strokes per cycle, compression ratio, and displacement are known from the engine specifications. Engine speed is measured using the RPM sensor of the PEMS. Volumetric efficiency is inferred from the measured fuel flow rate during dynamometer testing. In previous NCDOT Rail Division-sponsored research projects, engine dynamometer fuel use and emissions testing was conducted on the prime mover engine of the F59PH and GP40 locomotives while the engines were undergoing the rebuild process (Frey and Graver, 2010). For these locomotives, engine volumetric efficiency can be calibrated so that the fuel use rate observed during rail yard testing is equal to the fuel use rate observed during dynamometer testing.

Fuel-based emission rates (g/gal) are calculated based on the exhaust gas and fuel composition, as detailed in Appendix B. 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. 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. Molar ratios of NO, CO, and HC to CO_2 are used to estimate the amount of NO, CO, and HC, respectively, emitted per gallon of fuel consumed.

Engine output-based emission rates (g/bhp-hr) are calculated by multiplying the fuel-based emission factors (g/gal) and the fuel use rate (gal/bhp-hr). Gallon per brake horsepower-hour fuel use rate is derived by dividing the time based fuel use rate (g/sec) by the fuel density and the engine output (hp), and converting seconds into hours. Engine output was observed from the locomotive activity digital display, shown in Figure 3-6(a).

The engine output-based emission rates, along with the EPA line-haul duty cycle, were used to calculate the brake specific cycle average emission rates for all pollutants and locomotives. For the F59PH locomotives, “Low Idle” represents the Idle used in the EPA line-haul duty cycle.

2.5 Results

The results include locomotive characteristics and test conditions, the field data collection schedule, benchmarking of locomotive emission results to other data, overall comparison of locomotives, and detail characterization of each locomotive.

2.5.1 Characteristics of Locomotives, Engines, and Fuel

Six locomotives were tested. Specifications of the prime mover and HEP engines of each locomotive are summarized in Table 3-1. NC 1810, NC 1859, and NC 1869 are model F59PH locomotives that were each built in 1988. These locomotives were rebuilt in 2010. NC 1755 and NC 1797 are model F59PHI locomotives that were built in 1998 and 1997, respectively. These locomotives are currently being rebuilt. NC 1792 is a model GP40 locomotive that was built in

Table 3-1. Specifications of the Tested Locomotive Engines

(a) F59PH locomotives

Engine	Prime Mover	Head-End Power
Model	EMD 12-710G3	CAT C18 ACERT
Strokes	2	4
Cylinders	12	6
Displacement (L)	140	18
Horsepower (hp)	3,000	766
Compression Ratio	15:1	---

(b) F59PHI locomotives

Engine	Prime Mover	Head-End Power
Model	EMD 12-710G3	CAT 3412
Strokes	2	4
Cylinders	12	12
Displacement (L)	140	27
Horsepower (hp)	3,000	625
Compression Ratio	16:1	---

(c) GP40 locomotive

Engine	Prime Mover	Head-End Power
Model	EMD 16-645E3	Cummins KTA19
Strokes	2	4
Cylinders	16	6
Displacement (L)	169	19
Horsepower (hp)	3,000	600
Compression Ratio	18:1	---

1968. This locomotive was rebuilt in 1992 and 2008. The prime mover engine was rebuilt in 1992 and 2008, and the HEP engine was rebuilt in 2005. Unfortunately, after rail yard and over-the-rail measurements were completed, NC 1792 was irreparably damaged in a rail grade crossing accident, and is no longer in service. There was no loss of life or major injury as a result of the accident. The five other locomotives are either in service or currently undergoing rebuilds.

All locomotives were operated on ULSD during testing. The fuel properties for ULSD and B20 biodiesel, which will be used in an evaluation of the emissions implications of B20 biodiesel versus ULSD using a life cycle inventory approach in Chapter 6, are summarized in Table 3-2.

Table 3-2. Properties of Ultra Low Sulfur Diesel Fuel and B20 Biodiesel

Quantity	Ultra Low Sulfur Diesel	B20 Biodiesel
Density (g/gal)	3,200	3,220
Heat Value (BTU/gal)[a]		
Higher	138,700	126,200
Lower	128,700	117,100
Carbon Content (g/gal)[b]	2,778	2,721
Elemental Composition		
Carbon (wt.%)	86.4	84.5
Hydrogen (wt.%)	13.6	13.3
Sulfur (ppm)	15	2.2

[a] (ORNL, 2010)
[b] (EPA, 2005)

2.5.2 Scheduling of Field Data Collection

Field data collection occurred during the period of March 2008 to July 2011, as summarized in Table 3-3. The F59PH locomotives were tested after locomotive and prime mover engine rebuild. The F59PHI locomotives were tested prior to locomotive and prime mover engine rebuild. The GP40 locomotive was tested prior to and after locomotive and prime mover engine rebuild.

2.5.3 Test Schedules

A test schedule is defined as the order and test duration of each prime mover engine throttle notch position or HEP electrical load. During installation, the PEMS was warmed up for at least 45 minutes. Once all of the exhaust sampling lines and engine sensor were installed, the locomotive engines were also warmed up for at least 45 minutes.

The test schedule for the throttle notch positions for the prime mover engine is shown in Table 3-4(a). After a 45-minute warm up period, the engine is run at Notch 8 for a period of at least three minutes, after which the engine is returned to idle. During testing under load, the electrical power produced by the DC generator connected to the prime mover engine is dissipated in an electrical resistance grid that is referred to as the dynamic brake grid. There are cooling fans above the grid that are used for forced-air cooling. However, the grid is not intended for sustained operation at such high electrical current; such a situation would not normally occur in normal duty cycles and is an artifact of conducting the test under stationary conditions. Thus, during stationary load tests, the grid can overheat. To prevent overheating of the grid at high engine load, including Notches 6 through 8, the load test at each of these throttle notches was immediately followed by a period of idle in order to allow the grid to cool down. A cooling duration of approximately five minutes was used. After the tests were completed at Notches 6 through 8, testing occurred sequentially for Notches 1 through 5 without any intermediate idling.

Table 3-3. Rail Yard Data Collection Schedule

Model	Locomotive	Prime Mover Engine	Head-End Power Engine
F59PH	NC 1810	5/23/2011 6/27/2011	7/14/2011
	NC 1859	3/8/2011 6/28/2011	7/14/2011
	NC 1869	7/15/2011	7/15/2011
F59PHI	NC 1755	3/13/2008	3/14/2008 7/24/2008 12/2/2009
	NC 1797	7/22/2008	7/22/2008 12/15/2009
GP40	NC 1792	3/25/2008 11/4/2009	3/26/2008 7/23/2008 11/5/2009

Table 3-4. Test Schedules for Prime Mover and Head End Power Engines

(a) Prime Mover Engine

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

(b) Head End Power Engine

Passenger Cars	Time (min)
Idle for Warm Up	45
0	5-10
1	5-10
2	5-10
3	5-10
4	5-10

The test schedule for the HEP engines is shown in Table 3-4(b). After a 45 minute warm up period, the engine is run at different electrical loads for a period of five to ten minutes. Electrical loads were created by coupling passenger cars to the locomotive and operating the lighting and heating/air conditioning 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 test day, there is some test-to-test variability in the number of cars used. During the tests, voltages and currents for each load were measured for the F59PHI and GP40 locomotives to estimate the electrical loads. For the F59PH locomotives, percent load was recorded from the HEP digital display to estimate the electrical loads.

2.5.4 Prime Mover Engine Results – Fuel Use and Emission Rates

In this section, the results are given for time-based, fuel-based, and engine output-based emission rates for each of the six tested locomotives.

The time-, fuel-, and engine output-based average fuel use and emission rates for the F59PH locomotives numbered NC 1810, NC 1859, and NC 1869 are shown in Tables 3-5 through 3-7, respectively. Rail yard testing for these locomotives was conducted after locomotive and prime mover engine rebuild. The engine volumetric efficiency was calibrated so that the fuel specific engine output (FSEO) calculated were the same as the FSEO observed during the dynamometer testing of the prime mover engines of NC 1810 and NC 1869.

The time-, fuel-, and engine output-based average fuel use and emission rates for the F59PHI locomotives numbered NC 1755 and NC 1797 are shown in Tables 3-8 and 3-9, respectively. Rail yard testing for these locomotives was conducted prior to locomotive and prime mover engine rebuild. The engine volumetric efficiency was calibrated so that the FSEO calculated for Notches 1 through 8 were 20.8 bhp-hr/gal, the generic FSEO used by EPA (1997).

The time-, fuel-, and engine output-based average fuel use and emission rates for the GP40 locomotive numbered NC 1792 are shown in Tables 3-10 and 3-11 for rail yard testing before and after locomotive and prime mover engine rebuild, respectively. The engine volumetric efficiency for the rail yard test before engine rebuild was calibrated so that the FSEO calculated was the same as the FSEO observed during the dynamometer test after the rebuild but before some of the engine settings were finalized of the prime mover engine. The engine volumetric efficiency for the rail yard test after engine rebuild was calibrated so that the FSEO calculated was the same as the FSEO observed during the final dynamometer test of the prime mover engine.

For ease in comparing all five locomotives, Figures 3-15 and 3-16 depict the time-based fuel use and NO_x emission rates for the prime mover engines. The graphs provide information regarding fuel use and emission rate trends with respect to engine horsepower output, and enable comparisons between families of locomotives, and between individual locomotives.

Table 3-5. Average Prime Mover Engine Fuel Use and Emission Rates for F59PH Locomotive NC 1810

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Low Idle	203	1.6685	2.95	0.19	0.01	0.03	9.27	0.00
High Idle	350	1.6685	15.0	0.66	0.02	0.20	47.2	0.05
1	350	0.8826	10.2	0.49	0.00	0.25	31.9	0.05
2	350	1.0657	14.8	0.77	0.01	0.20	46.3	0.05
3	494	1.0874	30.6	1.62	0.01	0.05	96.2	0.05
4	569	1.0193	43.2	2.08	0.00	0.18	136	0.10
5	652	0.9785	58.5	2.51	0.00	0.68	184	0.15
6	730	0.8965	72.1	2.84	0.00	0.93	226	0.20
7	825	0.7696	97.2	3.31	0.01	2.35	304	0.30
8	907	0.6992	121	3.46	0.08	4.93	379	0.45

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Low Idle	205	13.8	9.01	10,052	17.0
High Idle	141	9.93	16.1	10,043	8.10
1	156	3.88	30.4	10,024	8.10
2	166	4.90	17.0	10,044	7.70
3	170	3.90	1.70	10,069	6.50
4	155	0.00	5.55	10,066	7.95
5	137	0.00	14.6	10,051	8.60
6	126	0.00	16.6	10,048	9.35
7	108	0.78	30.9	10,025	9.95
8	91.4	5.60	51.9	9,989	12.4

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Low Idle	9	2.71	75.9	5.10	3.32	3,708	6.30
High Idle	9	0.53	265	18.6	30.3	18,875	15.2
1	190	16.6	9.45	0.23	1.83	605	0.50
2	345	18.7	8.92	0.25	0.91	538	0.40
3	678	19.6	8.63	0.20	0.09	513	0.35
4	1004	20.0	7.73	0.00	0.28	504	0.40
5	1305	20.1	6.82	0.00	0.73	501	0.45
6	1601	19.7	6.40	0.00	0.84	509	0.50
7	2240	20.1	5.41	0.05	1.54	498	0.50
8	2700	19.8	4.62	0.28	2.63	505	0.65

Fuel use and emission rates are based on two tests: May 23, 2011 and June 27, 2011.

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 3-6. Average Prime Mover Engine Fuel Use and Emission Rates for F59PH Locomotive NC 1859

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Low Idle	198	1.5362	2.95	0.20	0.03	0.00	9.27	0.00
High Idle	338	1.5362	7.70	0.42	0.08	0.01	24.2	0.00
1	338	1.1241	10.2	0.54	0.05	0.01	32.1	0.00
2	338	1.0967	14.3	0.88	0.03	0.00	44.9	0.05
3	493	1.1770	31.7	2.03	0.05	0.01	99.8	0.05
4	565	1.0983	44.5	2.63	0.03	0.03	140	0.05
5	653	0.9813	57.6	3.03	0.05	0.06	181	0.10
6	726	0.9437	72.1	3.60	0.10	0.12	227	0.10
7	825	0.8413	106	4.18	0.05	0.89	332	0.20
8	902	0.7329	121	4.30	0.20	1.15	380	0.40

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Low Idle	214	28.5	4.13	10,050	19.2
High Idle	175	33.3	2.88	10,049	10.4
1	167	36.8	1.59	10,063	6.15
2	198	6.83	1.11	10,068	5.75
3	205	4.08	0.88	10,070	4.05
4	188	2.23	2.17	10,069	4.20
5	168	2.45	3.18	10,068	4.20
6	160	4.15	5.41	10,063	4.55
7	126	1.88	26.9	10,031	6.60
8	114	5.18	30.3	10,023	10.8

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Low Idle	9	2.71	79.0	10.5	1.52	3,708	7.10
High Idle	9	1.04	167	32.0	2.77	9,669	10.0
1	190	16.6	10.1	0.88	0.10	608	0.35
2	305	18.7	10.5	0.38	0.06	539	0.30
3	688	19.6	10.5	0.20	0.04	513	0.20
4	985	20.0	9.47	0.10	0.11	505	0.20
5	1310	20.1	8.40	0.13	0.16	502	0.20
6	1600	19.7	8.10	0.20	0.27	510	0.25
7	2300	20.1	6.27	0.10	1.33	498	0.35
8	2700	19.8	5.73	0.25	1.53	507	0.55

Fuel use and emission rates are based on two tests: March 8, 2011 and June 28, 2011.

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 3-7. Average Prime Mover Engine Fuel Use and Emission Rates for F59PH Locomotive NC 1869

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Low Idle	241	1.5696	3.60	0.23	0.03	0.01	11.3	0.00
High Idle	373	1.5696	9.56	0.55	0.23	0.02	29.9	0.00
1	372	1.0196	10.3	0.60	0.08	0.02	32.2	0.00
2	372	1.0957	16.0	1.21	0.08	0.01	50.4	0.05
3	495	1.0907	30.0	2.34	0.18	0.02	94.3	0.05
4	567	1.0542	44.0	3.31	0.15	0.02	138	0.05
5	654	0.9752	56.6	3.86	0.10	0.05	178	0.10
6	733	0.9304	70.3	4.56	0.20	0.05	221	0.10
7	825	0.8431	104	5.34	0.20	0.63	327	0.20
8	907	0.7320	119	4.99	0.35	1.09	373	0.40

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Low Idle	207	32.8	8.52	10,041	10.9
High Idle	184	75.3	5.45	10,019	7.20
1	187	20.0	6.49	10,052	6.55
2	241	17.1	2.23	10,060	5.10
3	250	17.5	1.75	10,061	4.30
4	241	11.0	1.43	10,065	4.45
5	219	5.95	2.58	10,067	4.55
6	207	9.30	2.42	10,065	4.20
7	164	6.23	19.3	10,040	6.35
8	134	9.48	29.4	10,022	10.1

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Low Idle	11	2.72	76.4	12.0	3.14	3,695	4.00
High Idle	11	1.02	180	73.5	5.33	9,793	7.00
1	190	16.5	11.4	1.20	0.39	610	0.40
2	345	19.1	12.6	0.90	0.12	526	0.25
3	675	20.0	12.4	0.88	0.09	503	0.20
4	1000	20.2	11.9	0.55	0.07	498	0.20
5	1300	20.4	10.7	0.30	0.13	493	0.20
6	1600	20.2	10.3	0.45	0.12	497	0.20
7	2400	20.5	8.00	0.30	0.94	490	0.30
8	2700	20.2	6.65	0.48	1.46	497	0.50

Fuel use and emission rates are based on one test day: July 15, 2011.

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 3-8. Average Prime Mover Engine Fuel Use and Emission Rates for F59PHI Locomotive NC 1755

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Idle	200	1.6853	3.61	0.26	0.03	0.01	11.3	0.00
1	307	0.9603	8.08	0.42	0.00	0.01	25.4	0.05
2	343	0.9823	15.0	0.92	0.05	0.01	47.0	0.05
3	490	0.9859	28.7	1.78	0.08	0.01	90.2	0.10
4	568	0.9374	42.6	3.10	0.05	0.04	134	0.10
5	651	0.8787	56.5	3.74	0.08	0.08	178	0.15
6	729	0.8069	68.2	4.37	0.05	0.11	215	0.15
7	819	0.7581	98.3	7.30	0.18	0.45	309	0.20
8	904	0.7147	129	8.65	0.33	2.50	403	0.35

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Idle	238	12.0	9.36	10,052	19.6
1	167	4.90	4.14	10,065	104
2	195	10.9	2.44	10,064	12.2
3	199	7.93	0.86	10,068	8.85
4	208	4.25	3.33	10,066	9.15
5	212	3.83	4.37	10,065	8.35
6	205	1.83	5.21	10,065	8.05
7	238	5.63	14.6	10,048	6.85
8	214	8.28	61.8	9,972	8.80

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Idle	11	2.71	87.6	4.43	3.45	3,708	7.20
1	189	20.8	8.03	0.23	0.20	484	0.50
2	350	20.8	9.38	0.53	0.12	484	0.60
3	671	20.8	9.57	0.15	0.04	484	0.45
4	998	20.8	10.0	0.38	0.16	484	0.45
5	1323	20.8	10.2	0.18	0.21	484	0.40
6	1597	20.8	9.86	0.08	0.25	484	0.40
7	2300	20.8	11.5	0.28	0.70	483	0.35
8	3026	20.8	10.3	0.40	2.97	479	0.40

Fuel use and emission rates based on one test: March 13, 2008.

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 3-9. Average Prime Mover Engine Fuel Use and Emission Rates for F59PHI Locomotive NC 1797

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Idle	200	1.7862	3.61	0.24	0.05	0.05	11.2	0.00
1	342	1.0734	8.08	0.46	0.13	0.09	25.2	0.05
2	343	1.1938	14.9	0.90	0.13	0.06	46.6	0.05
3	490	1.1771	28.7	1.81	0.23	0.07	90.2	0.10
4	568	1.1019	42.7	2.80	0.23	0.21	134	0.15
5	651	1.0060	56.5	3.60	0.15	1.58	175	0.15
6	729	0.9073	68.2	4.05	0.10	1.19	213	0.15
7	820	0.8328	102	5.83	0.33	1.12	320	0.20
8	904	0.7448	129	6.05	0.63	1.43	405	0.40

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Idle	217	54.0	47.0	9,967	12.1
1	185	45.8	36.5	9,989	12.9
2	193	29.0	12.3	10,037	14.0
3	201	26.5	7.85	10,046	10.2
4	210	17.4	15.6	10,039	9.65
5	203	8.98	89.3	9,928	8.45
6	190	4.50	55.7	9,984	7.50
7	182	10.4	35.1	10,013	6.85
8	150	15.6	35.3	10,009	9.45

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Idle	11	2.71	79.9	20.0	17.3	3,677	4.45
1	189	20.8	8.92	2.00	1.76	480	0.60
2	348	20.8	9.26	1.40	0.59	483	0.65
3	672	20.8	9.68	1.28	0.38	483	0.50
4	999	20.8	10.1	0.85	0.75	483	0.45
5	1323	20.8	9.78	0.43	4.29	477	0.40
6	1596	20.8	9.14	0.23	2.68	480	0.35
7	2396	20.8	8.76	0.50	1.69	481	0.35
8	3028	20.8	7.20	0.75	1.70	481	0.45

Fuel use and emission rates are based on one test: July 22, 2008

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 3-10. Average Prime Mover Engine Fuel Use and Emission Rates for GP40 Locomotive NC 1792, Before Rebuild

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Idle	254	2.0762	5.96	0.47	0.08	0.10	18.6	0.05
1	318	1.9672	11.9	1.03	0.08	0.12	37.3	0.05
2	386	1.1816	17.5	1.32	0.10	0.08	54.9	0.05
3	503	1.1838	32.4	2.59	0.15	0.09	102	0.10
4	573	1.1011	47.3	4.05	0.13	0.05	149	0.15
5	660	0.9168	60.0	5.16	0.08	0.05	189	0.15
6	734	0.7749	74.3	6.39	0.03	0.11	234	0.15
7	838	0.7688	113	9.62	0.15	0.22	357	0.20
8	914	0.6607	137	10.2	0.38	0.57	432	0.35

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Idle	257	34.8	54.4	9,967	17.5
1	276	21.3	33.2	10,009	10.2
2	240	20.0	14.5	10,039	12.5
3	256	13.8	9.01	10,052	10.2
4	274	8.03	3.48	10,064	9.00
5	275	4.45	2.89	10,067	7.95
6	276	0.93	4.86	10,066	6.75
7	272	3.98	6.22	10,062	5.35
8	239	8.85	13.3	10,048	7.60

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Idle	20	2.98	86.2	11.7	18.2	3,343	5.85
1	190	14.2	19.5	1.50	2.34	706	0.70
2	345	17.5	13.7	1.15	0.82	573	0.70
3	675	18.5	13.8	0.75	0.49	542	0.55
4	1000	18.8	14.6	0.43	0.19	535	0.50
5	1300	19.3	14.3	0.23	0.15	523	0.40
6	1600	19.2	14.4	0.05	0.25	526	0.35
7	2400	18.8	14.4	0.20	0.33	535	0.30
8	3000	19.4	12.3	0.45	0.69	518	0.40

Fuel use and emission rates are based on one test: March 25, 2008.

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 3-11. Average Prime Mover Engine Fuel Use and Emission Rates for GP40 Locomotive NC 1792, After Rebuild

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Idle	252	1.9826	5.62	0.27	0.13	0.18	17.3	0.05
1	319	1.9662	11.0	0.63	0.30	0.21	34.0	0.05
2	383	1.2394	16.6	0.76	0.23	0.13	51.8	0.10
3	501	1.2279	31.4	1.53	0.30	0.14	98.5	0.15
4	566	1.1409	46.2	2.55	0.25	0.08	145	0.20
5	661	0.9478	59.9	3.14	0.25	0.18	188	0.25
6	728	0.7903	73.2	3.79	0.25	0.21	230	0.35
7	828	0.7454	108	5.17	0.30	0.25	340	0.60
8	901	0.7785	136	6.31	1.00	0.36	428	1.25

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Idle	155	71.0	102	9,871	19.5
1	183	86.5	62.5	9,923	15.4
2	146	44.8	25.9	10,006	16.8
3	155	30.0	14.7	10,033	16.0
4	176	17.3	5.63	10,055	14.4
5	167	13.3	9.41	10,051	12.5
6	165	10.9	9.03	10,053	14.5
7	153	9.08	7.52	10,057	17.4
8	148	23.7	8.52	10,046	29.9

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Idle	20	3.16	49.0	22.4	32.1	3,121	6.15
1	190	15.4	11.9	5.63	4.06	645	1.00
2	345	18.5	7.88	2.40	1.40	540	0.90
3	675	19.1	8.13	1.58	0.77	525	0.85
4	1000	19.2	9.17	0.90	0.29	523	0.75
5	1300	19.3	8.70	0.68	0.49	521	0.65
6	1600	19.4	8.52	0.55	0.46	517	0.75
7	2400	19.7	7.76	0.45	0.38	510	0.90
8	3000	19.5	7.57	1.23	0.44	514	1.55

Fuel use and emission rates are based on one test: November 4, 2009.

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

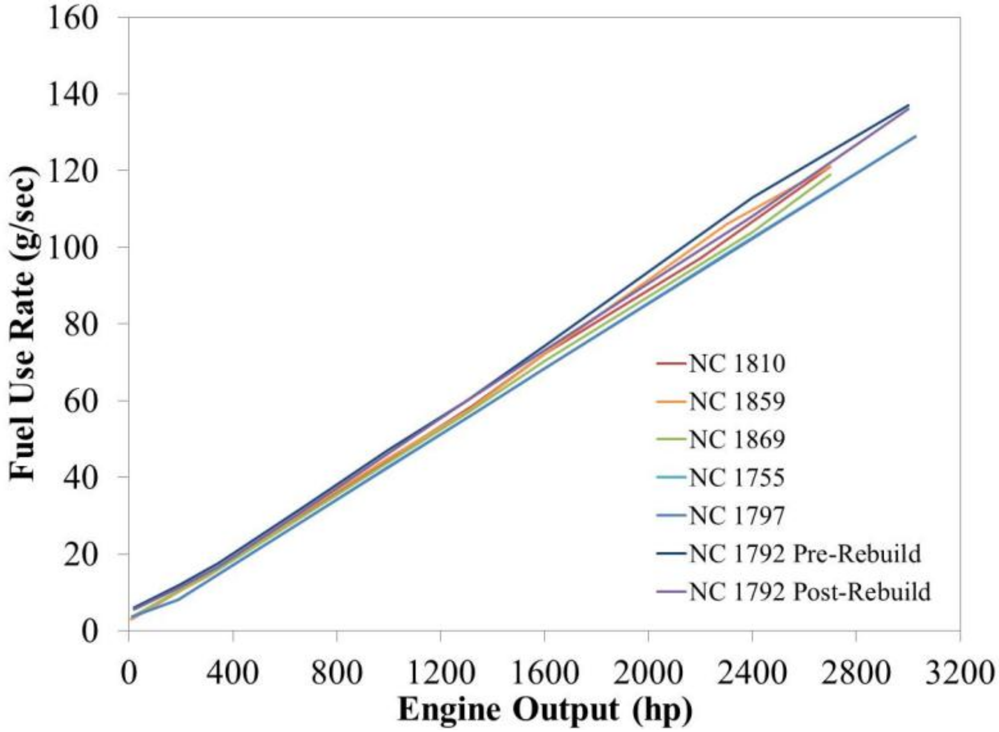


Figure 3-15. Time-Based Rail Yard Fuel Use Rates for the NCDOT Prime Mover Engines

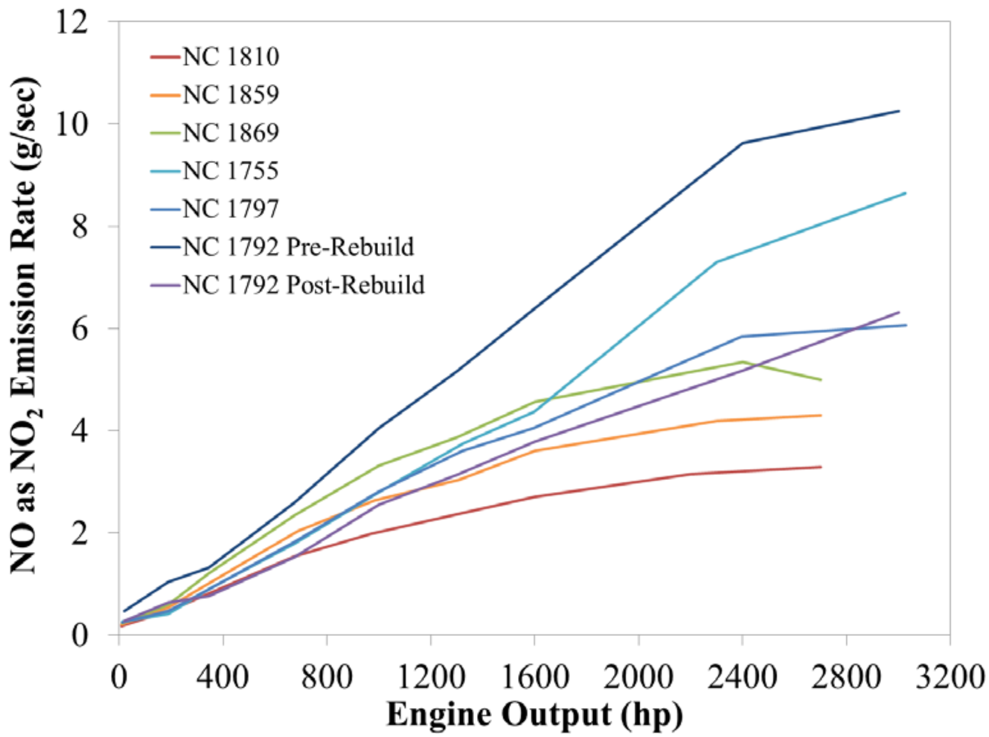


Figure 3-16. Time-Based Rail Yard NO_x Emission Rates for the NCDOT Prime Mover Engines

For all locomotives, the time-based fuel use, CO_2, NO_x, and PM emission rates increase as the engine load increases. As engine load increases, the engine RPM and MAP increases. This leads to an increase in the air, fuel, and exhaust flow for the engine. The CO and HC emission rates tend to increase with engine load, with some scatter in the data. On average, the CO exhaust concentration is above the PEMS detection limit of 0.008 volume percent for Notches 7 and 8. Most HC exhaust concentrations are below the PEMS detection limit of 13 ppm. As expected for diesel engines, the emission rates of CO and HC tend to be low compared to other types of emission sources.

For the F59PH locomotives, the time-based fuel use rates were similar to each other at all notches. The Notch 8 fuel use rates of all three locomotives averaged around 120 g/sec, and were 33 to 41 times higher than the low idle fuel use rates. On average, there was a 44 percent increase in fuel use for every step up in throttle position between Notches 1 and 8. The largest increases in fuel use rates occurred between idle and Notch 1 and between Notch 2 and 3. Figure 3-15 shows a linear trend in fuel use rate as engine output increases. On an engine output-basis, the average FSEO for Notches 2 through 8 was 19.8 bhp-hr/gal, approximately 7.3 times higher than the average FSEO for low idle.

The emission rates for all pollutants varied amongst the three F59PH locomotives. Focusing on NO_x emissions, the Notch 8 emission rates were 18 to 22 times higher than the low idle emission rates. The NO_x emission rates increase, on average, 39 percent for every step up in throttle position between Notches 1 and 8, with one exception; there was a 7 percent decrease in the NO_x emission rate between Notches 7 and 8 of NC 1869. A NO_x emission rate of 5.34 g/sec at Notch 7 for NC 1869 is relatively high, given that the NO_x emission rates at Notches 7 and 8 for the other locomotives were far less than 5 g/sec. As throttle notch increases, the spread in variation of NO_x emission rates between the three F59PHs widens, as seen in Figure 3-16. The three prime mover engines have similar emission rates at idle and Notch 1. For Notches 2 through 8, NC 1869 has significantly higher NO_x emission rates compared to NC 1859 and NC 1810.

For the F59PHI locomotives, the time-based fuel use rates were, on average, within 9 percent of each other at all notches, due primarily to the calibration of the engine volumetric efficiencies so that FSEO were equal to 20.8 bhp-hr/gal, which was obtained for Notches 4 through 8 with NC1755 and for Notches 6 through 8 with NC 1797. The Notch 8 fuel use rates of 129 g/sec were 64 to 67 times higher than the low idle fuel use rates. On average, there was a 52 percent increase in fuel use for every step up in throttle position between Notches 1 and 8. The largest increases in fuel use rates occurred between idle, Notch 1, Notch 2, and Notch 3.

For both F59PHI locomotives, the NO_x emission rates varied substantially with engine load. The Notch 8 mass per time emission rates were 48 to 59 times higher than the low idle emission rates. The NO_x emission rates increase, on average, 54 percent for every step up in throttle position from Notches 1 through 8. NC 1755 consistently has a higher NO_x emission rate than NC 1797. Both locomotives are scheduled for engine rebuilds.

For the GP40 locomotive, the time-based fuel use rates were similar at all notches both before and after the engine rebuild. On average, the post-rebuild fuel use rate was 5 percent lower than the pre-rebuild fuel use rate; a successful outcome for engine rebuilding. The Notch 8 fuel use rates were approximately 50 times higher than the low idle fuel use rates. On average, there was a 62 percent increase in mass per time fuel use for every step up in throttle position for Notches 1 through 8. The largest increases in fuel use rates occurred between idle, Notch 1, Notch 2, and Notch 3.

The GP40 Notch 8 NO_x emission rates were 46 to 50 times higher than the idle emission rates before and after rebuild. On average, the post-rebuild emission rate was 41 percent lower than the pre-rebuild emission rate at every notch position. This shows the success of the engine rebuild in reducing NO_x emissions.

On a relative basis, the opacity-based PM emission rates increase with engine load for all locomotives. Highest time-based opacity emission rates were observed at Notch 8, while highest fuel- and engine output-based opacity emission rates were observed during idle, with a few exceptions.

Using Figure 3-15 to compare the time-based fuel use rates for all five locomotives, the trends are fairly similar, especially for idle through Notch 6. This indicates similar changes in fuel use rates between notch positions. As throttle position increases from Notch 2, the spread in the fuel use rates tends to increase. At Notch 8, the GP40 has a higher fuel use rate than the F59PHIs, which have a higher fuel use rate than the F59PHs. The GP40 had a larger prime mover engine, at 16 cylinders, than the 12-cylinder engines used in the F59PHs and F59PHIs. And while the same model engine is used in the F59PHs and the F59PHIs, the prime mover engines in the F59PHs were rebuilt.

Comparisons in the NO_x emission rates for all five locomotives can also be made using Figure 3-16. On an absolute basis, variability between engines increases with notch position. At Notch 8, the GP40 and the F59PHIs had the highest emission rates. The F59PHIs consistently have higher emission rates compared to the F59PHs that have been rebuilt, with the exception of NC 1869 at Notch 7.

A comparison can be made between the F59PH fuel use and emission rates measured in the rail yard and on the dynamometer after engine rebuild to determine similarity in the rates. The focus will be on fuel use and NO_x emission rates. CO and HC emission concentrations tend to be at or near the detection limit of the PEMS during both sets of testing so large relative, but statistically insignificant, differences between emission rates are observed. Low flow through the PM sensor during the dynamometer test does not allow for a comparison of PM emission rates. Figures 3-17 and 3-18 depict the time- and engine-output based fuel use rates for the prime mover engines during dynamometer and rail yard testing of the F59PH locomotives. Figures 3-19 and 3-20 depict the time- and engine-output based NO_x emission rates for the prime mover engines during dynamometer and rail yard testing of the F59PH locomotives.

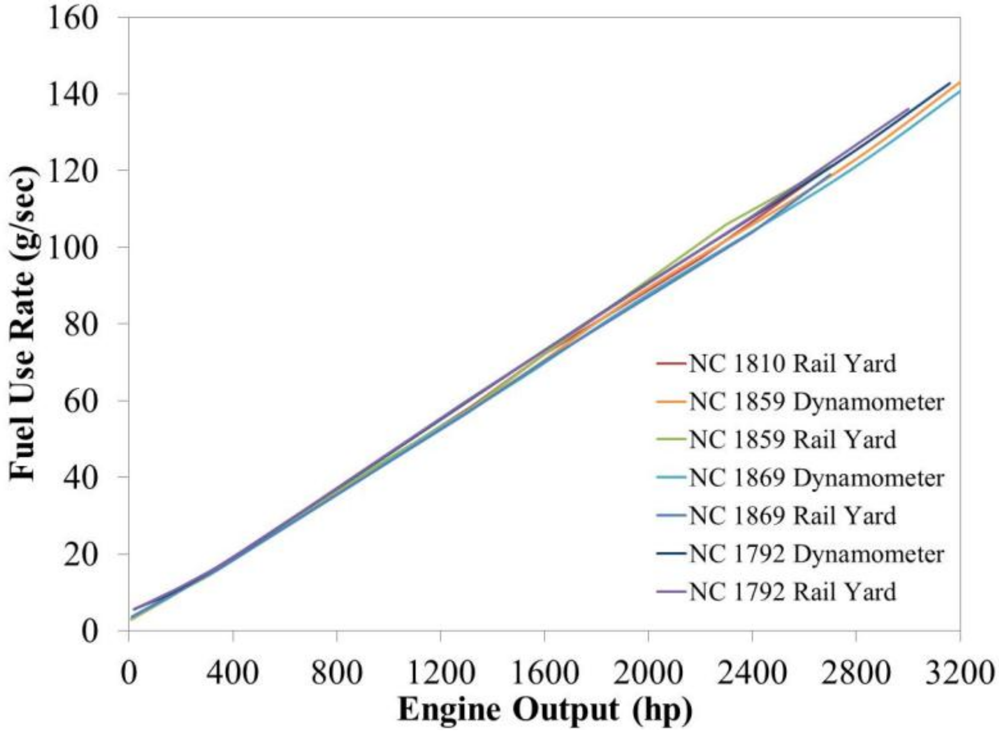


Figure 3-17. Time-Based Fuel Use Rates for the F59PH and GP40 Prime Mover Engines During Dynamometer and Rail Yard Testing

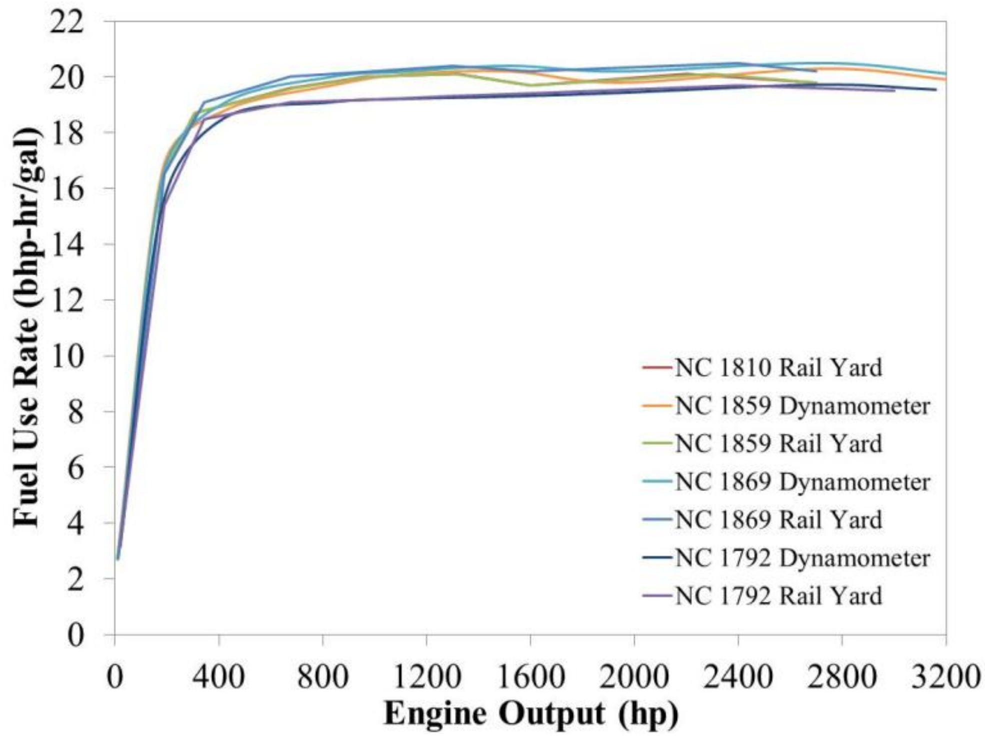


Figure 3-18. Engine Output-Based Fuel Use Rates for the F59PH and GP40 Prime Mover Engines During Dynamometer and Rail Yard Testing

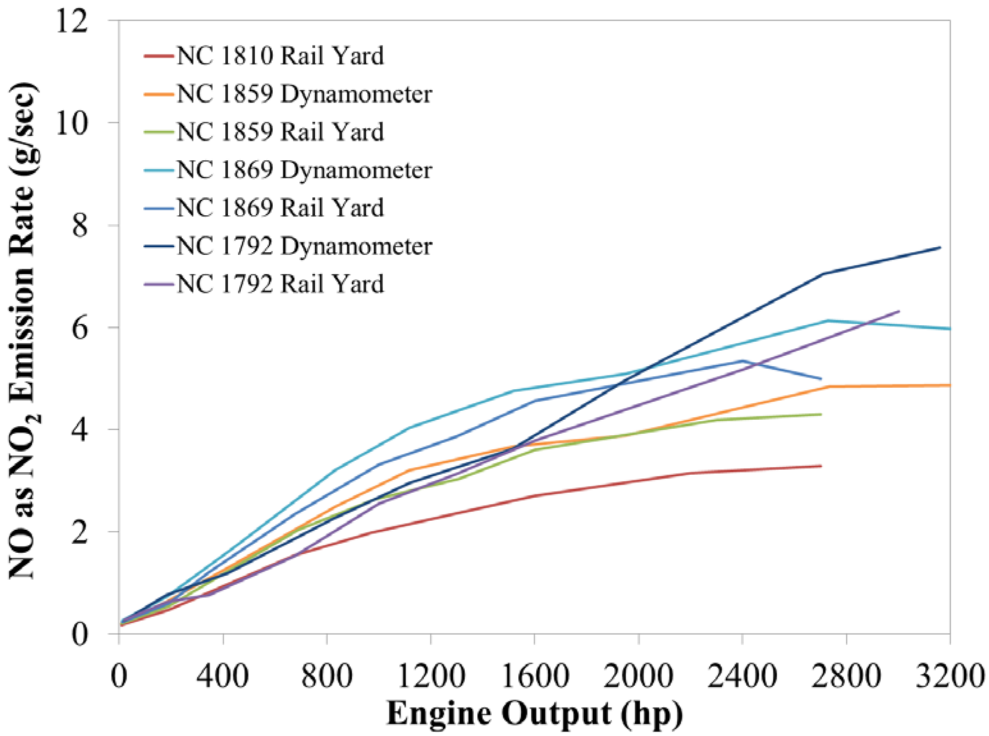


Figure 3-19. Time-Based NO_x Emission Rates for the F59PH and GP40 Prime Mover Engines During Dynamometer and Rail Yard Testing

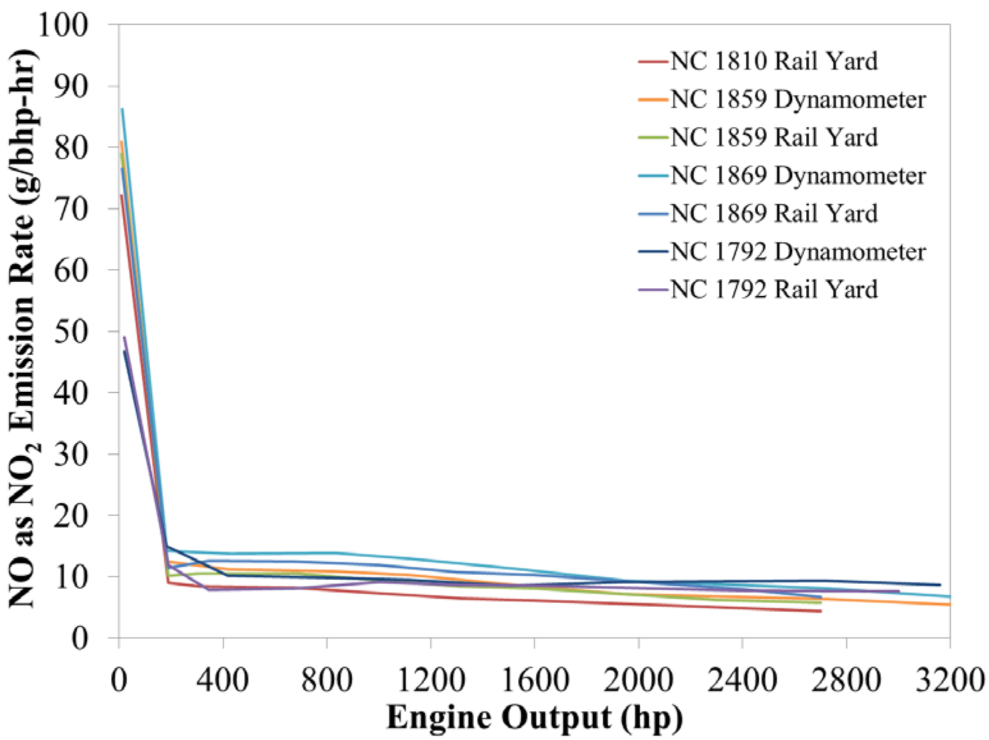


Figure 3-20. Engine Output-Based NO_x Emission Rates for the F59PH and GP40 Prime Mover Engines During Dynamometer and Rail Yard Testing

The trends in fuel use are similar between dynamometer and rail yard tests, as shown in Figures 3-17 and 3-18. In Figure 3-18, engine output-based fuel use rates increase up to approximately 400 hp, then approximately level off. The F59PH fuel use rates reach a maximum of between 19.5 and 20.0 bhp-hr/gal, while the GP40 fuel use rates reach a maximum of 18 and 18.5 bhp-hr/gal for both dynamometer and rail yard tests.

There is little variability in the time-based NO_x emission rates at low engine output, as shown in Figure 3-19, for the locomotives tested on the dynamometer and in the rail yard. The variability increases as engine output increases from approximately 250 hp. However, absolute variability decreases in the engine output-based NO_x emission rates as engine output increases from approximately 250 hp in Figure 3-20. The brake-specific output-based NO_x emission rate is very sensitive to engine output at low engine output. In the rail yard tests, the maximum engine output observed was approximately 2,700 hp at Notch 8 for the F59PH locomotives, not the engine rated 3,000 hp.

Rail yard testing produced NO_x emission rates that were less than emission rates observed during dynamometer testing, perhaps in part because the engine load was lower for the higher notch positions in the rail yard tests. The average difference in emission rates between Notches 1 and 8 and between dynamometer and rail yard testing is 17 percent. However, the average difference in emission rates decreases as throttle position increases, from an average of 27 percent at Notch 1 to 6 percent at Notch 8.

2.5.5 Prime Mover Engine Results – Cycle Average Emission Rates

A key challenge in rail yard testing is that fuel flow rate is not measured. Instead, it is estimated using the "speed density" method (described in Section 3.1.3 and detailed in Appendix B) based on measurements of RPM, MAP, and IAT. Therefore, a potential source of uncertainty in estimating cycle average emission rates on an engine output (bhp-hr) basis is the fuel flow rate. A key parameter in the speed density calculation is the engine volumetric efficiency, which can be inferred from measurements of fuel flow rate, RPM, MAP, and IAT conducted during dynamometer tests. For the three engines for which dynamometer tests were available, volumetric efficiency was calibrated for each notch position based on dynamometer data. However, for engines for which dynamometer data were not available, volumetric efficiency is estimated either as a default value or is calibrated based on an assumed fuel consumption rate. For the latter, a commonly used value in the literature is 20.8 bhp-hr/gallon of fuel. Thus, in reporting cycle average results for rail yard tests, the following two case studies were developed:

- Case 1: Volumetric Efficiency Calibrated Based on Dynamometer Data
- Case 2: Volumetric Efficiency Calibrated to Default Fuel Consumption of 20.8 bhp-hr/gallon.

Emission rates, in g/bhp-hr, are used to make comparisons to the EPA emission standards. The calculated brake specific cycle average emission rates for NO_x, HC, CO, and opacity-based PM for all locomotives are compared to the EPA Tier 0+ and Tier 1+ emission standards in Table 3-12. The results shown are intended for relative comparisons. The PEMS-based measurements do not constitute an FRM, and thus cannot be used for certification. The reported emission rates for NO_x, HC, and opacity-based PM include adjustment factors discussed in Section 3.1.1 and documented in the footnotes to the table. Nonetheless, the PEMS-based data provide information that can help inform a judgment as to whether an engine is likely or not to be in compliance with a standard.

Volumetric efficiency was calibrated based on dynamometer tests for F59PH and GP40 locomotives to match measured fuel flow.

For NC 1810 and NC 1859, both locomotives have NO_x, CO, and HC emission rates below the Tier 1+ standard, as shown in Table 3-12. The PM results are not conclusive in terms of absolute emission rates or comparison to the standard, because of differences in methods used versus the FRM. They are useful for relative comparisons among the locomotives. For example, NC 1810 has a higher PM emission rate than NC 1859. For NC 1869, the NO_x emission rate was above the Tier 0+ standard (at 8.7 g/bhp-hr, versus the standard of 8.0 g/bhp-hr), and was well above the Tier 1+ standard (of 7.4 g/bhp-hr).

The HC emission rate was below Tier 0+ but above Tier 1+ (0.58 g/bhp-hr based on measurement versus 0.55 g/bhp-hr for the standard). However, given uncertainties in the bias correction factor for HC, it is not unreasonable to conclude that the actual HC emissions could be below Tier 1+. The CO emission rate was below Tier 1+. The PM emission rate was actually lower than for NC 1810 and NC 1859. Hence, NC 1869 is the best of the three F59PH locomotives for PM, but the worst for NO_x. On this basis, it is reasonable to infer that NC 1810 and NC 1859 are in Tier 0+ compliance for NO_x, HC, and CO. NC 1869 meets Tier 0+ with the exception of NO_x, with an observed emission rate that is 9 percent higher than the standard. Whether this is 'close enough' to meeting the standard would be a judgment call. Another factor to consider is how this engine performs during over-the-rail operation, which is described further in Chapter 4. Results from over-the-rail measurements indicate that in-use NO_x emissions are slightly lower than dynamometer or rail yard measurements; thus, from a practical perspective, the emission rate may be acceptable.

Rebuilding and tuning of the prime mover engine helped reduce the cycle average NO_x emission rates of the GP40 by 40 percent. However, HC and opacity-based PM emission rates more than doubled after the engine rebuild. CO emission rates remained relatively similar. Due to the date of original manufacture of the GP40, it did not have to achieve any of the EPA emission standards.

For the F59PHI locomotives, engine rebuild is pending. Measurement of fuel use and emissions rates in the rail yard and comparison to EPA emission standards will be assessed in future work.

Table 3-12. Cycle Average Prime Mover Engine Emission Rates for NCDOT Locomotive Fleet

Locomotive	NO_x (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	Opacity-based PM (g/bhp-hr)
NC 1810 (F59PH)[a,e]	6.0	0.23	1.9	0.59
NC 1859 (F59PH)[b,e]	7.3	0.30	1.1	0.47
NC 1869 (F59PH)[e]	8.7	0.58	1.0	0.42
NC 1755 (F59PHI)[c,f]	10.8	0.37	2.0	0.47
NC 1797 (F59PHI)[d,f]	8.5	0.87	1.9	0.47
NC 1792 (GP40)[e] *Before Rebuild*	14.1	0.58	0.8	0.48
NC 1792 (GP40)[e] *After Rebuild*	8.4	1.43	0.9	1.31
EPA Tier 0+	8.0	0.90	5.0	0.22
EPA Tier 1+	7.4	0.55	2.2	0.22

MEASUREMENT RESULTS ARE INTENDED FOR COMPARISONS BETWEEN TESTS, AND CANNOT BE USED FOR CERTIFICATION PURPOSES.

NO_x includes NO and NO_2. Only NO was measured. Typically, NO_x is comprised of 95 vol-% NO. Total NO_x is estimated to be approximately 5 percent higher than the values shown. NO_x is always reported as equivalent mass of NO_2. Cycle average emission rates include a multiplicative correction factor of 1.053 to approximate for total NO_x.

HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds, but responds only partially to others. Actual HC emissions may be a factor of 2 to 2.5 greater than the values shown. Cycle average emission rates include a multiplicative correction factor of 2.5 to approximate for total HC.

Opacity is measured using a light scattering technique, which provides useful relative comparisons of particle levels in exhaust. The actual PM emission rate may be a factor of 5 to 20 greater than the value shown. Cycle average emission rates include a multiplicative correction factor of 5 to approximate total PM.

[a] Average of May 23, 2011 and June 27, 2011 rail yard tests of NC 1810
[b] Average of March 8, 2011 and June 28, 2011 rail yard tests of NC 1859
[c] Average of March 13, 2008 and December 2, 2009 rail yard tests of NC 1755
[d] Average of July 2, 2008 and December 4, 2009 rail yard tests of NC 1797
[e] Rail yard fuel specific engine output (FSEO) calibrated to FSEO observed during dynamometer testing
[f] Rail yard FSEO calibrated to 20.8 bhp-hr/gal

For the engines that did not undergo dynamometer testing, or for the condition of such engines prior to being rebuilt, there is uncertainty in the prime mover engine FSEO. A sensitivity analysis is conducted to compare emission rates for the measured locomotives to emission rates cited in literature. All engine volumetric efficiencies were calibrated so that FSEO of 20.8 bhp-hr/gal were achieved. These calculated brake specific cycle average emission rates for NO_x, HC, CO, and opacity-based PM for all locomotives are compared to the EPA Tier 0+ and Tier 1+ emission standards in Table 3-13.

For the F59PH locomotives, a FSEO of 20.8 bhp-hr/gal is 4 percent more fuel efficient than the dynamometer FSEO of approximately 20.0 bhp-hr/gal. Therefore, theoretically, the cycle average emission rates for all pollutants should decrease by 4 percent; however, this is not the case due to variations in actual FSEO. Estimated emission rates decreased, on average, between 2.5 and 3.5 percent.

For the F59PHIs, a FSEO of 20.8 bhp-hr/gal is already used in determining emission rates given the absence of dynamometer testing of the locomotives. Thus, there is no change compared to the results given in Table 3-12.

Emissions associated with the GP40 also decreased when engine volumetric efficiencies were calibrated. A FSEO of 20.8 bhp-hr/gal is more fuel efficient than the dynamometer FSEO of approximately 19.0 bhp-hr/gal between Notches 2 and 8. Estimated emission rates for HC, NO_x, and opacity-based PM decreased approximately 4, 6, and 6 percent, respectively. The CO emission rate remained approximately unchanged in the pre-rebuild case, and decreased 14 percent in the post-rebuild case.

Comparing the estimated cycle average emission rates for the locomotive fleet in Table 3-13 to the EPA's 1998 data in Table 2-3, all estimated emission rates are within the same magnitude of the published emission rates. The F59PH and F59PHIs, which use EMD 12-710G3 prime mover engines, had similar or lower NO_x emission rates. The NO_x rates observed for the F59PH locomotives are lower than the published 10.55 g/bhp-hr because of recent engine rebuilds. Estimated emission rates for HC and CO are within 2.5 and 2.0 times the published values, respectively. The GP40, which has an EMD 16-645E3 prime mover engine, had similar or lower NO_x emission rates compared to the published data. The NO_x rate observed after the engine rebuild is lower than the published 13.64 g/bhp-hr because of the engine rebuild. However, the NO_x emission rate of 13.0 g/bhp-hr before the engine rebuild is similar to the published value. The estimated CO emission rate of approximately 0.9 g/bhp-hr is below the published value of 1.85 g/bhp-hr. The estimated HC emission rate is similar to the published rate before the engine rebuild and nearly 3 times higher after the rebuild.

Table 3-13. Sensitivity Case: Cycle Average Prime Mover Emission Rates for NCDOT Locomotive Fleet, Fuel Specific Engine Output of 20.8 bhp-hr/gal

Locomotive	NO_x (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	Opacity-based PM (g/bhp-hr)
NC 1810 (F59PH)[a]	5.7	0.12	1.8	0.56
NC 1859 (F59PH)[b]	6.9	0.28	1.0	0.45
NC 1869 (F59PH)	8.4	0.56	1.0	0.41
NC 1755 (F59PHI)[c]	10.8	0.37	2.0	0.47
NC 1797 (F59PHI)[d]	8.5	0.87	1.9	0.47
NC 1792 (GP40) *Before Rebuild*	13.0	0.54	0.8	0.44
NC 1792 (GP40) *After Rebuild*	7.9	1.34	0.9	1.23
EPA Tier 0+	8.0	0.90	5.0	0.22
EPA Tier 1+	7.4	0.55	2.2	0.22

MEASUREMENT RESULTS ARE INTENDED FOR COMPARISONS BETWEEN TESTS, AND CANNOT BE USED FOR CERTIFICATION PURPOSES.

NO_x includes NO and NO_2. Only NO was measured. Typically, NO_x is comprised of 95 vol-% NO. Total NO_x is estimated to be approximately 5 percent higher than the values shown. NO_x is always reported as equivalent mass of NO_2. Cycle average emission rates include a multiplicative correction factor of 1.053 to approximate for total NO_x.

HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds, but responds only partially to others. Actual HC emissions may be a factor of 2 to 2.5 greater than the values shown. Cycle average emission rates include a multiplicative correction factor of 2.5 to approximate for total HC.

Opacity is measured using a light scattering technique, which provides useful relative comparisons of particle levels in exhaust. The actual PM emission rate may be a factor of 5 to 20 greater than the value shown. Cycle average emission rates include a multiplicative correction factor of 5 to approximate total PM.

[a] Average of May 23, 2011 and June 27, 2011 rail yard tests of NC 1810
[b] Average of March 8, 2011 and June 28, 2011 rail yard tests of NC 1859
[c] Average of March 13, 2008 and December 2, 2009 rail yard tests of NC 1755
[d] Average of July 2, 2008 and December 4, 2009 rail yard tests of NC 1797

2.5.6 Head End Power Engine Results – Emission Rates

This section summarizes the measurement results for the HEP engines. As noted earlier, these engines were tested under various loads. These measurements are intended to serve as a baseline for future comparisons, but are not representative of an actual duty cycle for this type of engine in actual passenger train service. The electrical loads are based on connecting passenger cars to the locomotives during the tests. Each passenger car has lights and air conditioning/heating. For each car, all lights were turned on and the air conditioner/heater was run at its default thermostat setting. The variation in electrical load for a given number of passenger cars from one test to another is because of variability in ambient temperature and solar irradiation, which affects the cooling load. When no passenger cars are connected to the HEP engine, some power was consumed to maintain charge of batteries in the locomotive. When the HEP engines were being tested, the main engines were not operating.

The duty cycles of the HEP engines are not comparable to those of the prime mover engines. While power demand on the prime mover engine changes substantially during operation, power demand on the HEP engine is typically less variable. The HEP engine runs at a constant 1800 RPM while hotel services are provided to up to 4 passenger cars during testing.

There is variability in the electrical load per passenger car, in part because of different passenger car configurations. The baggage/lounge/vending car may need a different electrical load to power lighting, electrical outlets, heating and air conditioning, and vending machines than the passenger seating cars. There are also different seating capacities in the passenger cars that may lead to varying electrical loads. NCDOT passenger cars have seating capacities of either 56 or 66 passengers. Electrical load per passenger car, on average, is between 13 and 24 kW.

Fuel-based emission factors are estimated for all HEP engines, as reported in Table 3-14. Published data on HEP engines have not been identified, and thus there is not a benchmark available for comparison to these data. The HEP engines used in the F59PH locomotives, however, are expected to meet the EPA Tier 2 standard for heavy-duty and nonroad engines.

The CAT C18 ACERT engines on the F59PHs had fuel-based NO_x emission factors varying between 86 and 107 g/gallon. Fuel-based NO_x emission factors for the two CAT 3412 engines in the F59PHI locomotives are in the range of 116 to 175 g/gallon, depending on the engine and the load level. These numbers are less than the fuel-based emission factors for the prime mover engines, which had a line-haul cycle average of 218 to 249 g/gallon. The Cummins KTA19 engine on the GP40 had a substantially low fuel-based NO_x emission rate, ranging from 40 to 67 g/gallon.

The CAT C18 ACERT engines had fuel-based HC emission rates ranging from 11.5 to 35.0 g/gallon. The fuel-based HC emission rates for the CAT 3412 engines ranged from 15.8 to 30.8 g/gallon, similar to the CAT 3412 engines, depending on the engine and the load. These are comparable to the fuel-based rates for prime mover engines inferred from EPA data. The Cummins KTA19 engine had lower emission rates for a given load than the two CAT 3412 engines. The fuel-based HC emission factors typically decrease with load. The average exhaust HC concentrations for the Cummins KTA19 engine are typically below the detection limit.

Table 3-14. Fuel-Based Emission Factors of Head End Power Engines

Locomotive (Engine Model)	Number of Passenger Cars	Electrical Load (kW)	NO as NO_2[a] (g/gal)	HC[a] (g/gal)	CO (g/gal)	Opacity-based PM[a] (g/gal)
NC 1810 F59PH (CAT C18 ACERT)	0	< 6.42[b]	94.6	20.0	80.9	---[c]
	1	< 6.42[b]	98.5	16.3	73.8	---[c]
	2	41.7	101	13.8	59.1	---[c]
	3	57.8	98.4	16.5	46.8	---[c]
	4	---	---	---	---	---
NC 1859 F59PH (CAT C18 ACERT)	0	< 6.42[b]	99.4	17.5	83.5	---[c]
	1	< 6.42[b]	107	15.0	67.2	---[c]
	2	48.2	104	11.5	63.6	---[c]
	3	57.8	99.7	11.5	43.7	---[c]
	4	---	---	---	---	---
NC 1869 F59PH (CAT C18 ACERT)	0	< 6.42[b]	86.6	40.0	109	---[c]
	1	< 6.42[b]	99.3	20.5	93.6	---[c]
	2	44.9	94.2	14.3	69.1	---[c]
	3	---	---	---	---	---
	4	---	---	---	---	---
NC 1755 F59PHI (CAT 3412)	0	1.3	141	30.8	81.6	7.5
	1	16.6	157	22.3	59.8	5.0
	2	26.9	161	20.0	52.2	6.5
	3	---	---	---	---	---
	4	52.8	175	16.3	37.7	6.5
NC 1797 F59PHI (CAT 3412)	0	1.8	116	19.8	73.9	7.0
	1	---	---	---	---	---
	2	36.5	138	22.8	49.5	8.0
	3	---	---	---	---	---
	4	62.4	148	15.8	38.6	7.5
NC 1792 GP40 (Cummins KTA19)	0	1.4	40.6	24.0	41.3	4.5
	1	24.0	44.9	9.25	19.4	4.0
	2	37.0	52.7	9.00	11.1	5.5
	3	---	---	---	---	---
	4	62.4	66.5	8.50	9.4	5.0

[a] NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.
[b] Digital display on the HEP engine read an electrical load of between 0 and 1 percent of maximum electrical load.
[c] Calculation of fuel-based opacity-based PM emission factors not possible under testing setup without voiding engine warranty.

The fuel-based CO emission factors varied between 43.7 and 109 g/gallon for the CAT C18 ACERT engines. For the CAT 3412 engines, the fuel-based emission rates ranged from 38 to 82 g/gallon among various loads, similar to the CAT C18 ACERT engines. The CO emission rates decreases with load, and the average exhaust CO concentrations for the Cummins KTA19 engine are typically below the detection limit.

The fuel-based PM emission rates for the CAT 3412 and Cummins KTA19 engines are approximately similar and appear to be higher than for the substantially larger prime mover engines. There is not a strong trend of fuel-based PM emission rates with respect to load. Due to the inability to sensor the CAT C18 ACERT engines with engine sensors and to locate engine fuel use specifications, opacity-based PM emission rates could not be calculated. However, during certification tests, the fuel-based, opacity-based PM of the CAT C18 ACERT engines were measured as 0.9 g/gallon, similar to the CAT 3412 and Cummins KTA19 engines when the PM bias correction factor is not included (CARB, 2009).

2.6 Summary

In this chapter, the following items were discussed:

- A portable emissions measurement system (PEMS) was used to measure the exhaust gas concentrations, engine speed, intake air temperature, and manifold absolute pressure used to calculate locomotive emission factors.
- Prime mover engine fuel use and emission factors were calculated on time, fuel, and engine output bases. In general, the GP40 locomotive had highest fuel use and NO_x emission rates, followed by the F59PHIs and F59PHs. The engine rebuild and tuning reduced fuel use and emission rates for the GP40.
- Cycle average prime mover emission rates were estimated for the locomotive fleet based on the EPA line-haul duty cycle. The NC 1810 and NC 1859 may be able to achieve EPA Tier 0+ status for NO_x, HC, and CO. The NC 1869 may be able to achieve EPA Tier 0+ status for HC and CO.
- The prime mover and head end power engines for each locomotive in the fleet were tested in the rail yard. The resulting fuel use and NO_x emission rates were similar to the fuel use and emission factors estimated during dynamometer testing.
- Comparing the measured rail yard cycle average emission rates to those cited in literature, the NO_x and HC emission rates for the GP40 and F59PHIs were similar to the emission rates of the same engines in Table 2-4. The cycle average emission rates for the F59PH locomotives are lower than the emission rates of the same engine in Table 2-4 due to the engine rebuild to meet EPA Tier 0+ status.
- Head end power engine fuel use and emission factors were calculated. The newer CAT C18 ACERT engines had lower NO_x and HC emission rates and similar CO emission rates compared to the older CAT 3412 engines. However, the Cummins KTA19 engine had lower emissions of NO_x, HC, and CO compared to the CAT C18 ACERT engines.

3.0 OVER-THE-RAIL TESTING

The general technical approach for over-the-rail testing of the locomotives and their prime mover engines involved four major components: (1) instrumentation; (2) preparation for field data collection; (3) field data collection; and (4) quality assurance and quality control. Each of these components of the technical approach is described. The results of data analysis are given and summarized.

Over-the-rail testing is a unique fuel use and emissions measurement method. Most testing is conducted on an engine dynamometer or in the rail yard. A literature review turned up no journal articles or technical reports where locomotive prime mover engines were tested during normal operation. Over-the-rail testing allows for locomotive operators to test their prime mover engines without taking their locomotives out of service.

Duty cycles can be calculated from locomotive activity data logged by onboard event recorders. This gives locomotive operators a means of determining the amount time spent in each notch along a particular route, and whether there are differences in duty cycles based on different locomotive models and driving behaviors of engineers.

Three objectives of the over-the-rail testing are to: (1) collect fuel use and emissions data from prime mover engines of locomotives in service; (2) compare fuel use and emission rates to those estimated from dynamometer and rail yard testing of the same locomotives; and (3) measure duty cycles of locomotives in service and compare the measured duty cycles to the EPA duty cycles used for regulatory purposes.

3.1 Instrumentation

The PEMS used in this project are the OEM-2100 Montana and the OEM-2100AX Axion systems, both manufactured by Clean Air Technologies International, Inc. (CATI). More information regarding the PEMS can be found in Section 3.1 of this report.

A Garmin GPSmap 76CSx GPS unit with barometric altimeter recorded location and elevation on a second-by-second basis. The location coordinates were used to match locomotive location along the track, and to estimate distances between elevation measurements. The differences in elevation over a distance were used to estimate rail grade. Future work includes analyzing the measured rail grade between Raleigh and Charlotte, NC to determine a model to estimate fuel use and emissions based on rail grade.

Each locomotive has an EMD EM2000 Locomotive Computer System, or locomotive activity data recorder, installed. Real-time locomotive activity data are provided on a digital display, as shown in Figure 3-15. These data include 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. Event Recorder Download Analysis Software for Windows (WinDAS) is needed to open the saved data recorder file and export the data into a comma separated values (CSV) file that can be opened and analyzed in spreadsheet software such as Microsoft Excel.

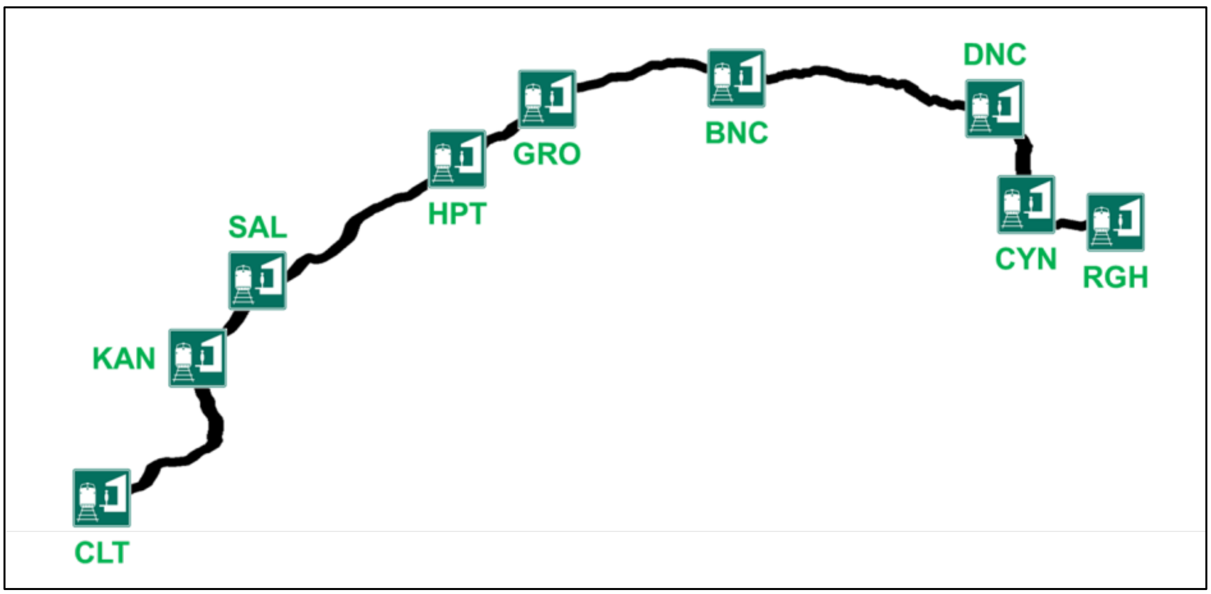
3.2 Preparation for Field Data Collection

Through a joint effort between NCDOT and AMTRAK, daily rail service is provided between the cities of Raleigh and Charlotte, NC, as well as seven cities in between, as shown in Figure 4-1. Currently, two trains operate in both directions each day, for a total of four trains daily. Each train is scheduled to travel the 173 miles of track between North Carolina's largest two cities in 3 hours and 15 minutes. The top speed of the locomotive is 79 miles per hour, but averages 53 miles per hour if time stopped at each station is considered. Typically, each train is comprised of one locomotive and a consist of one baggage/lounge car and two passenger cars. Additional passenger cars are added if warranted by ridership figures.

Preparations for field data collection include four major components: (1) verification of the status of the PEMS and that all necessary parts and consumables are available; (2) laboratory calibration of the PEMS; (3) completion of a field study design; and (4) coordination with the locomotive owner/operator regarding scheduling of the test and access to the locomotive.

As part of the preparation, NCSU ensured that the PEMS had functioning electrochemical sensors for NO and O_2, and that all consumables were replaced, such as filters in the exhaust sampling line. A span calibration of the PEMS using a standard calibration gas was conducted before any testing.

Figure 4-1. Map of the Piedmont Rail Service[a]



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

Field study design includes specifying which locomotives are to be tested, when they are to be tested, and what fuel will be used. As part of this project, NCDOT allowed NCSU to access its fleet of locomotives for testing. Early in the study, each locomotive was tested at least four times roundtrip in order to allow for loss of test data due to mechanical and/or technical problems with the PEMS and/or locomotive. NC 1869 was only tested during one roundtrip. Locomotives were fueled by NCDOT with ultra low sulfur diesel.

3.3 Field Data Collection Procedure

Field data collection includes the following main steps: (1) installation; (2) data collection; and (3) decommissioning. Appendix A provides checklists that are used during all three steps of the field data collection procedure.

Installation of the PEMS and its various components was performed the day before a scheduled test. This step involved installing the exhaust sampling lines, power cables, the engine sensor array and its sensors, and the PEMS unit. Sampling lines were directly connected from the PEMS to the sampling port on the exhaust gas duct of the prime mover engine. The PEMS was placed either inside of the locomotive cab or generator room. The installation of all instrumentation for over-the-rail testing is shown in Figure 4-2. Exhaust gas lines and sensor cables were routed from the engine to the location in which the PEMS was housed. Installation time for over-the-rail testing was similar to the installation time needed for rail yard testing—approximately two to four hours based on the availability of locomotive mechanics to assist in the placement of sample fittings and routing of exhaust gas lines and sensor cables.

Data collection involved continuously recording, on a second-by-second basis, exhaust gas concentrations and engine data. At the end of each test day, data collected from the PEMS and locomotive activity data recorder were copied and the PEMS was powered down and removed from the locomotive. Collection of over-the-rail test data is similar to rail yard data collection. The main difference between the two testing methods is that the PEMS unit operation status could not be checked during some over-the-rail tests due to PEMS placement, such as in the GP40 generator room. The PEMS unit could only be checked when the locomotive reached its final destination. During a few over-the-rail tests, the PEMS lost power due to an unexpected failure of the HEP engine. The PEMS was restarted when the locomotive reached the destination train station. Any valid data collected up to the point when the PEMS turned off was used in fuel use and emissions analyses.

Decommissioning occurs after the end of the test period. The exhaust sample lines, power cables, the engine sensor array and its sensors were removed from the locomotive.

Figure 4-2. Placement of Instrumentation for Over-the Rail Testing of Locomotives
(a) GPS units on left side of locomotive cab during testing of F59PH locomotives; (b) PEMS unit in the locomotive cab during testing of F59PH locomotives; (c) PEMS unit in the generator room during testing of GP40 locomotive

3.4 Quality Assurance and Quality Control

For quality assurance purposes, the combined data set for a test was screened to check for errors or possible problems. More information on the quality assurance and quality control procedures are found in Section 3.4.

There are some additional steps needed to process the over-the-rail data, compared to processing rail yard data. Data from the handheld GPS units and the locomotive activity data recorder must be time synchronized with the PEMS data. GPS and locomotive activity data are synchronized based on locomotive speed. PEMS and locomotive activity data are synchronized based on engine speed. While the locomotive activity data recorder does not explicitly report engine speed in the downloaded WinDAS file, it can be inferred from notch position, which is reported by the data recorder. The notch position is reported by the locomotive activity data recorder and is updated as soon as the engineer changes the notch position, and therefore, includes data for when the engine is transitioning from its current notch position to the intended notch position. The transition period could be as much as 30 seconds when switching from idle to Notch 8. RPM reported by the PEMS was used to remove this transitioning period from each reported notch position.

During some over-the-rail tests, the engine speed sensor malfunctioned causing RPM measurements not to be recorded. In those instances, MAP was used as a surrogate for RPM in determining notch position. Like RPM, MAP is stable and varies for each notch position.

3.5 Results

The results include the field data collection schedule, observed duty cycles during testing, benchmarking of locomotive emission results to other data, overall comparison of locomotives, and detail characterization of each locomotive.

3.5.1 Scheduling of Field Data Collection

Field data collection occurred during the period of March 2008 to August 2011, as summarized in Table 4-1. Five of the six locomotives tested in the rail yard were also tested over-the-rail; the

F59PHI locomotive numbered NC 1797 was not tested over-the-rail. The F59PH locomotives were tested after locomotive and prime mover engine rebuild. F59PHI locomotive NC 1755 was tested prior to locomotive and prime mover engine rebuild. The GP40 locomotive was tested prior to and after locomotive and prime mover engine rebuild.

3.5.2 Observed Duty Cycles

Data collected by the locomotive activity data recorder for each test were used to derive duty cycles. These observed duty cycles for each locomotive model are compared to the EPA line-haul and suggested passenger duty cycles in Table 4-2. The observed duty cycles for the three locomotive models are based on averages of multiple one-way trips. Dynamic braking is not available in the F59PH locomotives and, therefore, is not observed in the duty cycle.

The percent time spent in idle is comparable to the EPA passenger duty cycle for the F59PH, and approximately 25 percent higher than the EPA line-haul duty cycle. For the F59PHI and GP40 locomotives, the percent time spent in idle is comparable to the EPA line-haul duty cycle.

For this particular intercity passenger rail service, a substantial fraction of time is spent in Notch 8. Notch 8 is used to get the train up to 79 mph once leaving each station, and to maintain 79 mph where necessary, such as over rail with positive rail grade. Relatively little time is spent in each of Notches 3 through 7. To slow the train down, the throttle is lowered briefly to one or two intermediate notch positions between Notches 1 through 7 and then to idle. The largest discrepancies between the observed Piedmont duty cycles and the EPA duty cycles are in Notch 8. Engineers running the NCDOT locomotives spent nearly 2 to 3 times more time in Notch 8 than is the case for the EPA line-haul duty cycle. The consequence of this is that using the EPA line-haul duty cycle as a surrogate for the duty cycle operated on the Piedmont service would lead to an underestimate of total fuel use and emissions over the entire route.

The observed duty cycles varied for each one-way trip, as depicted by the ranges in percent time in each notch in Table 4-2. This can be attributed to differences in running behavior by the engineers and unscheduled stops or slowdowns, such as slow orders from Norfolk Southern (NS), who controls traffic on the rail corridor, due to weather or track repair, stopping in the rail siding to allow other rail traffic to pass, and stopping due to malfunctioning signals or rail crossing gates. More detailed run-by-run duty cycle results are found in Appendix D.

Table 4-1. Over-the-Rail Data Collection Schedule

Model	Locomotive	Prime Mover Engine
F59PH	NC 1810	March 10-13, 2011 and May 24-27, 2011
	NC 1859	June 7-8, 2011
	NC 1869	July 15, 2011
F59PHI	NC 1755	June 13-14, 2010
GP40	NC 1792	December 6-7, 2009 and December 13-14, 2009 April 29 – May 1, 2010

Table 4-2. Observed Over-the-Rail Duty Cycles Compared to EPA Duty Cycles

Notch	Percent Time in Notch (Range of Observed Values)				
	Locomotive Model			EPA (1998)	
	F59PH[a]	F59PHI	GP40	Line-Haul	Passenger
Idle	40.8 (28.0-71.0)	33.0 (25.8-40.9)	26.9 (20.7-32.6)	38.0	47.4
Dynamic Brake	---	5.9 (4.9-6.9)	15.5 (10.5-20.3)	12.5	6.2
1	5.6 (1.1-10.5)	4.9 (2.7-9.8)	4.4 (1.9-9.6)	6.5	7.0
2	6.4 (1.8-14.6)	3.7 (1.9-5.8)	4.9 (2.2-8.9)	6.5	5.1
3	3.5 (1.6-6.1)	2.2 (1.6-3.8)	4.0 (1.6-8.3)	5.2	5.7
4	2.8 (0.6-6.9)	1.7 (1.1-2.8)	4.1 (1.1-8.2)	4.4	4.7
5	2.2 (0.5-4.6)	0.9 (0.4-1.2)	2.7 (0.9-4.6)	3.8	4.0
6	2.2 (0.2-8.4)	1.6 (1.2-2.1)	2.8 (1.2-6.7)	3.9	2.9
7	0.5 (0.0-2.5)	0.5 (0.1-1.2)	1.7 (0.3-3.2)	3.0	1.4
8	36.2 (16.7-50.0)	45.8 (41.9-50.9)	33.2 (19.8-41.2)	16.2	15.6

[a] The F59PH locomotives do not have dynamic braking.

3.5.3 Fuel Use and Emission Rate Calculations

A discussion of the equations used in emission rate calculation is given in Appendix B.

Time-based fuel use and emission rates (g/sec) are dependent on various engine parameters, including strokes per cycle, compression ratio, speed, displacement, and volumetric efficiency. Strokes per cycle, compression ratio, and displacement are known from the engine specifications. Engine speed is measured using the RPM sensor of the PEMS. Volumetric efficiency is inferred from the measured fuel flow rate during dynamometer testing or from calibration to a specified FSEO rate. In previous NCDOT Rail Division-sponsored research projects, fuel use and emissions testing were conducted on the prime mover engine of the F59PH and GP40 locomotives while the engines were undergoing the rebuild process (Frey and Graver, 2010). For these locomotives, engine volumetric efficiency is calibrated so that the FSEO observed during rail yard testing is equal to the FSEO observed during dynamometer testing.

Fuel-based emission rates (g/gal) are calculated based on the exhaust gas and fuel composition. 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. 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, as shown in Table 3-2. Molar ratios of NO, CO, and HC to CO_2 are used to estimate the amount of NO, CO, and HC, respectively, emitted per gallon of fuel consumed.

Engine output-based emission rates (g/bhp-hr) are calculated by multiplying the fuel-based emission factors and the fuel use rate (gal/bhp-hr). Gallon per brake horsepower-hour fuel use rate is derived by dividing the time-based fuel use rate by the fuel density, shown in Table 3-2, and the engine output (hp), and converting seconds into hours. Engine output was observed from the locomotive activity digital display.

The engine output-based emission rates, along with the EPA line-haul duty cycle, were used to calculate the brake specific cycle average emission rates for all pollutants and all locomotives. For the F59PH locomotives, “Low Idle” represents the Idle used in the EPA line-haul duty cycle. The emission rates, in g/bhp-hr, are used to make comparisons to the EPA emission standards.

3.5.4 Prime Mover Engine Results – Fuel Use and Emission Rates

In this section, the results are given for time-, fuel-, and engine output-based emission rates for each of the five tested locomotives.

The time-, fuel-, and engine output-based average fuel use and emission rates for the F59PH locomotives numbered NC 1810, NC 1859, and NC 1869 are shown in Tables 4-3 through 4-5, respectively. The engine volumetric efficiency was calibrated so that the calculated FSEO was the same as that observed during the dynamometer testing of the prime mover engines of NC 1810 and NC 1869.

The time-, fuel-, and engine output-based average fuel use and emission rates for the F59PHI locomotive numbered NC 1755 are shown in Table 4-6. The engine volumetric efficiency was calibrated so that the FSEO calculated for Notches 1 through 8 were 20.8 bhp-hr/gal, the generic FSEO used by EPA.

The time-, fuel-, and engine output-based average fuel use and emission rates for the GP40 locomotive numbered NC 1792 are shown in Tables 4-7 and 4-8 for over-the-rail testing before and after locomotive and prime mover engine rebuild, respectively. The engine volumetric efficiency for the rail yard test before engine rebuild was calibrated so that the calculated FSEO for each notch was the same as the FSEO observed during the initial, baseline dynamometer test of the prime mover engine after rebuild but before engine tuning. The engine volumetric efficiency for the rail yard test after engine rebuild was calibrated so that the calculated FSEO for each notch was the same as the FSEO observed during the final dynamometer test after engine tuning.

For ease in comparing all five locomotives tested, Figures 4-3 and 4-4 depict the time-based fuel use and NO_x emission rates for the prime mover engines. The graphs provide information regarding fuel use and emission rate trends with respect to engine horsepower output, and enable comparisons between families of locomotives, and between individual locomotives.

Table 4-3. Over-the-Rail Average Prime Mover Engine Fuel Use and Emission Rates for F59PH Locomotive NC 1810

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Low Idle	200	1.4623	2.95	0.21	0.10	0.01	9.21	0.05
High Idle	349	1.4623	7.18	0.40	0.33	0.05	22.3	0.10
1	349	1.3911	10.3	0.60	0.28	0.03	32.1	0.05
2	349	1.4997	15.6	0.94	0.33	0.04	48.9	0.10
3	493	1.3683	30.4	1.79	0.40	0.05	95.5	0.10
4	568	1.2717	44.0	2.56	0.38	0.08	138	0.25
5	651	1.0465	57.8	3.12	0.63	0.22	181	0.20
6	728	1.0169	72.1	3.62	0.80	0.29	226	0.45
7	823	0.8738	95.3	4.23	1.20	0.34	299	0.40
8	904	0.8566	135	4.81	0.83	1.38	422	0.40

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Low Idle	222	114	14.6	9,981	30.5
High Idle	181	140	22.4	9,953	35.1
1	188	87.3	9.38	10,006	21.4
2	192	66.3	7.85	10,021	16.0
3	188	41.3	5.31	10,041	11.5
4	186	26.8	5.55	10,049	16.5
5	173	35.0	12.1	10,034	10.7
6	161	35.8	12.9	10,032	19.5
7	142	40.0	11.2	10,032	13.6
8	114	19.7	32.7	10,011	9.80

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Low Idle	9	2.71	82.1	42.0	5.38	3,682	11.3
High Idle	9	1.11	162	126	20.1	8,933	31.5
1	191	16.6	11.4	5.28	0.57	604	1.30
2	328	18.7	10.3	3.55	0.42	537	0.85
3	672	19.6	9.58	2.10	0.27	512	0.60
4	987	20.0	9.32	1.35	0.28	504	0.85
5	1304	20.1	8.61	1.75	0.60	500	0.55
6	1601	19.7	8.15	1.83	0.66	508	1.00
7	2158	20.1	7.06	2.00	0.56	498	0.65
8	3003	19.8	5.77	1.00	1.65	506	0.50

Average fuel use and emission rates are based on 13 one-way trips between Raleigh and Charlotte, NC.

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 4-4. Over-the-Rail Average Prime Mover Engine Fuel Use and Emission Rates for F59PH Locomotive NC 1859

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Low Idle	187	1.8156	2.95	0.19	0.08	0.00	9.25	0.05
High Idle	324	1.8156	6.66	0.37	0.15	0.00	20.9	0.10
1	323	1.4776	10.3	0.58	0.15	0.01	32.2	0.05
2	323	1.6933	14.5	0.85	0.25	0.01	45.5	0.10
3	488	1.3137	30.6	1.82	0.18	0.03	96.1	0.10
4	557	1.3324	43.3	2.49	0.40	0.08	136	0.15
5	650	1.0863	58.4	3.02	0.15	0.06	184	0.20
6	721	1.0229	72.2	3.74	0.20	0.29	227	0.20
7	820	0.9372	102	4.24	0.13	0.26	319	0.25
8	894	0.9245	136	4.96	0.45	0.92	425	0.35

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Low Idle	206	80.5	0.00	10,025	42.8
High Idle	178	77.5	1.83	10,024	39.7
1	182	49.8	1.94	10,041	20.4
2	188	55.0	2.37	10,037	16.6
3	191	18.2	3.54	10,057	11.6
4	184	29.8	5.78	10,047	12.7
5	165	8.90	3.16	10,064	9.80
6	165	8.30	12.9	10,049	9.35
7	134	3.70	8.06	10,059	8.00
8	117	10.8	21.6	10,034	8.15

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Low Idle	9	2.71	76.1	29.8	0.00	3,698	15.8
High Idle	9	1.20	148	64.5	1.53	8,344	33.1
1	191	16.6	11.0	3.00	0.12	606	1.25
2	305	18.7	10.1	2.95	0.13	537	0.90
3	675	19.6	9.74	0.93	0.18	513	0.60
4	971	20.0	9.21	1.50	0.29	503	0.65
5	1318	20.1	8.24	0.45	0.16	501	0.50
6	1603	19.7	8.38	0.43	0.65	509	0.45
7	2300	20.1	6.64	0.18	0.40	500	0.40
8	3018	19.8	5.92	0.55	1.09	507	0.40

Average fuel use and emission rates are based on 4 one-way trips between Raleigh and Charlotte, NC.

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 4-5. Over-the-Rail Average Prime Mover Engine Fuel Use and Emission Rates for F59PH Locomotive NC 1869

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Low Idle	239	1.4861	3.60	0.21	0.08	0.03	11.2	0.00
High Idle	370	1.4861	9.12	0.42	0.35	0.77	27.3	0.00
1	370	1.1688	10.3	0.55	0.23	0.49	31.4	0.05
2	370	1.3822	16.9	1.04	0.35	0.28	52.7	0.05
3	493	1.1524	29.9	1.95	0.40	1.14	92.2	0.05
4	565	1.1566	42.7	2.83	0.35	0.43	134	0.10
5	653	1.0751	56.8	3.65	0.28	0.25	178	0.20
6	731	0.9570	70.6	3.89	0.20	0.91	221	0.25
7	821	0.8764	93.7	4.59	0.20	0.89	293	0.35
8	904	0.8920	133	5.10	0.10	1.55	416	0.35

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Low Idle	191	76.5	23.0	9,991	13.2
High Idle	148	122	271	9,573	7.20
1	172	70.3	154	9,789	9.65
2	198	68.0	52.1	9,951	7.80
3	208	42.0	122	9,857	6.75
4	212	26.0	32.3	10,008	9.00
5	205	16.5	14.1	10,043	10.5
6	176	9.35	41.4	10,003	11.1
7	157	6.65	30.3	10,023	11.5
8	123	2.33	37.4	10,014	8.50

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Low Idle	11	2.72	70.2	28.3	8.46	3,677	4.85
High Idle	11	1.10	139	114	253	8,928	6.70
1	190	16.5	10.4	4.28	9.34	594	0.60
2	365	19.1	10.3	3.55	2.72	520	0.40
3	674	20.0	10.4	2.10	6.09	493	0.35
4	970	20.2	10.5	1.28	1.60	496	0.45
5	1303	20.4	10.1	0.75	0.69	492	0.50
6	1606	20.2	8.71	0.45	2.05	494	0.55
7	2159	20.5	7.67	0.33	1.48	489	0.55
8	3014	20.2	6.10	0.13	1.85	497	0.40

Average fuel use and emission rates are based on 2 one-way trips between Raleigh and Charlotte, NC.

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 4-6. Over-the-Rail Average Prime Mover Engine Fuel Use and Emission Rates for F59PHI Locomotive NC 1755

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Idle	200	1.3345	3.61	0.21	0.08	0.02	11.3	0.00
DB[a]	200	1.3345	5.68	0.27	0.08	0.04	17.8	0.00
1	307	0.8810	8.08	0.39	0.15	0.05	25.3	0.05
2	343	1.1494	15.0	0.74	0.18	0.13	46.8	0.05
3	490	1.1719	28.7	1.60	0.95	0.07	89.6	0.10
4	568	1.6413	42.6	2.33	0.28	0.14	134	0.25
5	651	1.6255	56.5	2.73	0.25	0.21	178	0.35
6	729	1.3003	68.2	3.96	1.43	0.15	214	0.35
7	819	1.3220	98.3	4.78	0.48	0.93	308	0.50
8	904	0.9245	129	6.72	0.98	0.80	405	0.40

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Idle	190	62.3	22.0	10,001	15.9
DB[a]	154	49.3	25.1	10,005	11.9
1	157	54.8	20.3	10,009	15.0
2	157	35.8	27.7	10,009	15.2
3	179	107	7.64	9,997	13.8
4	175	20.6	10.7	10,045	20.1
5	154	13.9	12.0	10,047	20.8
6	185	66.3	6.98	10,023	15.7
7	156	15.8	30.2	10,017	16.5
8	166	23.9	19.7	10,029	9.55

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Idle	11	2.71	70.1	23.0	8.12	3,691	5.85
DB[a]	11	1.72	89.4	28.5	14.6	5,815	6.90
1	189	20.8	7.52	2.63	0.98	481	0.70
2	350	20.8	7.56	1.73	1.33	481	0.75
3	671	20.8	8.58	5.13	0.37	481	0.65
4	998	20.8	8.40	1.00	0.51	483	0.95
5	1323	20.8	7.41	0.68	0.58	483	1.00
6	1597	20.8	8.93	3.18	0.34	482	0.75
7	2300	20.8	7.48	0.75	1.45	482	0.80
8	3026	20.8	7.99	1.15	0.95	482	0.45

[a] DB: Dynamic brake

RPM sensor malfunctioned in middle of test. MAP used as a surrogate for notch position determination.

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 4-7. Over-the-Rail Average Prime Mover Engine Fuel Use and Emission Rates for GP40 Locomotive NC 1792, Before Rebuild

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Idle	297	2.4029	5.97	0.35	0.30	0.04	18.5	0.05
DB[a]	513	2.4029	19.9	0.86	0.68	0.09	62.0	0.10
1	318	2.9726	11.9	0.69	0.48	0.06	37.1	0.05
2	381	1.8631	17.5	0.78	0.30	0.05	54.9	0.15
3	500	1.8099	32.4	1.40	0.40	0.06	102	0.20
4	566	1.5822	47.3	2.14	0.40	0.07	148	0.25
5	658	1.1959	59.9	2.71	0.33	0.07	188	0.25
6	725	0.9809	74.1	3.33	0.30	0.08	233	0.30
7	827	1.0247	113	4.95	0.35	0.11	357	0.30
8	899	0.9386	137	6.00	0.35	0.16	432	0.30

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Idle	190	166	23.9	9,935	27.1
DB[a]	139	108	15.1	9,984	15.3
1	186	125	15.5	9,973	19.9
2	142	55.0	9.04	10,026	24.7
3	138	39.3	6.32	10,040	19.2
4	145	26.5	4.97	10,050	16.5
5	144	17.7	3.56	10,058	14.0
6	144	13.1	3.25	10,061	12.2
7	140	10.1	3.02	10,063	9.10
8	140	7.88	3.75	10,064	7.05

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Idle	20	2.98	63.4	55.8	8.02	3,334	9.10
DB[a]	20	0.89	155	121	16.9	11,165	17.1
1	190	14.2	13.2	8.78	1.09	702	1.40
2	345	17.5	8.10	3.15	0.52	573	1.40
3	675	18.5	7.47	2.13	0.34	543	1.05
4	1000	18.8	7.70	1.43	0.26	535	0.85
5	1300	19.3	7.50	0.93	0.18	521	0.70
6	1600	19.2	7.50	0.68	0.17	524	0.65
7	2400	18.8	7.42	0.53	0.16	535	0.50
8	3000	19.4	7.21	0.40	0.19	519	0.35

[a] DB: Dynamic brake

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 4-8. Over-the-Rail Average Prime Mover Engine Fuel Use and Emission Rates for GP40 Locomotive NC 1792, After Rebuild

(a) Time-based fuel use and emission rates

Notch	RPM	η_{ev}	Fuel Use (g/sec)	NO as NO_2 (g/sec)	HC (g/sec)	CO (g/sec)	CO_2 (g/sec)	Opacity (g/sec)
Idle	297	2.1200	5.61	0.34	0.33	0.05	17.4	---
DB[a]	536	2.1200	19.8	1.03	1.13	0.11	61.4	---
1	323	2.3816	11.0	0.69	0.35	0.06	34.2	---
2	381	1.6800	16.6	0.92	0.23	0.05	52.0	---
3	500	1.4138	31.4	1.86	0.35	0.07	98.6	---
4	566	1.2781	46.3	2.58	0.15	0.05	146	---
5	657	1.0911	59.9	3.13	0.20	0.17	188	---
6	725	0.9915	73.3	3.82	0.35	0.24	230	---
7	826	0.8930	108	5.36	0.20	0.33	340	---
8	899	0.9742	137	8.07	0.60	0.19	430	---

(b) Fuel-based emission rates

Notch	NO as NO_2 (g/gal)	HC (g/gal)	CO (g/gal)	CO_2 (g/gal)	Opacity (g/gal)
Idle	192	186	29.1	9,914	---
DB[a]	166	184	18.4	9,932	---
1	202	105	18.7	9,980	---
2	178	43.3	10.6	10,031	---
3	190	36.3	7.10	10,041	---
4	178	21.1	3.43	10,062	---
5	167	10.2	8.85	10,054	---
6	166	15.4	10.7	10,048	---
7	158	5.75	9.63	10,056	---
8	188	14.0	4.55	10,059	---

(c) Engine output-based fuel use and emission rates

Notch	HP Output	Fuel Use (bhp-hr/gal)	NO as NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	Opacity (g/bhp-hr)
Idle	20	3.17	60.4	58.8	9.19	3,128	---
DB[a]	20	0.90	185	205	20.5	11,059	---
1	190	15.4	13.2	6.83	1.21	648	---
2	345	18.5	9.59	2.35	0.57	542	---
3	675	19.1	9.92	1.90	0.37	526	---
4	1000	19.2	9.28	0.55	0.18	524	---
5	1300	19.3	8.66	0.53	0.46	521	---
6	1600	19.4	8.60	0.80	0.55	518	---
7	2400	19.7	8.04	0.30	0.49	510	---
8	3000	19.5	9.69	0.73	0.23	516	---

[a] DB: Dynamic brake
PM values invalid due to low flow through PM meter. RPM sensor malfunctioned in middle of test. MAP used as a surrogate for notch position determination.
NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

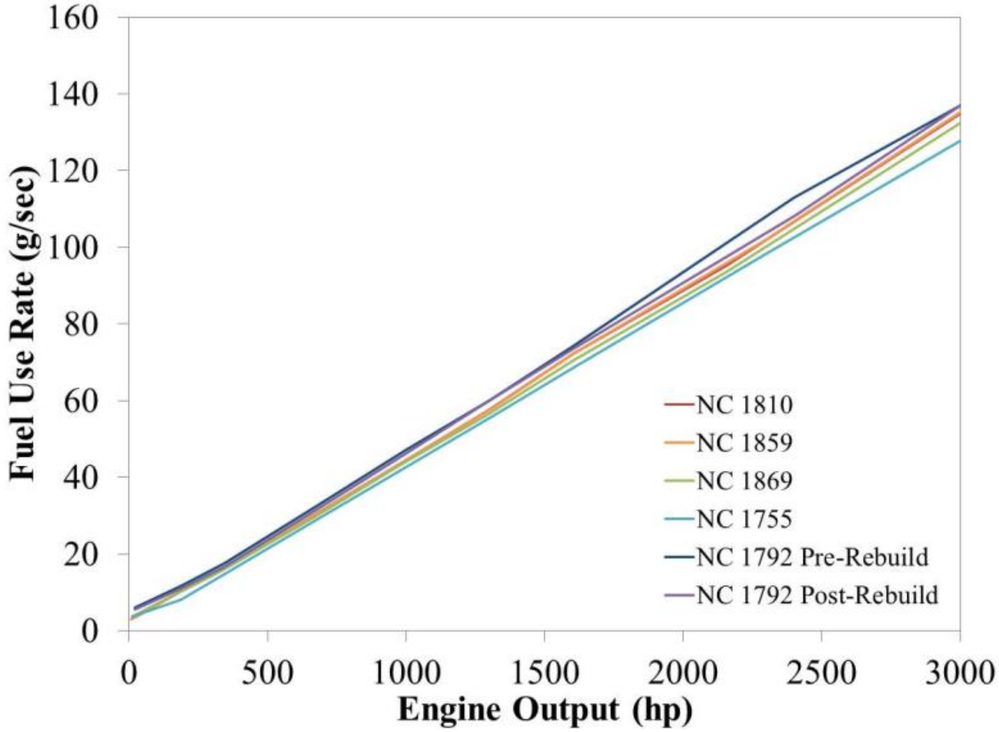


Figure 4-3. Time-Based Over-the-Rail Fuel Use Rates for the NCDOT Prime Mover Engines

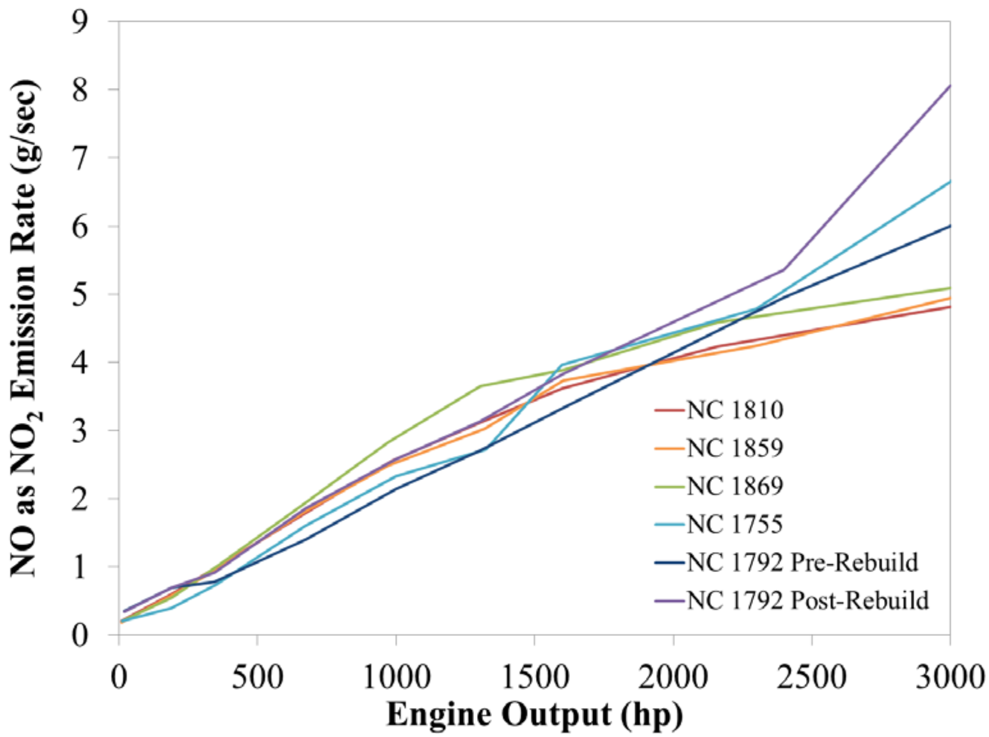


Figure 4-4. Time-Based Over-the-Rail NO_x Emission Rates for the NCDOT Prime Mover Engines

For F59PH locomotive NC 1810, the time-based fuel use and emission rates increase montonically with engine RPM, as shown in Table 4-3. Compared to idle, the fuel use rate at Notch 8 is approximately 46 times larger. Emission rates at Notch 8 versus idle are larger by a factor of 23 for NO_x, 8 for HC, 138 for CO, and 8 for PM. For rail yard tests, the fuel use rate at Notch 8 is approximately 41 times larger than the idle fuel use rate. Rail yard emission rates at Notch 8 versus idle are larger by a factor of 18 for NO_x, 8 for HC, 197 for CO, and 9 for PM. The time-based fuel use was 12 percent higher in over-the-rail testing compared to rail yard testing at Notch 8. For low idle and Notches 1 through 7, the difference between over-the-rail and rail yard fuel use was within 2.4 percent of each other.

Figure 4-3 shows a linear trend in fuel use rate as engine output increases. It also shows that the variability in fuel use among the F59PH locomotives increases as engine output increases. Comparable fuel use results were observed for the NC 1859 and NC 1869 locomotives. However, the time-based fuel use rate for NC 1869 at Notch 8 is 2.2 percent lower than the NC 1810 and NC 1859 locomotives because the FSEO at Notch 8 for the NC 1869 is 2 percent higher than NC 1810 and NC 1859.

The trends in fuel use are shown in Figures 4-5 and 4-6. The fuel use trends are similar between dynamometer and rail yard tests, because fuel use rates were calibrated either to dynamometer data for the same engine or to the generic FSEO number typically used by EPA if a dynamometer test was not available for a particular engine. In Figure 4-6, engine output-based fuel use rates increase up to approximately 400 hp, then approximately level off. The F59PH fuel use rates reach a maximum of between 19.5 and 20.0 bhp-hr/gal, while the GP40 fuel use rates reach a maximum of 18 and 18.5 bhp-hr/gal for both dynamometer and rail yard tests.

Using NC 1810 as an example, based on results in Table 4-3, the fuel-based NO_x emission rate tends to decrease with engine load. The rate at Notch 8 is approximately 51 percent that at idle. At low to moderate engine loads, the NO_x emission rate is approximately 190 g/gal. While there is significant variability in the fuel-based NO_x emission rate, the relative variability is much less than that for time-based emission rates. This implies that, to a first order approximation, total NO_x emission might be estimable based on a duty cycle average emission factor and observed fuel consumption. However, the HC fuel-based emission factor varies by a factor of 6 from highest to lowest values, which is similar to the relative range of variability for time-based emission factors. The fuel-based CO emission factor varies by a factor of 6, which is substantially lower than the relative range of variation for the time-based emission factors. The relative range of variability in the PM fuel-based emission factors is approximately half that compared to the time-based emission factors. Overall, there is typically less variation in emissions per unit fuel use over a wide range of engine load compared to mass per time emissions. This implies that fuel-based emissions inventories might be more robust to variations in engine load than time-based inventories.

There is little variability in the time-based NO_x emission rates at low engine output, as shown in Figure 4-7, for the locomotives tested on the dynamometer and over-the-rail. The variability increases as engine output increases from approximately 250 hp. However, absolute variability decreases for the engine output-based NO_x emission rates as engine output increases from

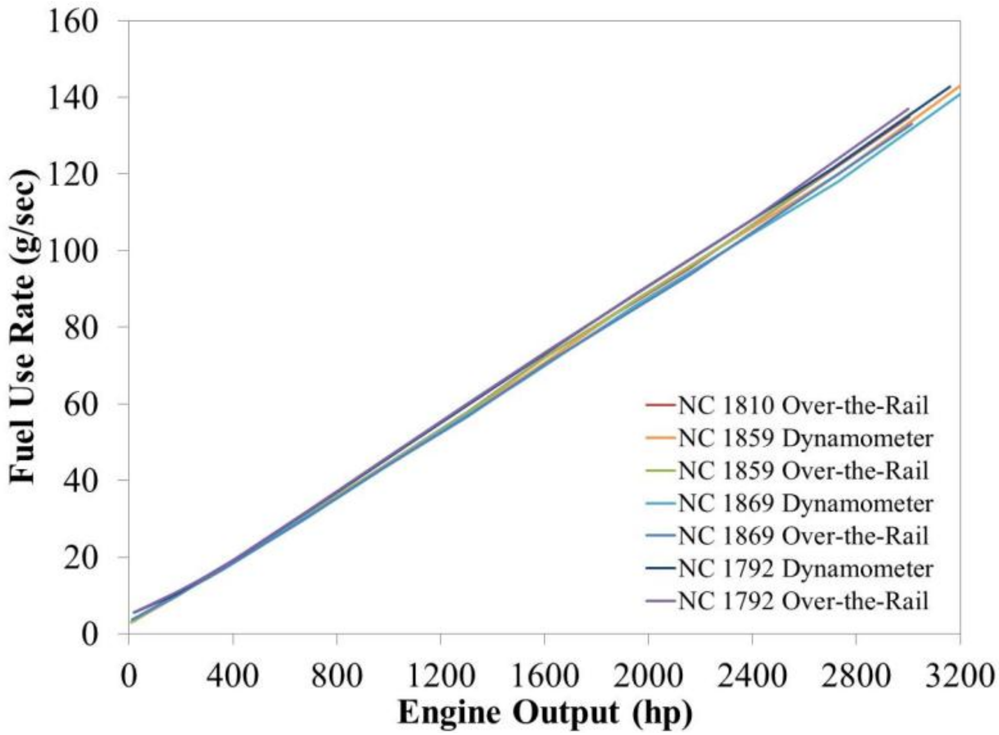


Figure 4-5. Time-Based Fuel Use Rates for the F59PH and GP40 Prime Mover Engines During Dynamometer and Over-the-Rail Testing

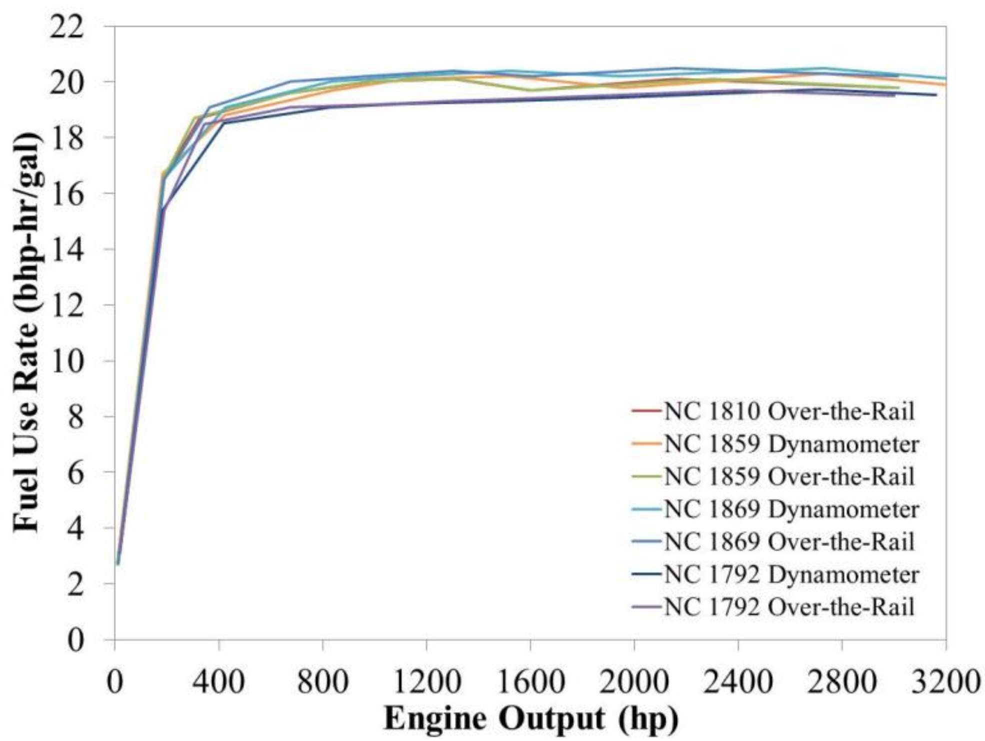


Figure 4-6. Engine Output-Based Fuel Use Rates for the F59PH and GP40 Prime Mover Engines During Dynamometer and Over-the-Rail Testing

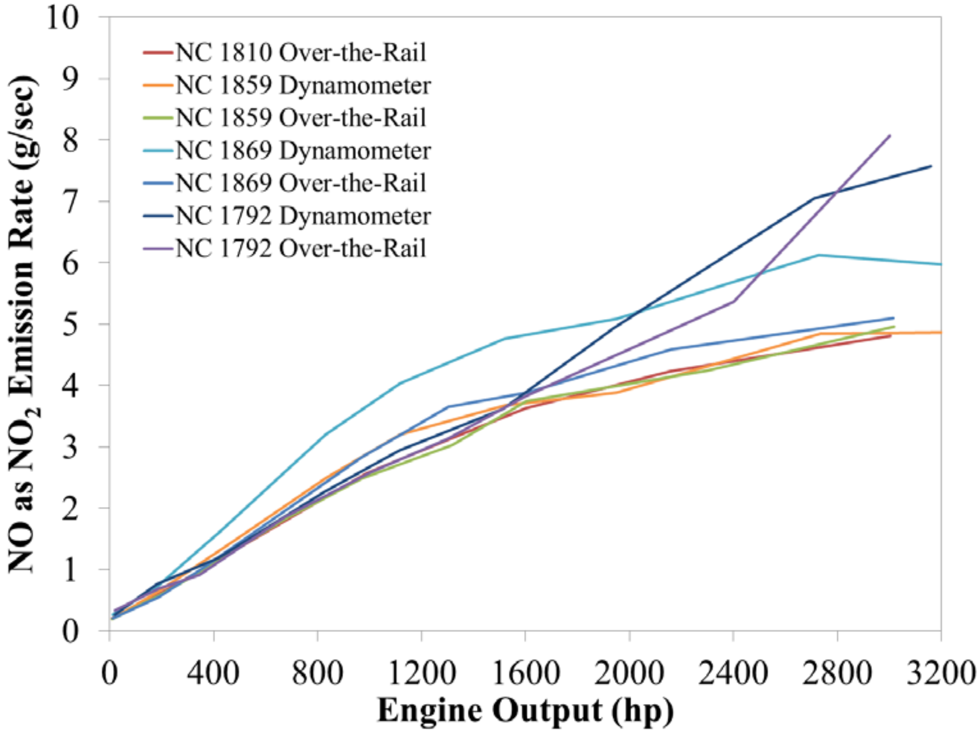


Figure 4-7. Time-Based NO_x Emission Rates for the F59PH and GP40 Prime Mover Engines During Dynamometer and Over-the-Rail Testing

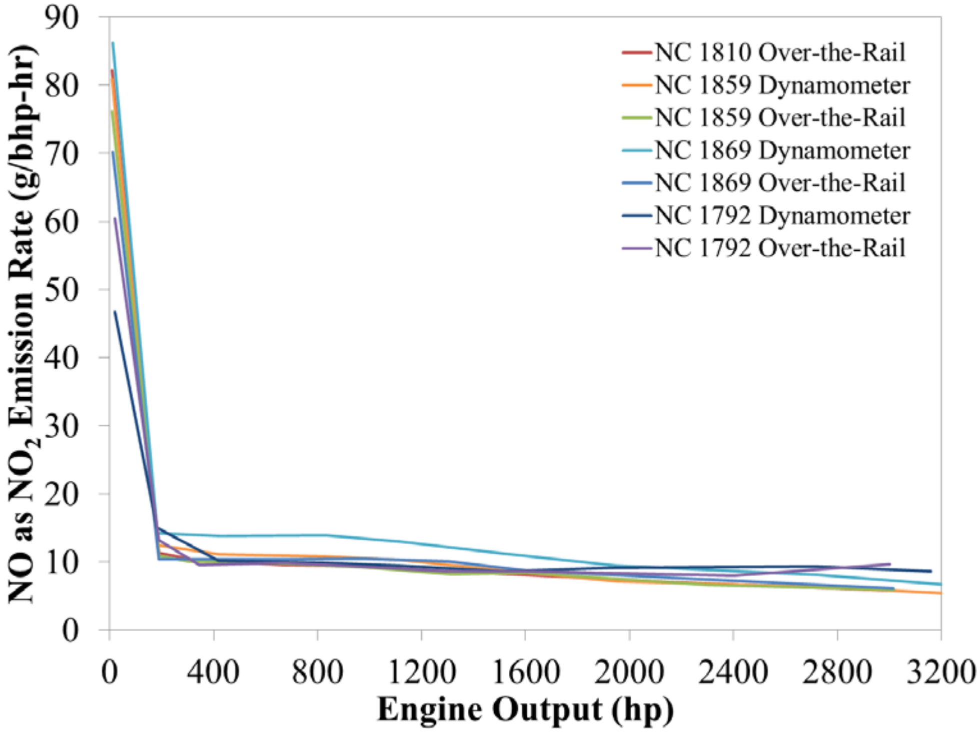


Figure 4-8. Engine Output-Based NOx Emission Rates for the F59PH and GP40 Prime Mover Engines During Dynamometer and Over-the-Rail Testing

approximately 250 hp, as indicated in Figure 4-8. The engine output-based NO_x emission rate is sensitive to engine output at low horsepower values. Similar results and trends were observed when comparing dynamometer and rail yard tests.

Emission rates observed for NC 1859 and NC 1869 were comparable to the rates for NC 1810. The fuel-based NO_x and CO emission rates at Notch 8 for NC 1869 were, on average, 7 and 44 percent higher than the other two F59PHs. The PM fuel-based emission factor varies by a factor of 2 from highest to lowest values for NC 1869, and by factors of 3 and 5 for NC 1810 and NC 1859. NO_x emission rates for the F59PH locomotives are similar at low and high engine output, with variability observed in intermediate engine outputs, especially between 1,000 and 1,500 hp, as shown in Figure 4-4.

The CO_2 emission rate is approximately constant at about 10,000 g/gal for all three F59PHs. This is because the vast majority of carbon in the fuel is emitted as CO_2. Only a small fraction of carbon is emitted as CO, HC, or PM.

The engine output-based fuel use rate has much less relative variability than the time-based fuel use rate. At idle, only 2 to 4 bhp-hr are produced per gallon of fuel consumed. In contrast, at Notch 8, approximately 20 bhp-hr are produced per gallon of fuel consumed. The engine output per unit of fuel consumed is approximately similar over a wide range of engine loads.

Engine-output based emission rates tend to have less relative variability than either time- or fuel-based rates. For example, although the NO_x emission rate at idle appears to be very high, at approximately 70 to 160 g/bhp-hr, when comparing Notches 1 to 8, the emission rates range from 5.8 to 11.4 g/bhp-hr, a relative variation of only a factor of two, whereas engine load for this range varies by a factor of 15. Thus, other than for idle, the engine output-based emission rates have only modest variability. When comparing HC, CO, and PM emission rates among Notches 1 to 8, the relative range of variation is a factor of 4 for HC, factor of 29 for CO, and factor of 8 for PM. Since NO_x and PM are the two pollutants from diesel engines of greatest concern, and since emission rates of CO and HC tend to be very low, engine output-based emission factors are of potential utility, since they are less variable over a wide range of load for NO_x and PM than either time- or fuel-based emission rates. Although the g/bhp-hr emission rates at idle appear to be very high for all pollutants, the engine output at idle is approximately 0.3 percent of that at full load; thus, the mass emission rate at idle are much lower than at Notch 8.

Since the FSEO for NC 1755, the F59PHI, was calibrated to 20.8 bhp-hr/gal for Notches 1 through 8 in both the rail yard and over-the-rail tests, the fuel use rates are exactly the same. However, the emission rates are different. The time-based NO_x and CO emission rates were 22 and 68 percent lower for Notch 8 in over-the-rail testing than in the rail yard, respectively. Conversely, PM and HC emission rates were 1.1 and 3.5 times higher over-the-rail. Thus, the NO_x and PM emission rates were relatively similar, whereas the largest relative differences were for pollutants that have low emission rates.

In rail yard tests, the engine rebuild for the GP40 reduced fuel use rate, especially between 2,000 and 3,000 hp, as shown in Figure 3-15, and also observed based on over-the-rail tests, as shown in Figure 4-4. The time-based fuel use rate was, on average, 2.8 percent lower after engine rebuild than before. The dynamometer and over-the-rail fuel use rates were similar to each other for both the pre- and post-rebuild cases, as shown in Figures 4-7 and 4-8. The results and trends were similar to those observed when comparing dynamometer and rail yard fuel use rates.

While the GP40 emission rates were lower after engine rebuild than before based on rail yard tests, the same is not true in over-the-rail tests. Time-based post-rebuild NO_x emission rates in over-the-rail tests were, on average, 16 percent higher than pre-rebuild rates. The exhaust NO_x concentration for the over-the-rail tests averaged 26 percent higher post-rebuild compared to pre-rebuild measurements. Furthermore, the post-rebuild over-the-rail measurements for NO_x concentration averaged 44 percent higher than the pre-rebuild rail yard test. There was no significant difference in engine output, MAP, or engine RPM between the two sets of over-the-rail tests. Although the intake air temperatures were 4 to 6 °C higher in the pre-rebuild over-the-rail tests compared to the post-rebuild over-the-rail tests, this difference would affect emission rates by only 1-2 percent and cannot explain the large observed difference. Thus, there was no significant difference in exhaust flow rate. The implication is that the only significant difference was the exhaust concentration. Possibly, some factor associated with engine operation that was working well during the rail yard test may have failed by the time the over-the-rail test was conducted; however, because the GP40 was subsequently totaled in a rail grade crossing, it is no longer possible to investigate possible causal reasons for the increase.

3.5.5 Prime Mover Engine Results – Cycle Average Emission Rates

The calculated brake specific cycle average emission rates for NO_x, HC, CO, and opacity-based PM based on the EPA line-haul duty cycle for all tested locomotives are shown in Table 4-9(a). The calculated brake specific cycle average emission rates for NO_x, HC, CO, and opacity-based PM based on the observed duty cycles for all tested locomotives are shown in Table 4-9(b). The results shown are intended for relative comparisons. The PEMS-based measurements do not constitute an FRM, and thus cannot be used for certification. The reported emission rates for NO_x, HC, and opacity-based PM include adjustment factors discussed previously and documented in the footnotes to the table.

For the F59PH locomotives, the EPA line haul duty cycle-based cycle average CO emission rates based on over-the-rail emission factors were lower for NC 1810 and NC 1859, but higher for NC 1869, compared to cycle average CO emission rates based on rail yard emission factors. With regard to NO_x, the EPA line haul duty cycle-based average emission rate based on over-the-rail emission factors for NC 1869 was 10 percent lower than the cycle average emission rate based on rail yard emission factors. There was no difference in NO_x cycle average emission rates between rail yard and over-the-rail tests. The NC 1810 NO_x cycle average emission rate based on over-the-rail emission factors was 22 percent higher than the cycle average emission rate based on rail yard emission factors. Both HC and PM cycle average emission rates based on over-the-rail emission factors were higher than the cycle average emission rates based on rail yard emission factors.

Similar to NC 1810 and NC 1859, the F59PHI and GP40 had significantly lower CO cycle average emission rates based on emission factors measured over-the-rail compared to in the rail yard. The cycle average NO_x emission rates based on over-the-rail emission factors were also significantly lower for the NC 1755 and NC 1792 before engine rebuild compared to the cycle average emission rates based on rail yard emission factors. For the after rebuild NC 1792, a NO_x cycle average emission rate 25 percent higher than in the rail yard was observed. Both the HC and PM over-the-rail cycle average emission rates were 34 to 335 percent higher than the cycle average emission rates based on rail yard emission factors, depending on the locomotive and pollutant.

The cycle average NO_x, HC, and PM emission rates based on the observed duty cycle are lower for the F59PHI and GP40 compared to the cycle average emission rates derived from the EPA line-haul duty cycle.

3.6 Summary

In this chapter, the following items were discussed:

- A portable emissions measurement system (PEMS) was used to measure the exhaust gas concentrations, engine speed, intake air temperature, and manifold absolute pressure used to calculate locomotive emission factors while the locomotive was operating revenue service.
- Locomotive activity data were used to calculate the duty cycle observed while operating the Piedmont service. Overall, the observed duty cycle differed from the EPA line-haul duty cycle used for regulatory purposes, especially at idle and Notch 8. Differences in time spent in these two throttle positions will have a large effect on cycle average emission factors. Idle and Notch 8 constituted 69 to 81 percent of the entire duty cycle, based on the locomotive family.
- Trends in fuel use and NO_x emissions were similar for the F59PH and GP40 locomotives between dynamometer, rail yard, and over-the-rail testing.
- EPA line-haul duty cycle average NO_x emission rates based on over-the-rail engine-output based emission factors were 40 percent lower to 25 percent higher than cycle average NO_x emission rates based on rail yard engine-output based emission factors depending on the locomotive. Over-the- rail cycle average CO emission rates were also mixed – 63 percent lower to 110 percent higher depending on the locomotive – compared to in the yard. HC and PM cycle average emission rates based on over-the-rail emission factors were significantly higher than the cycle average emission rates based on rail yard emission factors.
- In general, cycle average emission factors based on the observed over-the-rail duty cycles and engine-output based emission factors were lower than the EPA line-haul duty cycle and engine output factor-based emission rates, with the exception of a few cases in CO emissions. While the more time is spent in Notch 8 in the observed duty cycles, engine-output based NO_x, HC, CO, and PM emission rates tend to decrease as engine load increases.

Table 4-9. Over-the-Rail Cycle Average Prime Mover Engine Emission Rates for the NCDOT Locomotive Fleet

(a) EPA line-haul duty cycle-based

Locomotive	NO_x (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	Opacity-based PM (g/bhp-hr)
NC 1810 (F59PH)	7.3	1.64	1.2	0.66
NC 1859 (F59PH)	7.3	0.83	0.8	0.55
NC 1869 (F59PH)	7.8	0.72	2.1	0.48
NC 1755 (F59PHI)	8.5	1.61	0.9	0.63
NC 1792 (GP40) *Before Rebuild*	8.4	1.72	0.3	0.66
NC 1792 (GP40) *After Rebuild*	10.5	2.05	0.5	---

(b) Observed duty cycle-based

Locomotive	NO_x (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	Opacity-based PM (g/bhp-hr)
NC 1810 (F59PH)	6.5	1.37	1.5	0.58
NC 1859 (F59PH)	6.6	0.70	0.9	0.49
NC 1869 (F59PH)	6.9	0.44	2.0	0.46
NC 1755 (F59PHI)	8.2	1.31	1.0	0.50
NC 1792 (GP40) *Before Rebuild*	7.8	1.06	0.3	0.50
NC 1792 (GP40) *After Rebuild*	10.2	1.43	0.3	---

MEASUREMENT RESULTS ARE INTENDED FOR COMPARISONS BETWEEN TESTS, AND CANNOT BE USED FOR CERTIFICATION PURPOSES.

NO_x includes NO and NO_2. Only NO was measured. Typically, NO_x is comprised of 95 vol-% NO. Total NO_x is estimated to be approximately 5 percent higher than the values shown. NO_x is always reported as equivalent mass of NO_2. Cycle average emission rates include a multiplicative correction factor of 1.053 to approximate for total NO_x.

HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds, but responds only partially to others. Actual HC emissions may be a factor of 2 to 2.5 greater than the values shown. Cycle average emission rates include a multiplicative correction factor of 2.5 to approximate for total HC.

Opacity is measured using a light scattering technique, which provides useful relative comparisons of particle levels in exhaust. The actual PM emission rate may be a factor of 5 to 20 greater than the value shown. Cycle average emission rates include a multiplicative correction factor of 5 to approximate total PM.

4.0 AVOIDED EMISSIONS

The purpose of this task is to estimate the avoided emissions attributable to the reduction in personal automobile trips for riders of the NCDOT Piedmont train service between Raleigh and Charlotte, and to compare the avoided emissions to train emissions apportioned to each passenger.

According to the U.S. Department of Energy (DOE), the energy intensity of intercity rail is 2,398 British thermal units (BTU) per passenger-mile, approximately 30 and 34 percent lower than passenger cars and trucks, respectively (ORNL, 2010). The energy intensity values are based on load factors of 1.59 passengers per car, 1.84 passengers per truck, and 22.7 passengers per train. Trucks include pickup trucks, minivans, and sport utility vehicles. Intuitively, less energy use leads to fewer emissions. This chapter is intended to confirm or reject this hypothesis.

The objective of this chapter is to: (1) calculate the mass per passenger-mile emission factors for rail travel between select rail stations; (2) calculate the mass per passenger-mile emission factors for passenger vehicle travel between select cities; and (3) compare total emissions for travel between select cities for both rail and passenger vehicle travel.

4.1 Calculation of Per Passenger-Mile Emission Factors

To enable direct comparison of various modes of transportation, energy use and emissions rates are calculated on a per passenger-mile basis. The number of passengers in each vehicle and the travel distance varies. For example, the travel distance between Raleigh and Charlotte by rail may be longer than the travel distance between the two cities by light-duty gasoline vehicle (LDGV). LDGVs consist of passenger cars and passenger trucks. Passenger trucks include pickups, minivans, and sport utility vehicles. Trains accommodate many more passengers than LDGVs.

4.1.1 Locomotives

The Piedmont service was divided into eight segments, in which each segment is between consecutive rail stations, as shown in Table 5-1. A map of the Piedmont rail service was previously shown in Figure 4-1. The prime mover engine activity data collected for all over-the-rail measurements were stratified to create individual duty cycles for travel over each segment. Activity data and duty cycles are locomotive-specific (e.g., the GP40 activity data is used to create individual duty cycles for travel by the GP40 over each segment). The derivation of total prime mover emissions released over a segment is shown in Equation 3. Total prime mover emissions released between origin and destination (O/D) stations are the summation of the total emissions released over all of the segments between them, as shown in Equation 4.

The scheduled travel time between Raleigh and Charlotte is approximately 3 hours and 15 minutes. The scheduled travel time is used as a base case for estimating emission rates associated with train travel. Many of the observed trips were within 15 minutes of schedule.

Actual travel time was observed to exceed scheduled travel time in many of the over-the-rail measurements. For example, during measurements of NC 1859 in April 2011, Norfolk Southern was conducting track maintenance on the Piedmont corridor between Greensboro and Charlotte. During the track maintenance period, AMTRAK and NCDOT adjusted the Piedmont schedule, resulting in a scheduled travel time of approximately 3 hours and 23 minutes.

Any large train delays are noted with each individual duty cycle in Appendix D.

$$E_{xij} = \sum_{n=idle}^{8} (t_{nij})(ER_{xn}) \quad (3)$$

Where,

E_{xij} = mass of pollutant x between station i and station j (g)
ER_{xn} = emission rate of pollutant x at notch position n (g/sec)
n = notch position
t_{nij} = time in notch position n between station i and station j (sec)

$$E_{xOD} = \frac{\sum_{O}^{D} E_{xij}}{d_{OD}} \quad (4)$$

Where,

d_{OD} = distance between origin station O and destination station D (mi)
E_{xij} = mass of pollutant x between station i and station j (g)
E_{xOD} = mass of pollutant x between origin station O and destination station D, summed over all constituent station-to-station pairs i and j, per mile (g/ mi)

Table 5-1. Rail Segments of the Piedmont Route

Rail Segment	Station Pair[a]	Distance (mi)	Travel Time Between Stations (sec)			Average Ridership (pax)[c]
			Scheduled	Observed[b]	% Difference	
A	RGH ↔ CYN	8.3	900	1,453	61	32.2
B	CYN ↔ DNC	18.0	1,200	1,714	43	45.0
C	DNC ↔ BNC	33.2	2,220	3,311	49	64.3
D	BNC ↔ GRO	21.3	1,620	1,866	15	67.3
E	GRO ↔ HPT	15.4	1,080	1,483	37	63.9
F	HPT ↔ SAL	34.4	2,010	2,561	27	63.0
G	SAL ↔ KAN	15.7	960	1,217	27	58.2
H	KAN ↔ CLT	26.6	1,680	2,840	69	56.3
All	RGH ↔ CLT	172.9	11,670	16,445	41	---

[a] Segments are not directional-specific. For example, Segment A consists of travel from RGH to CYN and from CYN to RGH.
[b] Average travel time between station pairs for the 28 one-way trips traveled during testing. Travel time is not directional-specific. For example, travel time is 1,453 seconds from RGH to CYN and 1,453 seconds from CYN to RGH.
[c] Average ridership is not directional-specific. For example, there are an average of 32.2 passengers on the train from RGH to CYN and an average of 32.2 passengers on the train from CYN to RGH. Average ridership based on Fiscal Year 2006-2011 ridership.

Total HEP emissions released between O/D stations are derived by multiplying the mass per gallon emission factor measured during rail yard testing, an estimate of fuel flow rate and travel time. Since fuel flow rate was not available for the CAT C18 ACERT engines used by the F59PH locomotives, a fuel flow rate of 3.9 g/sec is assumed based on a FSEO of 20.8 bhp-hr/gal. Also, since PM concentrations were not measured from the CAT C18 ACERT due to low flow through the PM sensor, the EPA nonroad compression-ignition engine Tier 2 emission standard of 0.20 g/kW-hr was used to estimate the PM emission rate of 11.6 g/hr, which is then multiplied by time to calculate total PM emissions from the HEP.

Mass per passenger prime mover and HEP emission factors over a segment are derived using Equation 5. Piedmont ridership data for fiscal years 2006 to 2010 were obtained from AMTRAK. Mass per passenger emission factors over a route are based on the summation of the mass per passenger emission factors for all of the segments between any selected O/D pair.

$$EP_{xij} = \frac{E_{xij}}{p_{ij}} \tag{5}$$

Where,

E_{xij}	=	mass of pollutant *x* between station *i* and station *j* (g)
EP_{xij}	=	mass of pollutant *x* between station *i* and station *j* per passenger (g/pax)
p_{ij}	=	ridership between station *i* and station *j* (pax)

Mass per passenger-mile prime mover and HEP emission factors over a segment are calculated using Equation 6. Mass per passenger-mile emission factors over an O/D pair is based on the sum of the mass per passenger emission factors over all of the segments between the station pair, divided by the distance between O/D pair.

$$ED_{xOD} = \frac{\sum_{O}^{D} EP_{xij}}{d_{OD}} \tag{6}$$

Where,

d_{OD}	=	distance between origin station *O* and destination station *D* (mi)
ED_{xOD}	=	mass of pollutant *x* between origin station *O* and destination station *D*, summed over all constituent station-to-station pairs *i* and *j*, per passenger-mile (g/pax-mi)
EP_{xij}	=	mass of pollutant *x* between station *i* and station *j* per passenger (g/pax)

4.1.2 Light-Duty Gasoline Vehicles

To estimate fleet highway vehicle average mass per passenger-mile emission factors, the EPA's Motor Vehicle Emissions Simulator (MOVES) software was utilized. MOVES provides an accurate estimate of mobile source emissions for user-defined conditions. The user specifies vehicle types, geographical areas, pollutants, vehicle operating characteristics, and road types. The model performs a series of calculations to provide estimates of emission rates (EPA, 2010). MOVES is the official regulatory model for mobile source emission estimates. The latest version of the software, MOVES2010a, estimates emission for highway vehicles. Future versions of MOVES are planned, that will be able to estimate pollutants from non-highway mobile sources such as aircraft, locomotives, and commercial marine vehicles (EPA, 2010).

All input files related to the distributions of vehicle type and age, fuel type, emissions inspection compliance, and weather conditions were obtained from the Division of Air Quality (DAQ) at the North Carolina Department of Environment and Natural Resources (NC DENR). Data from Wake County, NC were assumed to be representative of the state average for vehicle type, vehicle age, and fuel type. Data from Wake County, NC were used in all MOVES model runs. Appendix E contains the Wake County, NC model input data. Passenger cars and passenger trucks fueled with gasoline were analyzed by MOVES.

To obtain speed and road grade profiles between a pair of stations, a passenger vehicle was instrumented with an electronic control unit (ECU) data recorder and a handheld GPS unit with barometric altimeter. The ECU data recorder plugs into the on-board diagnostics (OBD) port of the vehicle and collects second-by-second measurements of various vehicle variables, including vehicle speed. The handheld GPS unit records second-by-second latitude and longitude coordinates, as well as elevation. Latitude, longitude, and elevation are used to estimate road grade. Road grade is the change in elevation over a distance of roadway. Based on the second-by-second coordinates collected, speed can be calculated on a second-by-second basis. The GPS calculated speed is compared to the ECU data recorder calculated speed to synchronize the two datasets. The speed profile from the ECU data recorder and the road grade profile from the GPS unit are used as inputs into MOVES.

The instrumented passenger vehicle drove on three segments, as summarized in Table 5-2. Travel between the Raleigh and Charlotte O/D pair is estimated using Segment Road-A. For all other O/D pairs, a combination of two segments is needed. For 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 O/D 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.

Some simplifying assumptions were needed to estimate avoided highway mileage. For example, for a rider traveling between Raleigh and Charlotte, an assumption was made that the rider traveled to and from the train stations via a personal automobile. Thus, the avoided highway mileage will be approximately equal to the distance along the shortest roadway route from the Raleigh to the Charlotte train station. Such routes were determined by readily available online tools such as Google Maps, and evaluated based on judgment as to routes likely to be selected by knowledgeable drivers.

Table 5-2. Road Segments Used for Speed and Road Grade Profiles

Road Segment	Station Pair[a]	Travel Distance (mi)	Travel Time (sec)
Road-A	RGH ↔ CLT	164.3	8,713
Road-B	CYN ↔ DNC	19.7	1,377
Road-C	DNC ↔ GRO	51.7	3,152

[a] Segments are not directional-specific. For example, Segment A consists of travel from RGH to CLT and from CLT to RGH.

4.2 Results

In this section, mass per passenger-mile emission factors are discussed for travel between selected O/D pairs for both the NCDOT fleet of locomotives and an average light-duty gasoline vehicle. Differences in the locomotive and LDGV emission factors are also discussed.

4.2.1 Locomotives

Based on the Piedmont passenger data obtained from AMTRAK, the five O/D pairs with the highest ridership are listed in Table 5-3, along with the segments that are in between each pair of stations. Mass per passenger-mile emission factors for each O/D pair were calculated for the five NCDOT locomotives tested over-the-rail. The emission factors for the prime mover engines, based on a travel time of approximately 3 hours and 15 minutes (3:15) between Raleigh and Charlotte are shown in Table 5-4. The duty cycle for Train 74 on April 15, 2011, with a total travel time of 3:16, was used to calculate emission factors for the F59PH locomotives. The duty cycle for Train 76 on June 14, 2010, with a total travel time of 3:13, was used to calculate emission factors for the F59PHI locomotive. The duty cycle for Train 76 on December 6, 2009, with a total travel time of 3:17, was used to calculate emission factors for the GP40 locomotive.

The NO_x emission rate between Raleigh and Charlotte averages 2.66 g/passenger-mile among the recently rebuilt F59PH prime movers, and is substantially higher than the F59PHI (which has not yet been rebuilt) and the much older GP40, each with NO_x emission rates over 4.00 g/passenger-mile. The CO_2 emission rate averages approximately 206 g/passenger-mile for the F59PH's. The CO emission rates are generally low, at approximately 0.4 g/passenger-mile among the three categories of locomotives. The HC emission rates are similarly low, at approximately 0.3 to 0.5 g/passenger mile. The PM emission rates are in the range of approximately 0.17 to 0.25 g/passenger-mile. The F59PHs typically have the lowest emission rates for all pollutants except for CO. The NO_x emission rates for the F59PHs are approximately 39 percent lower than either the F59PHI or the GP40, 20 percent lower for CO_2, and 15 percent lower for PM. The HC emission rates for the F59PHs are approximately 50 percent lower than either the F59PHIs or the GP40, with the exception of the Durham and Charlotte O/D pair. Thus, the choice of locomotive has a significant effect on trip-based emission rates.

Average emission factors vary depending on the O/D pair. For example, for NO_x, the average emission factors for the F59PH's vary from 2.3to 3.3 g/bhp-hr when comparing the lowest rate, for the Greensboro and Charlotte O/D pair, to the highest rate, for the Raleigh and Greensboro O/D pair. The emission rates are higher by 40 to 48 percent per passenger mile among each of the pollutants when comparing these two O/D pairs, with the exception of CO where the Raleigh to Greensboro O/D pair emission rate is 88 percent higher than for the Greensboro and Charlotte O/D pair. There are a larger number of station stops per mile between Raleigh and Greensboro than between any of the other four O/D pairs.

Emission factors for the HEP engines are shown in Table 5-5. The HEP fuel use and emission rates used to calculate the mass per passenger-mile emission factors are based on the highest electrical load tested for each locomotive, which corresponds to three or four passenger cars connected to most locomotives. Since the maximum number of cars connected to the NC 1869 F59PH locomotive was two during rail yard tests, a mass per passenger-mile emission factor was not calculated.

The average HEP emission rates vary by locomotive and O/D pair. For example, the HEP trip-based NO_x emission factor averages 0.12 g/passenger-mile for the F59PHs, versus a range of 0.17 to 0.23 g/passenger-mile for the HEP of the GP40 and F59PHI, respectively. Thus, there is substantial inter-engine variability, with the Cummins HEP of the GP40 having substantially lower emission rates than the fleet average. Using the HEP of the F59PHI as a basis, since it has the highest NO_x emission rate, the NO_x emission rates of the HEPs of the F59PHs and the GP40 average 38 and 5 percent lower, respectively, taking into account all O/D pairs. The CO emission rates are lowest for the GP40 and highest for the F59PHs and F59PHI. The HC emission rates are approximately similar among all locomotives. The PM emission rates vary by a factor of approximately two, with the highest value for the HEP of the F59PHI and the lowest for the HEPs of the F59PHs.

However, there is also substantial variability between O/D pairs. For example, the HEP NO_x emission rate for the F59PH's for the Raleigh and Greensboro O/D pair is 0.14 g/passenger-mile, which is 27 percent higher than that of the Greensboro and Charlotte O/D pair. The emission rates of the other pollutants are approximately 35 percent higher for the Raleigh and Greensboro versus Greensboro and Charlotte O/D pairs.

The combined prime mover and HEP emission factors are shown in Table 5-6. For the NC 1869 F59PH locomotive, the measured prime mover mass per passenger-mile and the F59PH average HEP mass per passenger-mile emission factors were used to estimate the combined mass per passenger-mile emission factor.

Table 5-3. Piedmont Train Origin/Destination Pairs with Highest Ridership

Origin/Destination Pair	Fiscal Years 2006-2011 Total Ridership[a]	Average Passengers per Train	Segments	One-Way Distance (mi)
RGH ↔ CLT	92,570	17.4	A through H	172.9
DNC ↔ CLT	66,025	12.4	C through H	146.6
GRO ↔ CLT	53,474	10.1	E through H	92.1
CYN ↔ CLT	44,255	8.3	B through H	164.6
RGH ↔ GRO	40,727	7.7	A through D	80.8

[a] Total ridership on 5,312 trains in Fiscal Years 2006-2011

Table 5-4. Locomotive Per Passenger-Mile Emission Factors for Selected Piedmont Origin/Destination Pairs – Prime Mover Engines

(a) Raleigh (RGH) to Charlotte (CLT)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	2.60	206	0.59	0.53	0.240
F59PH (NC 1859)	2.63	207	0.39	0.30	0.210
F59PH (NC1869)	2.76	205	0.07	0.18	0.170
F59PH Average	2.66	206	0.35	0.34	0.210
F59PHI (NC 1755)	4.16	250	0.48	0.68	0.250
GP40 (NC 1792)	4.63	252	0.16	0.70	---
Fleet Average	3.36	224	0.34	0.48	0.218

(b) Durham (DNC) to Charlotte (CLT)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	2.45	195	0.56	0.50	0.225
F59PH (NC 1859)	2.50	196	0.37	0.28	0.195
F59PH (NC1869)	2.61	194	0.07	0.18	0.160
F59PH Average	2.52	195	0.33	0.32	0.193
F59PHI (NC 1755)	3.95	237	0.46	0.25	0.240
GP40 (NC 1792)	4.29	233	0.15	0.25	---
Fleet Average	3.16	211	0.32	0.29	0.205

(c) Greensboro (GRO) to Charlotte (CLT)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	2.16	173	0.51	0.43	0.200
F59PH (NC 1859)	2.20	174	0.33	0.25	0.170
F59PH (NC1869)	2.30	172	0.06	0.15	0.145
F59PH Average	2.22	173	0.20	0.28	0.172
F59PHI (NC 1755)	3.36	202	0.39	0.53	0.205
GP40 (NC 1792)	3.75	203	0.13	0.53	---
Fleet Average	2.75	185	0.28	0.38	0.180

(d) Cary (CYN) to Charlotte (CLT)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	2.52	200	0.58	0.50	0.230
F59PH (NC 1859)	2.56	201	0.38	0.28	0.200
F59PH (NC1869)	2.67	199	0.07	0.18	0.165
F59PH Average	2.58	200	0.34	0.32	0.198
F59PHI (NC 1755)	4.11	247	0.48	0.65	0.245
GP40 (NC 1792)	4.40	239	0.15	0.65	---
Fleet Average	3.25	217	0.33	0.45	0.210

(e) Raleigh (RGH) to Greensboro (GRO)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	3.10	243	0.69	0.65	0.290
F59PH (NC 1859)	3.14	245	0.45	0.35	0.250
F59PH (NC1869)	3.29	242	0.09	0.23	0.200
F59PH Average	3.17	243	0.41	0.41	0.247
F59PHI (NC 1755)	5.06	304	0.59	0.83	0.300
GP40 (NC 1792)	5.65	307	0.20	0.90	---
Fleet Average	4.05	268	0.40	0.59	0.260

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 5-5. Locomotive Per Passenger-Mile Emission Factors for Selected Piedmont Origin/Destination Pairs – Head End Power Engines

(a) Raleigh (RGH) to Charlotte (CLT)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	0.12	14	0.06	0.02	0.026
F59PH (NC 1859)	0.12	14	0.05	0.01	0.026
F59PH (NC1869)	0.12	14	0.05	0.01	0.026
F59PH Average	0.12	14	0.05	0.01	0.026
F59PHI (NC 1755)	0.20	22	0.05	0.02	0.023
GP40 (NC 1792)	0.19	29	0.03	0.02	---
Fleet Average	0.15	19	0.05	0.02	0.025

(b) Durham (DNC) to Charlotte (CLT)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	0.11	12	0.05	0.02	0.023
F59PH (NC 1859)	0.11	12	0.05	0.01	0.023
F59PH (NC1869)	0.11	12	0.05	0.01	0.023
F59PH Average	0.11	12	0.05	0.01	0.023
F59PHI (NC 1755)	0.18	19	0.04	0.02	0.020
GP40 (NC 1792)	0.17	25	0.02	0.02	---
Fleet Average	0.13	16	0.04	0.02	0.022

(c) Greensboro (GRO) to Charlotte (CLT)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	0.11	12	0.05	0.02	0.022
F59PH (NC 1859)	0.11	12	0.05	0.01	0.022
F59PH (NC1869)	0.11	12	0.05	0.01	0.022
F59PH Average	0.11	12	0.05	0.01	0.022
F59PHI (NC 1755)	0.17	19	0.04	0.02	0.020
GP40 (NC 1792)	0.17	25	0.02	0.02	---
Fleet Average	0.13	16	0.04	0.02	0.022

(d) Cary (CYN) to Charlotte (CLT)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	0.11	13	0.05	0.02	0.024
F59PH (NC 1859)	0.11	13	0.05	0.01	0.024
F59PH (NC1869)	0.11	13	0.05	0.01	0.024
F59PH Average	0.11	13	0.05	0.01	0.024
F59PHI (NC 1755)	0.18	20	0.04	0.02	0.021
GP40 (NC 1792)	0.18	27	0.02	0.02	---
Fleet Average	0.14	17	0.04	0.02	0.023

(e) Raleigh (RGH) to Greensboro (GRO)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	0.14	16	0.07	0.02	0.030
F59PH (NC 1859)	0.14	16	0.06	0.02	0.030
F59PH (NC1869)	0.14	16	0.06	0.02	0.030
F59PH Average	0.14	16	0.06	0.02	0.030
F59PHI (NC 1755)	0.23	26	0.06	0.02	0.027
GP40 (NC 1792)	0.22	34	0.03	0.03	---
Fleet Average	0.17	22	0.06	0.02	0.029

NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Table 5-6. Locomotive Per Passenger-Mile Emission Factors for Selected Piedmont Origin/Destination Pairs – Prime Mover and Head End Power Engines

(a) Raleigh (RGH) to Charlotte (CLT)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	2.72	220	0.65	0.55	0.266
F59PH (NC 1859)	2.75	221	0.44	0.31	0.236
F59PH (NC1869)[a]	2.88	219	0.12	0.19	0.196
F59PH Average	2.78	220	0.40	0.35	0.236
F59PHI (NC 1755)	4.36	272	0.53	0.70	0.273
GP40 (NC 1792)	4.82	281	0.19	0.72	---
Fleet Average	3.51	243	0.39	0.50	0.243

(b) Durham (DNC) to Charlotte (CLT)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO	CO	HC	PM
F59PH (NC 1810)	2.56	207	0.61	0.52	0.248
F59PH (NC 1859)	2.61	208	0.42	0.29	0.218
F59PH (NC1869)[a]	2.72	206	0.12	0.19	0.183
F59PH Average	2.63	207	0.38	0.33	0.216
F59PHI (NC 1755)	4.13	256	0.50	0.27	0.260
GP40 (NC 1792)	4.46	258	0.17	0.27	---
Fleet Average	3.29	227	0.36	0.31	0.227

(c) Greensboro (GRO) to Charlotte (CLT)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	2.27	185	0.56	0.45	0.222
F59PH (NC 1859)	2.31	186	0.38	0.26	0.192
F59PH (NC1869)[a]	2.41	184	0.11	0.16	0.167
F59PH Average	2.33	185	0.25	0.29	0.194
F59PHI (NC 1755)	3.53	221	0.43	0.55	0.225
GP40 (NC 1792)	3.92	228	0.15	0.55	---
Fleet Average	2.88	201	0.32	0.40	0.202

(d) Cary (CYN) to Charlotte (CLT)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	2.63	213	0.63	0.52	0.254
F59PH (NC 1859)	2.67	214	0.43	0.29	0.224
F59PH (NC1869)[a]	2.78	212	0.12	0.19	0.189
F59PH Average	2.69	213	0.39	0.33	0.222
F59PHI (NC 1755)	4.29	267	0.52	0.67	0.266
GP40 (NC 1792)	4.58	266	0.17	0.67	---
Fleet Average	3.39	234	0.37	0.47	0.233

(e) Raleigh (RGH) to Greensboro (GRO)

Locomotive	Emission Factor (g/passenger-mile)				
	NO_x	CO_2	CO	HC	PM
F59PH (NC 1810)	3.24	259	0.76	0.67	0.320
F59PH (NC 1859)	3.28	261	0.51	0.37	0.280
F59PH (NC1869)[a]	3.43	258	0.15	0.25	0.230
F59PH Average	3.31	259	0.47	0.43	0.277
F59PHI (NC 1755)	5.29	330	0.65	0.85	0.327
GP40 (NC 1792)	5.87	341	0.23	0.93	---
Fleet Average	4.22	290	0.46	0.61	0.289

[a] Uses F59PH (NC 1859) prime mover emission factor and F59PH Average HEP emission factor.
NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

Based on Table 5-6, the overall fleet average NO_x and CO_2 emission factor for the five selected routes is 3.46 and 239 g/passenger-mile, respectively. For each route, the lowest NO_x emission rates were observed with the F59PH locomotives, whose prime mover engines were retrofit to meet the EPA Tier 0+ emission standard. The F59PHs also had the lowest CO_2 emission rates. The NC 1755 and NC 1792 locomotives had similar CO_2 emission rates for each route. NO_x emission rates were approximately 10 percent higher for the NC 1792 than NC 1755. The highest NO_x and CO_2 emission factors for each locomotive were observed between the Raleigh and Greensboro O/D pair; the fleet average NO_x and CO_2 emission rate of 4.22 and 290 g/passenger-mile is approximately 29 percent higher than the overall fleet average NO_x and CO_2 emission factors for the five selected routes. This could be attributed to the O/D pair having the fewest number of station stops per mile. The three O/D pairs with the highest number of station stops per mile have the lowest fleet average NO_x and CO_2 emission rates.

The trends in the total emissions per locomotive chassis, including both the prime mover and the HEP based on data given in Table 5-6, are qualitatively similar to the trends for the prime mover alone. This is because the prime mover contributes an average of 89 percent of the total chassis emissions, with a range of 85 to 96 percent depending on the pollutant and locomotive. For example, the F59PHs have chassis NO_x emissions that average 36 to 44 percent less than the GP40 and F59PHI, respectively. The rebuilt F59PHs, combined with the new C18 HEPs, are estimated to have 16 to 24 percent lower CO_2 emission rates than the two older locomotives. The CO, HC, and PM emission rates are 14 to 50 percent lower than for the F59PHI, depending on the pollutant, with the exception of HC emissions for the Durham and Charlotte O/D pair. The trend when comparing O/D pairs is also similar to that for the prime mover alone. For example, the emission rates for the Greensboro and Charlotte O/D pair are 31 percent lower, on average, than for the Raleigh and Greensboro O/D pair. The variability in emission rates is influenced more by the choice of locomotive than by differences in duty cycles between O/D pairs, but both factors are important.

The HEP is a small, but significant, contributor to total emissions from the chassis, representing between 4 to 15 percent of total emissions depending on the pollutant and locomotive. Thus, the HEP is a non-negligible contributor to overall energy use and emissions.

The fleet average PM and HC emission factors were similar between the five origin and destination pairs.

To check the validity of the locomotive CO_2 emission factors, the average energy intensity for the NCDOT locomotive fleet was calculated, using Equation 7.

$$EI_{loco} = \left(EF_{CO_2}\right)\left(\frac{m_C}{m_{CO_2}}\right)\left(\frac{1}{f_C}\right)\left(\frac{1}{\rho_{diesel}}\right)\left(HV_{diesel}\right) \quad (7)$$

Where,

EF_{CO_2}	=	fleet average prime mover and head end power engine CO_2 emission factor (g/pax-mi)
EI_{loco}	=	average energy intensity of locomotives (BTU/pax-mi)
f_C	=	weight fraction of carbon in diesel (0.864 g/g gasoline)

HV_{diesel}	=	heating value of diesel (128,700 BTU/gal)
m_C	=	atomic mass of carbon (12 g/gmol)
m_{CO_2}	=	atomic mass of carbon (44 g/gmol)
ρ_{diesel}	=	density of diesel (3,200 g/gal)

The average CO_2 emission factor over the five O/D pairs is 246 g/passenger-mile. This equates to an average energy intensity of 3,125 BTU/passenger-mile. The NCDOT locomotive fleet average energy intensity is 30 percent higher than the intercity rail average energy intensity, based on a travel time of 3 hours and 15 minutes. The NCDOT locomotive fleet average energy intensity includes fuel use and emissions associated with both the prime mover and HEP engines. The DOE average locomotive energy intensity value is stated as "intercity rail energy use divided by passenger-miles" (ORNL, 2010); however, it is not clear if this value includes energy use from the HEP engine. The lowest observed CO_2 emission factor by any locomotive between any O/D pair was 221 g/passenger-mile for NC 1869 between Greensboro and Charlotte, and would equate to an average energy intensity of 2,806 BTU/passenger. This average energy intensity is 17 percent higher than the intercity rail average energy intensity.

4.2.2 Light-Duty Gasoline Vehicles

MOVES software was used to estimate the fleet average emission factors for travel with passenger cars and trucks fueled with gasoline between five city pairs, shown in Table 5-7. Also shown in Table 5-7 are the rail emission factors based on on-time rail travel, obtained from Table 5-6. The five city pairs correspond to the five rail station O/D pairs in which mass per passenger-mile emission factors were calculated, shown in Table 5-2.

The LDGV emission rates vary among the five O/D pairs for a given pollutant. For example, the average NO_x emission rate among the five O/D pairs is 0.87 g/mile, with a range of plus or minus 8 percent (0.80 to 0.94 g/mile). The average CO_2 emission rate is 365 g/mile, with a range of approximately plus or minus 5 percent. The emission rates of HC, PM, and CO are more variable than those for CO, with approximate ranges of plus or minus 8, 10, and 20 percent, respectively compared to the average of all five O/D pairs. Except for CO, there is more relative variability in the F59PH locomotive emission rates among the O/D pairs.

All comparisons between LDGVs and locomotives, including the emission factors in Table 5-8, are based on the scheduled travel time on the Piedmont route. This ensures that any analysis is based on normal operating conditions of the locomotive and normal traffic conditions for the LDGVs. No locomotive idling time at the origin and destination rail stations are considered because an LDGV driver would not idle before departing or upon arrival at a rail station.

As expected, the diesel locomotives have higher NO_x emission rates per passenger-mile than the LDGVs, since diesel engines tend to have higher NO_x emission rates than gasoline vehicles, and

Table 5-7. Passenger Vehicle Per Passenger-Mile Emission Factors for Selected Piedmont Train Origin/Destination Pairs

(a) Raleigh (RGH) to Charlotte (CLT)

Vehicle	Emission Factor (g/passenger-mile)[a]				
	NO_x	CO_2	CO	HC	PM
Light-Duty Gasoline Vehicle	0.91	401	6.63	0.20	0.013
F59PH Locomotive Average[b]	2.78	220	0.40	0.35	0.236
Locomotive Fleet Average[b]	3.51	243	0.39	0.50	0.243
F59PH vs. LDGV	+ 205%	- 45%	- 94%	+ 75%	+ 1715%
Locomotive Fleet vs. LDGV	+ 286%	- 39%	- 94%	+ 150%	+ 1769%

(b) Durham (DNC) to Charlotte (CLT)

Vehicle	Emission Factor (g/passenger-mile)[a]				
	NO_x	CO_2	CO	HC	PM
Light-Duty Gasoline Vehicle	0.83	372	5.24	0.17	0.010
F59PH Locomotive Average[b]	2.63	207	0.38	0.33	0.216
Locomotive Fleet Average[b]	3.29	227	0.36	0.31	0.227
F59PH Locomotives vs. LDGV	+ 217%	- 44%	- 93%	+ 94%	+ 2060%
Locomotive Fleet vs. LDGV	+ 296%	- 39%	- 93%	+ 82%	+ 2170%

(c) Greensboro (GRO) to Charlotte (CLT)

Vehicle	Emission Factor (g/passenger-mile)[a]				
	NO_x	CO_2	CO	HC	PM
Light-Duty Gasoline Vehicle	0.85	377	5.66	0.18	0.010
F59PH Locomotive Average[b]	2.33	185	0.25	0.29	0.194
Locomotive Fleet Average[b]	2.88	201	0.32	0.40	0.202
F59PH Locomotives vs. LDGV	+ 174%	- 51%	- 96%	+ 61%	+ 1840%
Locomotive Fleet vs. LDGV	+ 239%	- 53%	- 94%	+ 122%	+ 1920%

(d) Cary (CYN) to Charlotte (CLT)

Vehicle	Emission Factor (g/passenger-mile)[a]				
	NO_x	CO_2	CO	HC	PM
Light-Duty Gasoline Vehicle	0.94	406	7.25	0.20	0.012
F59PH Locomotive Average[b]	2.69	213	0.39	0.33	0.222
Locomotive Fleet Average[b]	3.39	234	0.37	0.47	0.233
F59PH Locomotives vs. LDGV	+ 186%	- 48%	- 95%	+ 65%	+ 1750%
Locomotive Fleet vs. LDGV	+ 261%	- 42%	- 95%	+ 135%	+ 1842%

(e) Raleigh (RGH) to Greensboro (GRO)

Vehicle	Emission Factor (g/passenger-mile)[a]				
	NO_x	CO_2	CO	HC	PM
Light-Duty Gasoline Vehicle	0.80	365	4.71	0.17	0.011
F59PH Locomotive Average[b]	3.31	259	0.47	0.43	0.277
Locomotive Fleet Average[b]	4.22	290	0.46	0.61	0.289
F59PH Locomotives vs. LDGV	+ 314%	- 29%	- 90%	+ 153%	+ 2418%
Locomotive Fleet vs. LDGV	+ 428%	- 21%	- 90%	+ 259%	+ 2527%

[a] Light-duty gasoline vehicle emission factors assumes a load factor of 1 passenger per vehicle.
[b] Locomotive emission factors based on a travel time of approximately 3 hours and 15 minutes.
NO_x, HC, and PM are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction.

the highway light duty fleet is predominately gasoline-based. The locomotive NO_x emission factors for the F59PHs are higher by 174 to 314 percent, depending on the O/D pair. The highest locomotive NO_x emission factor is for the Raleigh and Greensboro O/D pair, which had the lowest of the light duty vehicle NO_x emission rates. Thus, this O/D pair had the highest percentage difference between the two travel modes. The fleet average NO_x emission factor including the F59PHI and GP40 is substantially higher than that just for the F59PHs. The PM emission rates for diesel engines tend to be much higher than for gasoline engines, and thus the estimated 1715 to 2418 percent higher PM emission rates for the F59PH locomotives among the five O/D pairs is not surprising.

However, the train has clear advantages with respect to emissions of CO_2 and CO, when compared to a single occupancy vehicle (SOV). The locomotive CO_2 emission rate is approximately four-fifths to one-half that of the average highway vehicle on a per passenger-mile basis. The CO emission rates are 90 to 96 percent lower. Gasoline vehicles tend to produce high levels of engine-out CO emission rates. Even though gasoline vehicles have very effective control of CO emissions using three-way catalytic converters, their exhaust emissions are clearly much higher than those of the diesel engines used in the locomotives.

The F59PH locomotives do not have an advantage with respect to HC emissions compared to an SOV, with locomotive emission rates 61 to 153 percent higher than that of the SOV when a bias correction of 2.5 is considered. However, Diesel engines tend to have lower HC emissions than gasoline engines.

The passenger vehicle emission factors for all pollutants are of the same magnitude to emission factors, calculated using EPA total emissions and U.S. Department of Transportation (U.S. DOT) highway statistics, are of the same magnitudes as the emission factors in Table 5-4 (ORNL, 2010).

In order to check the validity of the LDGV CO_2 emission factors, the average energy intensity for the NCDOT locomotive fleet was calculated:

$$EI_{LDGV} = \left(EF_{CO_2}\right)\left(\frac{m_C}{m_{CO_2}}\right)\left(\frac{1}{f_C}\right)\left(\frac{1}{\rho_{gas}}\right)\left(HV_{gas}\right)\left(\frac{1}{LF}\right) \tag{8}$$

Where,

EF_{CO_2}	=	average CO_2 emission factor (g/passenger-mi)
EI_{LDGV}	=	average energy intensity of LDGV (BTU/passenger-mi)
f_C	=	weight fraction of carbon in gasoline (0.864 g/g gasoline)
HV_{gas}	=	heating value of gasoline (115,400 BTU/gal)
LF	=	passenger load factor
m_C	=	atomic mass of carbon (12 g/gmol)
m_{CO_2}	=	atomic mass of carbon (44 g/gmol)
ρ_{gas}	=	density of diesel (2,791 g/gal)

It is assumed in this analysis that the driver is the only passenger in the vehicle traveling between O/D stations. Therefore, the average LDGV load factor of 1.00 passengers per vehicle was used in Equation 8. However, the DOE estimate of 3,518 BTU/passenger-mile for the average LDGV assumes an average load factor of 1.69 passengers per vehicle.

The average CO_2 emission factor over the five O/D pairs is 384 g/passenger-mile. This equates to an average energy intensity of 4,993 BTU/passenger-mile with a load factor of 1 passenger per vehicle or 2,954 BTU/passenger-mile with a load factor of 1.69 passengers per vehicle. The MOVES-estimated LDGV average energy intensity is within 16 percent of the DOE-estimated LDGV average energy intensity.

Removing a passenger from a LDGV and placing them on the train would lend to a net reduction in CO_2 and CO emissions. On average, the F59PH per passenger-mile CO_2 and CO emission rates were 43 and 94 percent lower than the LDGV per passenger-mile emission rates, respectively. The relative decrease in CO_2 emission rates between locomotives and LDGVs is higher when only the F59PH locomotives are considered. When including the F59PHI and GP40 locomotives, there would still be a lower CO_2 emission rate compared to LDGVs, but not as large a decrease. There is little to no difference in CO emission rates when the entire locomotive fleet is compared to LDGVs, rather than just the F59PH locomotives versus LDGVs.

However, the NO_x and PM per-passenger emission rates were higher for the train than the LDGVs. On average, the F59PH per passenger-mile NO_x and PM emission rates were 219 and 1957 percent higher than the LDGV per passenger-mile emission rates, respectively. When comparing HC emission rates between locomotives and LDGVs, LDGVs have lower emission rates than the F59PH locomotives when a bias correction is considered.

Delays in rail travel time would lead to a less favorable comparison of the train versus avoided highway emissions. Looking at an F59PH duty cycle that is ten minutes delayed, per passenger-mile emission factors for all pollutants would increase an average of 16 percent for rail travel between Raleigh and Charlotte O/D station pairs using an F59PH locomotive. Thus, there is a significant environmental incentive to avoid travel delays to the extent possible.

Theoretically, if more passengers ride the train, then NO_x and PM emission rates would decrease. For example, in order for the LDGV and F59PH locomotive NO_x and PM emission rates to be equal on the Raleigh to Charlotte route, total train ridership would have to increase 300 percent. The peak ridership on a single train, which, on average, occurs on the segment between Burlington and Greensboro, would then be 270 passengers. The LDGV per-passenger emission rates are based on the driver being the only passenger in the vehicle. If a second passenger were traveling in the LDGV, then the 43 percent advantage the F59PH locomotives had with CO_2 emissions would be canceled out.

Potential delays in highway travel were not evaluated in this report. However, such delays are not uncommon. Highway travel delays would tend to make the comparison of the train to avoided highway vehicle travel more favorable for the rail travel.

Current ridership levels would have to increase approximately 225 percent in order for the F59PH average NO_x and PM per passenger-mile emission factors to be similar to or less than the NO_x and PM per passenger-mile emission factors for LDGVs between the Raleigh and Charlotte

O/D station pair. If locomotives that met EPA Tier 3 or Tier 4 standards were used, then ridership increases might not be necessary for rail NO_x and PM emission factors to be less than those from LDGV.

4.3 Summary

In this chapter, the following items were discussed:

- Locomotive per passenger-mile emission factors were calculated for five selected origin and destination pairs using emission factors and duty cycles measured during over-the-rail testing and ridership data. The emission factors were estimated for the prime mover engine, the HEP engine, and the prime mover and HEP engines combined.
- Light-duty gasoline vehicle per passenger-mile emission factors were calculated for the same five selected origin and destination pairs using estimated speed and road grade profiles and the EPA MOVES2010a software.
- The three O/D pairs with the highest number of station stops per mile have the lowest fleet average NO_x and CO_2 emission rates.
- Passenger rail travel on the Piedmont service leads to lower emissions per passenger mile for several key pollutants, including CO_2 and CO. The CO_2 emissions are reduced by approximately one-third for the recently rebuilt F59PH locomotives compared to an average highway vehicle. The CO emissions are reduced by approximately 90 percent. The energy intensity of rail travel is about one-third lower per passenger mile than that of a driver in a single occupancy highway vehicle.
- Diesel engines typically have higher emissions of NO_x and PM than gasoline engines, and thus it is not surprising that the NO_x and PM emissions per passenger mile are higher for the train than for equivalent travel by highway vehicle. However, the recently rebuilt F59PHs have lower NO_x emissions than the legacy fleet of other locomotives, and thus it is clear that engine rebuilds are leading to substantial reductions in NO_x emissions.
- NO_x and PM emissions per passenger-mile can be further reduced if passenger load can be increased. In the long-run, replacement of older higher emitting locomotives with newer low emitting locomotives, or installation of retrofit post-combustion emissions control systems could lead to lower emissions. However, retrofits may be constrained or infeasible depending on limited available of space within the engine housing.

5.0 BIODIESEL VERSUS PETROLEUM DIESEL

An objective of this project is to quantify the fuel use and emission rates of passenger rail locomotives for ULSD and B20 biodiesel, and to quantify fuel cycle emissions for both fuels using a life cycle inventory approach. This chapter serves as a review of the literature available on biodiesel use in on-road vehicles, including locomotives, and reports on results of emissions measurements conducted by NCSU on a locomotive engine operated on ULSD and B20 biodiesel while being tested on a dynamometer.

5.1 Biodiesel

Biodiesel is a naturally oxygenated and possibly cleaner burning diesel replacement fuel made from natural, renewable sources such as new and used vegetable oils or animal fats. It can be used directly in diesel engines without major modifications to the engines and vehicles. Biodiesel can be blended with petroleum diesel at any ratio. A common blend rate, referred to as B20, is 20 percent renewable source and 80 percent petroleum diesel (EPA, 2002).

An average increase of 2.2 percent in volume and 3.4 percent in mass of biodiesel is expected to supply the same amount of chemical energy as petroleum diesel to the engine (EPA, 2002). On the basis of engine dynamometer tests, the use of B20 is expected to reduce emissions of CO, PM, and HC by approximately 10, 10, and 20 percent, respectively. Conversely, NO_x emissions are expected to increase by 2 percent (EPA, 2002).

5.2 In-Use Biodiesel Testing

North Carolina State University has conducted numerous studies on B20 and petroleum diesel use in construction vehicles. They all involved the implementation of a PEMS to measure the real-world activity, fuel use, and emissions. The common conclusions in the studies have been a negligible change in NO_x emissions between B20 and petroleum diesel, and significant reductions in CO, HC, and PM emissions (Frey and Kim, 2006; Frey and Kim, 2009; Frey *et al.*, 2008a&b; Sandhu and Frey, 2011). Table 6-1 compares changes in emissions for select B20 biodiesel versus petroleum diesel studies. There is variability in emissions reductions accredited with B20 biodiesel use. In all of these studies, there were consistent reductions in CO and HC emissions. PM emissions rates were found to decrease in four of the five studies. However, while NO_x emissions increases were not observed as suggested by EPA, NO_x reductions of 2 percent or more were observed.

Table 6-1. Comparison of Real-World Emissions from B20 Biodiesel Versus Petroleum Diesel for In-Use Vehicles

Study	Number and Type of Vehicles Tested	B20 Biodiesel versus Petroleum Diesel			
		NO_x	CO	HC	PM
Frey and Kim, 2006	12 dump trucks	- 10%	- 11%	- 22%	- 10%
Frey and Kim, 2009	8 cement mixers	- 2%	- 21%	- 29%	- 20%
Frey *et al.*, 2008(a)	6 motor graders	- 1.6%	- 19%	- 20%	- 22%
Frey *et al.*, 2008(b)	5 backhoes 4 front end loaders 6 motor graders	- 1.8%	- 25%	- 26%	- 18%
Sandhu and Frey, 2011	5 combination trucks	- 16%	- 30%	---	+ 7.8%

5.3 Locomotive Biodiesel Testing

There have been two published studies of the use of biodiesel in stationary, rail yard tests in locomotives similar to the locomotives in the NCDOT fleet. The NCDOT GP40 prime mover engine was tested on a dynamometer with biodiesel during a rebuild.

5.3.1 CSX Freight Locomotive

A GP38-2 locomotive with a 2000 hp EMD 16-645-E prime mover engine owned and operated by CSX was used to test four different fuel blends in stationary, rail yard tests in October 2000 by the Southwest Research Institute. The four blends consisted of:

- EPA locomotive certification diesel (2996 ppm sulfur concentration)
- CARB diesel (50 ppm sulfur concentration)
- B20 blend (20% biodiesel and 80% EPA locomotive certification diesel)
- C20 blend (20% biodiesel and 80% CARB diesel)

The sulfur content of the CARB diesel blend is closest to the sulfur content of ULSD.

Exhaust concentrations of HC were measured using a Rosemount Analytical model 402 heated flame ionization detector (HFID). NO_x concentrations were measured using a Rosemount model 955 chemiluminescent analyzer. Exhaust concentrations of CO_2 and CO were measured using non-dispersive infrared (NDIR) instruments. PM emissions were measured using a dilution tunnel. Smoke opacity was measured using a smokemeter.

Comparing C20 versus CARB diesel, the gram per engine output emission rates of CO decreased 8 percent. The HC, NO_x, and PM emission rates increased 1, 4, and 4 percent, respectively, for the C20 versus CARB blends. There was no difference in the brake specific fuel consumption between the two fuels (Fritz, 2004).

For B20 versus EPA blends, the gram per engine output emission rates of CO decreased 17 percent. The HC, NO_x, and PM emission rates increased 1, 6, and 7 percent, respectively. There was a 1 percent reduction in the brake specific fuel consumption with B20 use (Fritz, 2004).

Overall, CO emissions decreased significantly with C20 and B20 use. Emissions of other pollutants did not change significantly or increased slightly.

5.3.2 NJ TRANSIT Line-Haul Locomotives

Two line-haul locomotives owned and operated by NJ TRANSIT were used to test 8 different fuel blends in stationary, rail yard tests from June 2007 to January 2009. The two locomotives were a GP40 with an EMD 16-645 prime mover engine and a PL42AC with an EMD 16-710 prime mover engine. Some of the fuel blends included:

- summer blend of ULSD (<15 ppm sulfur)
- winter blend of ULSD (40% kerosene, 60% ULSD)
- summer blend of B20 and ULSD (20% biodiesel, 80% ULSD)
- winter blend of B20 and ULSD (20% biodiesel, 56% kerosene, 24% ULSD)

Winter blends of ULSD and B20 and ULSD contained kerosene because the winter fuel tests of the GP40 were conducted in June and July 2008 and cloud point requirements had to be met. Summer fuel tests of the GP40 were conducted in November 2007.

A SEMTECH-D portable emissions measurement system (PEMS) was used to measure the exhaust emission concentrations of CO_2, CO, HC, NO_2, and NO. A Wager 6500RR Railroad Opacity Meter was used to quantify the opacity of the exhaust.

Total mass per hour exhaust emission rates were calculated based on the emission concentrations measured by the PEMS and weighted based on actual NJ TRANSIT duty cycle notch data, not the EPA line-haul duty cycle. The use of B20 increased the CO_2 emission rate by 2.45 and 4.22 percent in the summer and winter, respectively, compared to ULSD. The NO_x emission rate decreased 5.34 percent in the summer with the use of biodiesel instead of ULSD, but increased 5.11 percent in the winter. The HC emission rate increased 1.23 percent with B20 usage. A 43.2 percent increase in the CO emission rate was observed in the summer with biodiesel, but a 23.7 percent decrease was observed in the winter (Marchese *et al.*, 2009).

As expected, based on differences in fuel properties, a slight increase in fuel use was observed. NO_x emission rates increased for one pair of seasonal blends and decreased for another, as did CO emissions. The change in HC emissions was negligible. Overall, there is not a clear indication of any potential for year-round emission rate reductions with B20 for the engines.

The summer ULSD and B20 blend had lower levels of opacity at Notches 2 through 6 compared to the summer ULSD blend. In contrast, the winter ULSD and B20 blend had similar or higher levels of opacity at Notches 2 through 7 compared to the winter ULSD blend.

5.3.3 NCDOT GP40 Locomotive

During the rebuild of the NCDOT GP40 locomotive numbered NC 1792 in June 2009, dynamometer testing of the 3000 hp EMD 16-645 prime mover engine was conducted with both ULSD and B20 biodiesel once the engine was optimized.

The locomotive rebuild facility contained a water brake dynamometer test cell that is used for performance evaluation of the engine. A control room is connected to the test cell where the dynamometer operator uses a computer, referred to as the dynamometer control system, to both operate the dynamometer and record engine operation data. Unlike a dynamometer facility used for certification tests under the FRM, this facility does not include emissions measurement capabilities. Therefore, the Montana PEMS system was used in conjunction with the dynamometer to measure the exhaust emission concentrations of CO_2, CO, HC, NO_x, and PM.

Engine fuel use and horsepower output needed for the calculation of 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:

$$SFC = \frac{\Delta w_{fuel}}{(HP)\left(\frac{\Delta t}{3600}\right)} \tag{5}$$

Where,

HP	=	average engine horsepower output during each notch position
SFC	=	specific fuel consumption (lb/hp-hr)
Δt	=	duration of notch position (sec)
Δw_{fuel}	=	change in fuel tank weight during each notch position (lb)

Engine horsepower output is derived from the dynamometer torque meter. Other engine variables not directly needed in the calculation of fuel use and emission rates are also collected. These include: engine RPM, airbox pressure and temperature, intake air temperature, and barometric pressure. These data are useful for characterizing engine operation.

After a 45-minute warm up period of the PEMS and an approximately equal time of engine warm up, the engine was operated at each throttle notch position for approximately five minutes, starting at Notch 8. Data for each throttle notch were collected by the PEMS. There was a direct transition from one notch position to the next, and the time need to transition the engine was not included in data analysis. Emissions and engine operation data were collected once the engine reached a steady state at each notch position. The PEMS recorded emissions data on a second-by-second basis, including during each 5-minute interval. Five-second average engine operation data were logged by the dynamometer control system approximately every 30 seconds during each 5-minute interval.

The results of the ULSD and B20 biodiesel dynamometer tests are found in Table 6-2. The observed cycle average CO emission rate, based on the EPA line-haul duty cycle, was unchanged when ULSD was replaced with B20, contrary to the 10 percent decrease expected. NO_x emission rates increased by 6 percent with B20 usage. Cycle average emission rates of PM and HC from biodiesel increased by 8 and 17 percent, respectively.

FSEO for ULSD use averaged at 19.2 bhp-hr/gal for idle through Notch 8, while FSEO for B20 use averaged at 19.4 bhp-hr/gal, a 1% decrease in fuel use for B20.

Table 6-2. Cycle Average Emission Rates for GP40 Locomotive NC 1792 Prime Mover Engine with Ultra Low Sulfur Diesel and B20 Biodiesel

Locomotive	Fuel (bhp-hr/gal)	NO_x (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	Opacity-based PM (g/bhp-hr)
Ultra Low Sulfur Diesel	19.2	9.4	1.27	0.9	0.75
B20 Biodiesel	19.4	10.0	1.48	0.9	0.81
B20 vs. ULSD	+ 1.0%	+ 6.4%	+ 16.5%	0.0%	+ 8.0%

MEASUREMENT RESULTS ARE INTENDED FOR COMPARISONS BETWEEN TESTS, AND CANNOT BE USED FOR CERTIFICATION PURPOSES.

NO_x includes NO and NO_2. Only NO was measured. Typically, NO_x is comprised of 95 vol-% NO. Total NO_x is estimated to be approximately 5 percent higher than the values shown. NO_x is always reported as equivalent mass of NO_2. Cycle average emission rates include a multiplicative correction factor of 1.053 to approximate for total NO_x.

HC is measured using non-dispersive infrared (NDIR), which accurately measures some compounds, but responds only partially to others. Actual HC emissions may be a factor of 2 to 2.5 greater than the values shown. Cycle average emission rates include a multiplicative correction factor of 2.5 to approximate for total HC.

Opacity is measured using a light scattering technique, which provides useful relative comparisons of particle levels in exhaust. The actual PM emission rate may be a factor of 5 to 20 greater than the value shown. Cycle average emission rates include a multiplicative correction factor of 5 to approximate total PM.

Table 6-3. Comparison of Emissions for Biodiesel Versus Petroleum Diesel in Locomotives

Study	Biodiesel versus Petroleum Diesel			
	NO_x	CO	HC	PM
Fritz, 2004 *C20 vs. CARB*	+ 4.6%	- 7.7%	+ 0.5%	+ 4.3%
Fritz, 2004 *B20 vs. EPA*	+ 5.7%	- 16.8%	+ 1.0%	+ 6.4%
Marchese *et al*., 2009 *Summer Blends*	+ 1.5%	- 13.0%	+ 6.8%	---[a]
Marchese *et al*., 2009 *Winter Blends*	+ 0.8%	+ 21.5%	+ 0.8%	---[a]
NCSU, 2009	+ 6.4%	+ 16.5%	0.0%	+ 8.0%
Average	+3.8%	+0.1%	+1.8%	+6.3%

[a] No quantitative analysis of opacity given in literature.

Table 6-3 summarizes the results of the three locomotive biodiesel use studies, which included five separate cases. On average over these five cases, the NO_x emissions increased by 4 percent. The smallest increases were observed in the Marchese *et al.* study. On average, there was no change in CO emissions rates; however, the difference in CO emission rate was highly variable across studies, with increases as high as 21 percent and decreases as low as 17 percent. On average, the HC emission rates increased by 2 percent. The PM emission rates increased by an average of 6.2 percent among the three studies from which data were available. Overall, the results indicate that there is substantial engine-to-engine variability. Given the limited amount of data, and the wide range of variability, it is difficult to reach any conclusions for the fleet.

5.4 Life Cycle Inventory

A life cycle inventory (LCI) was used to estimate fuel cycle energy consumption and emissions of selected pollutants and greenhouse gases for the substitution of soy-based biodiesel fuels for petroleum diesel in construction vehicles (Pang *et al.*, 2009). LCIs are used to compare fuel, taking into account energy consumption and emissions for fuel production and use. Fuel consumption emission factors of NO_x, CO, HC, and PM were estimated using the Argonne National Laboratory Greenhouse Gasses, Regulated Emissions, and Energy Use in Transportation (GREET) model. Life cycle fossil energy reductions are estimated at 9 percent for B20 use versus petroleum diesel based on the current national energy mix (Pang *et al.*, 2009). The average differences in life cycle emissions for B20 versus diesel used in construction equipment are: 4.1 percent lower for CO; 11.8 percent lower for PM; 1.6 percent higher for HC; and 3.5 percent higher for NO_x (Pang *et al.*, 2009).

EPA line haul duty cycle average fuel-based emission factors from the dynamometer testing of the EMD 16-645 prime mover engine of NC 1792 on both ULSD and B20 biodiesel are combined with fuel cycle fuel-based emission factors from Pang *et al.* (2009) to compare life cycle emissions in Table 6-4. A similar life cycle inventory for the CAT C18 ACERT HEP engine is included in Table 6-5. Fuel cycle emissions approximate the emissions associated with fuel creation to the transport of the fuel to the locomotive, also referred to as “well-to-tank.”

Fuel-based prime mover CO emissions are lower for B20 biodiesel use than ULSD use. B20 biodiesel, however, contributes to higher prime mover emissions of NO_x, HC, and PM when compared to ULSD. Fuel cycle emissions associated with the creation and transport of B20 biodiesel are higher than for ULSD for all pollutants. Accounting for fuel production, transport, and use by the locomotive, B20 biodiesel use accounts for an 8 percent reduction in the fuel-based CO emission rate for the prime mover engine. In contrast, B20 biodiesel increases the fuel-based emission rates of HC, NO_x, and PM by 14, 21, and 33 percent, respectively, for the prime mover engine. Since these results are based on only one prime mover engine and one test of each HEP engine, they are not likely to be representative of the fleet of NCDOT locomotives, and further measurements should be made in the rail yard or over-the-rail as part of future work.

Three CAT C18 ACERT engines that are the HEP engines for the F59PH locomotives were tested in the rail yard. The HEP emission rates for ULSD use are an average of the three locomotives. These HEP engines were only tested on ULSD. The B20 emission factors for the 4-stroke HEPs are estimated based on the ULSD emission factors and percent changes for B20 versus ULSD given in Table 6-1. Accounting for fuel production, transport, and use by the locomotive, B20 biodiesel use accounts for a 16 percent reduction in the fuel-based CO emission rate for the prime mover engine. In contrast, B20 biodiesel increases the fuel-based emission rates of NO_x and HC by 6 and 11 percent, respectively, for the HEP engine. Further measurements should be made in the rail yard of these three HEP engines using B20, as well as any additional locomotives that use the CAT C18 ACERT engines (i.e., the F59PHIs once rebuild is complete).

Table 6-4. Life Cycle Inventory for Ultra Low Sulfur Diesel and B20 Biodiesel Use for the EMD 16-645 Prime Mover Engine of GP40 Locomotive NC 1792

Fuel	Emission Source	NO_x (g/gal)	HC (g/gal)	CO (g/gal)	PM (g/gal)
ULSD	Prime Mover (PM)[a]	157	22.6	70.7	5.0
	Fuel Cycle (FC)[b]	8	1.0	1.5	0.5
	PM + FC	165	23.6	72.2	5.5
B20	PM[a]	180	23.9	62.1	6.6
	FC[b]	20	3.0	4.0	0.7
	PM +FC	200	26.9	66.1	7.3
B20 vs. ULSD	PM[a]	+ 15%	+ 6%	- 12%	+ 32%
	FC[b]	+ 150%	+ 200%	+ 167%	+ 40%
	PM + FC	+ 21%	+ 14%	- 8%	+ 33%

[a] Duty cycle average emission factor for the EMD 16-645 prime mover engine of the NC 1792 GP40 locomotive.

[b] (Pang *et al.*, 2009)

Table 6-5. Life Cycle Inventory for Ultra Low Sulfur Diesel and B20 Biodiesel Use for the CAT C18 ACERT Head End Power Engine of the F59PH Locomotives

Fuel	Emission Source	NO_x (g/gal)	HC (g/gal)	CO (g/gal)	PM (g/gal)
ULSD	HEP[a]	93	5.6	53.2	---[c]
	Fuel Cycle (FC)[b]	8	1.0	1.5	0.5
	HEP + FC	101	6.6	54.7	---[c]
B20	HEP[a,d]	87	4.3	42.0	---[c]
	FC[b]	20	3.0	4.0	0.7
	HEP +FC	107	7.3	46.0	---[c]
B20 vs. ULSD	HEP[a,d]	- 6%	- 24%	- 21%	---[c]
	FC[b]	+ 150%	+ 200%	+ 167%	+ 40%
	HEP + FC	+ 6%	+ 11%	- 16%	---[c]

[a] HEP emissions based on the average of rail yard emission rates of the three F59PH HEP engines tested.

[b] (Pang *et al.*, 2009)

[c] Calculation of fuel-based opacity-based PM emission factors not possible under testing setup without voiding engine warranty.

[d] B20 emission factors for the HEPs are estimated based on the ULSD emission factors and percent changes for B20 versus ULSD given in Table 6-1 (NO_x: -6%, HC: -24%, CO: -21%, and PM: -12%).

Overall, taking into account both the prime mover and the HEP engines, a net reduction in CO emissions are expected for using B20 rather than ULSD in a passenger rail locomotive. However, findings for NO_x, HC, and PM are as yet inconclusive and merit further research.

5.5 Summary

In this chapter, the following items were discussed:

- The EPA expects biodiesel use to contribute to reductions in CO, HC, and PM emissions, and a modest increase in NO_x emissions for 4-stroke on-road engines that much smaller than the large 2-stroke locomotive engines.
- Emission rates for use of B20 biodiesel versus petroleum diesel in NCSU in-use testing of on-road and construction vehicles were approximately the same for NO_x, but decreased significantly for CO, HC, and PM.
- There are very few studies in which comparisons have been made for biodiesel versus petroleum diesel in locomotive prime mover engines. The limited available data suggests an average increase of 1 percent for fuel use rate, 4 percent for NO_x emissions, 2 percent for HC, 6 percent for PM. The average change for CO was neglible. However, there is substantial engine-to-engine and test-to-test variability, and thus these results are deemed to be not conclusive.
- Overall, the limited available evidence for 2-stroke locomotive engines indicates that the effect of B20 on emission rates is different from that on smaller 4-stroke engines, and the comparison is not as favorable.
- Although fuel cycle emissions are not negligible, they constitute only a small portion of the total fuel cycle and exhaust emissions. Whether the emissions are higher or lower for a given fuel will be most sensitivity to differences in exhaust emission rates.
- Life cycle inventory analyses of ULSD and B20 biodiesel use in the NC 1792 prime mover engine resulted in decreased CO emissions, but increased HC, NO_x, and PM emissions with B20 biodiesel use compared to ULSD use.
- Life cycle inventory analyses of B20 biodiesel versus ULSD use in the CAT C18 ACERT head end power engines lead to an estimated decrease in CO emissions, but estimated increases in NO_x and HC emissions. The latter are influenced by fuel cycle emissions, which are higher for B20 than for ULSD.
- The results obtained here for only one prime mover engine and an estimate of three HEP engines are not likely to be representative of the entire fleet. More extensive measurements are warranted on a larger number of locomotives, and are planned as part of a separate study.

6.0 CONCLUSIONS

This research study included one-of-a-kind fuel use and emission measurement campaigns on a fleet of passenger locomotives owned and operated by NCDOT. Dynamometer testing is used in emission measurements used for regulatory purposes. However, dynamometer testing can be cost prohibitive. The locomotive engine being tested needs to be removed from revenue service. If the locomotive operator does not have a dynamometer facility on site, which is expensive to build and maintain, then the operator needs to contract the testing to someone else. In this study, fuel use and emissions measurements were made by a PEMS in both the rail yard, where the locomotive was removed from revenue service for a maximum of one day, and over-the-rail while the locomotive was in revenue service.

For the NC 1792, NC 1810, NC 1859, and NC 1869 prime mover engines, fuel use and NO_x, CO_2, CO, HC, and PM emissions data from rail yard and over-the-rail testing were compared to the fuel use and emissions data from dynamometer testing conducted after the engines underwent rebuild. The FSEO from rail yard testing was calibrated, by adjusting the engine volumetric efficiency, to equal the FSEO from dynamometer testing. In the case of NC 1810, rail yard FSEO was calibrated to the dynamometer FSEO of NC 1859. In general, rail yard testing produced similar results to those observed during dynamometer testing. Overall, rail yard testing is a suitable, and less expensive, substitute for dynamometer testing; not for regulatory purposes, but for developing emission factors and as a basis for comparisons of emissions at different stages of the life an engine, including before and after rebuilds.

For NC 1792, rail yard testing was conducted prior to and after engine rebuild in order to assess the fuel use and emissions benefits of engine rebuild. Based on the results, the engine rebuild was effective in reducing fuel use and emissions of CO_2 and NO_x by 5 and 41 percent, respectively. However, factors that reduced NO_x emissions may have also reduced combustion efficiency, thereby leading to an increase in emissions of products of incomplete combustion, including CO, HC, and PM.

Currently, NC 1755 and NC 1797 are undergoing engine rebuild. Once completed, rail yard testing will be conducted as part of a separate project, and results will be compared to the fuel use and emissions data collected in the rail yard prior to engine rebuild.

Testing was conducted over-the-rail on the NCDOT/AMTRAK Piedmont route to estimate real-world fuel use and emissions, and compared to rail yard results. Similar to the rail yard testing, FSEO was calibrated to dynamometer FSEO for the GP40 and F59PH locomotives. NC 1755 over-the-rail FSEO was calibrated to 20.8 bhp-hr/gal. Overall, the over-the-rail fuel use and NO_x and PM emissions were similar to the results from rail yard testing for the F59PH and F59PHI locomotives. Over-the-rail testing could be used instead of removing a locomotive from revenue service and testing it in the rail yard. From the locomotive owner perspective, rail yard and over-the-rail testing imply a commitment to allow access to the locomotives for installing and removing the PEMS, but otherwise do not entail nearly the time commitment and opportunity cost of sending the locomotive to a centralized test facility. Furthermore, the over-the-rail tests provide data on representative duty cycles.

For the GP40, NO_x emissions rates were found to decrease after engine rebuild based on rail yard tests. However, the NO_x emissions rates in over-the-rail measurements were higher after the rebuild. HC emissions were significantly higher in over-the-rail testing compared to rail yard testing. CO emissions were generally higher for over-the-rail testing compared to rail yard testing. The exhaust gas concentrations were higher for NO_x, HC, and CO in the after rebuild over-the-rail tests compared to the before rebuild over-the-rail tests. There was no significant difference in engine output, airbox pressure, intake air temperature, or engine RPM between the two sets of over-the-rail tests. Possibly some operational factor in the engine may have failed or operated differently in the field; however, because the locomotive was subsequently totaled in an at-grade rail crossing accident, it was not possible to further investigate why the NO_x emissions appeared to increase in the over-the-rail measurements.

The duty cycle was observed for travel between Raleigh and Charlotte, NC and compared to the EPA line-haul duty cycle used for regulatory purposes. There were significant differences in actual time spent in idle and Notch 8 compared to the EPA duty cycle. This would lead to significant differences in the total emissions estimation based on the duty cycle used.

Over-the-rail prime mover engine emission rates, the actual Piedmont duty cycles, and ridership data were used to calculate per passenger-mile prime mover emission factors for five selected origin and destination rail station pairs. Rail yard HEP emission rates, the actual Piedmont duty cycles, a typical three car train, and ridership data were used to calculate per passenger-mile HEP emission factors. The combined prime mover and HEP emission factors were compared to the LDGV per passenger-mile emission factors calculated using EPA MOVES for travel between the same five O/D rail station pairs. Overall, rail travel CO_2, and CO per passenger-mile emission factors were less than LDGV per passenger-mile emission factors for the same pollutants. HC emission factors for the F59PH locomotives were greater than the HC emission factors for the LDGV. NO_x and PM per passenger-mile emission factors were higher for rail travel than LDGV travel. The rail-based emission rates are mostly dependent on the prime mover engine, since their emissions are substantially higher than those of the HEP engines.

Travel time has a significant impact on per passenger-mile emission factors. Delays in the train trip lead to increases in total emissions and, therefore, in emissions per passenger mile. The changes in emissions depend in complex ways on differences in duty cycles for trains operating under delays versus those that are on schedule. As an example, we compare a duty cycle in which an F59PH locomotive traveled between Raleigh and Charlotte in 3 hours and 25 minutes, a delay of 10 minutes, versus on-time travel for the same type of locomotive. Even though 10 minutes is only about 5 percent additional travel time, the emission rates of NO_x, HC, CO_2, and PM per passenger-mile increase an average of 16 percent for travel between Raleigh and Charlotte. The HC emission factors increases by 14 percent. The increases in emissions are in part because of the additional travel time and in part because of a change in the distribution of throttle notch positions between the two scenarios. The duty cycle associated with delayed operation had a 6 percentage point increase in the percent time spent in Notch 8 and nearly an 8 percentage point decrease in the percent time spent in idle. To compensate for the delay, the engineers are spending less time in lower throttle notch settings; attempting to get the train back on schedule. As shown in Tables 4-3 through 4-5, time-based emission factors typically increase substantially from idle to Notch 8. Thus, there is a significant environmental incentive to avoid travel delays to the extent possible.

For a trip between Raleigh and Charlotte, the CO_2 emissions produced by 10 cars on the road are equivalent to that produced by 14 people who ride the train. Thus, more people can ride the train for the same total emissions as created on the highway for the same trip. However, ridership on the Piedmont service would have to increase substantially, or locomotive emission rates would need to decrease further, in order for the per passenger-mile NO_x emission rates to be equal for rail and LDGV travel. If LDGV load factor increased to 2 passengers per vehicle, then the LDGV CO_2 per passenger-mile emission rates would be lower than the locomotive CO_2 emission rates. If traffic congestion on the highway was taken into account in these analyses, the comparison of LDGV to locomotive emissions would improve for rail service.

An analysis was conducted to evaluate changes in locomotive fuel use and emission factors based on a change from ULSD to B20 biodiesel. NCSU measured emissions of a 2-stroke EMD 16-645 prime mover engine during a controlled dynamometer engine load test for both B20 biodiesel and ULSD. Based on these measurements, engine exhaust NO_x emissions were found to increase by 15 percent. Furthermore, HC and PM emissions rates increased by 6 and 32 percent, respectively, and CO emissions decreased by 12 percent. The reduction in CO emission rate is expected, since biodiesel is an oxygenated fuel, and increased oxygen availability is expected to reduce emissions of products of incomplete combustion. The other observed differences in emission rates tend to differ from those observed for much smaller 4-stroke engines. From the available literature, there are very few data pertaining to comparison of locomotive prime mover engines for B20 versus ULSD, and the limited available data indicate substantial variability in results. Whether this variability is related to engine-to-engine or test-to-test factors is difficult to discern. Clearly, more data are needed before a clear picture will emerge regarding the effect of biodiesel on average emissions for a locomotive fleet.

Accounting for fuel production, transport, and use by the locomotive in a life cycle inventory, B20 biodiesel use accounts for an 8 percent reduction in the fuel-based CO emission rate for the prime mover engine of the GP40 locomotive. In contrast, B20 biodiesel increases the fuel-based emission rates of HC, NO_x, and PM by 14, 21, and 33 percent, respectively.

The effect of B20 biodiesel on the emissions from HEP engines was estimated based on ULSD emission rates measured for CAT C18 ACERT engines and prior work on other engines from which the relative change in emissions rates were inferred for 4-stroke diesel engines. Based on this analysis, the HEP engine are estimated to have lower exhaust emissions of HC, CO, and PM when operating on B20 biodiesel, and approximately no significant change in NO_x emissions. When fuel cycle emissions are also taken into account, the next reduction in CO emissions is estimated at 16 percent. Even though engine exhaust HC emissions are estimated to decrease by 21percent, or a reduction of 1.3 g/gallon, the fuel cycle HC emissions increase by approximately 2.0 g/gallon, leading to a net increase in total HC emissions for the sum of the fuel cycle and engine exhaust. The net change in NO_x emissions is also predicted to be a small increase. However, empirical data are needed for in-use emission rates of the HEP on B20 biodiesel, and such data are planned for collection in future work under a different project.

This research has demonstrated the application of portable emissions measurement systems (PEMS) to measurements of locomotive prime mover engines operated on a dynamometer, in the rail yard, and during revenue-generating over-the-rail travel. The emission factors obtained from PEMS measurements are comparable to those reported by others. Results from tests on dynamometers and in the rail yard are approximately similar. Over-the-rail measurements lead to trends in fuel use and emission rates that are qualitatively similar to those of the static engine tests (dynamometer and rail yard), but that sometimes differ. Such differences are not unexpected, since real-world operation of the engine is not identical to operations during static load tests. The data obtained in this study demonstrate the effectiveness of engine rebuilds in reducing NO_x emission rates for several locomotives. The newly obtained data enabled a comparison of emissions per passenger-mile between rail and highway travel, illustrating the emissions trade-offs typically found when comparing diesel versus gasoline engines. The comparison demonstrates that train travel is energy efficient and has low emissions of CO and HC, but that there is an ongoing need to reduce NO_x and PM emission rates either through enhanced ridership or adoption of lower emitting locomotive technologies in the future. The potential impact of biofuel usage was evaluated based on literature data and measurements made for B20 versus ULSD for one prime mover engine. There is a need for additional data to support such comparisons, which will be the focus of a separate project. Overall, this work has been successful in demonstrating the applicability of PEMS measurements methods through an intensive series of measurements on six locomotives under a wide variety of operating conditions.

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APPENDIX A

Checklists Used During Locomotive Emissions Testing

In order to insure that the PEMS testing procedure was identical for all locomotives, checklists were used. It was ensured that the PEMS was calibrated prior to each measurement campaign. An installation checklist was used so that all exhaust lines, engine sensors, and PEMS was properly installed on the engine for both rail yard and over-the-rail testing. A rail yard data collection form was used to ensure that the prescribed test schedule was used (amount of time spent at each notch) and that the PEMS was checked routinely for valid emissions and engine variable values. An over-the-rail data collection form was used to note the amount of time it took to travel between rail stations and any interruptions in service (e.g. slow and stop orders). This checklist eased in the calculation of the locomotive duty cycle for each trip. A decommissioning checklist ensured that all test equipment was removed from the locomotive engine and cab.

COMPUTATIONAL LABORATORY FOR ENERGY, AIR, AND RISK
PORTABLE EMISSIONS MEASUREMENT SYSTEM MAINTENANCE LOG

DATE (MM-DD-YYYY)	
RESEARCHER(S)	

PEMS MODEL: ☐ MONTANA ☐ AXION

CALIBRATION

FILE NAME: ____________________

START TIME: ______________ AM / PM

END TIME: ______________ AM / PM

LEAK TEST PERFORMED? ☐ Yes ☐ No

PUMPS INSPECTED, CLEANED? ☐ Yes ☐ No

VERIFICATION

FILE NAME: ____________________

START TIME: ______________ AM / PM

END TIME: ______________ AM / PM

DESCRIPTION OF TEST ROUTE: ______________________________

____

____

NOTES

Any sensor replacement warnings? ☐ Yes ☐ No

If yes, describe: ______________________________

Additional notes: ______________________________

____

____

CERTIFICATION

I certify that I have completed the maintenance on the PEMS as described above.

SIGNATURE ________________________

MUST BE COMPLETED BY THE LAST DAY OF THE MONTH OR PRIOR TO DATA COLLECTION

COMPUTATIONAL LABORATORY FOR ENERGY, AIR, AND RISK
LOCOMOTIVE EMISSIONS TESTING CHECKLIST

LOCOMOTIVE	
RESEARCHER(S)	

Wearing personal protective equipment? ☐ Yes ☐ No

I. ENGINE EXHAUST SAMPLING LINES

- ☐ Install exhaust sampling port on prime mover engine.
- ☐ Install copper tubing to exhaust sampling port.
- ☐ Attach rubber sampling lines to copper tubing.
- ☐ Route sampling lines to location where PEMS unit will be housed.

II. RPM SENSOR

- ☐ Inspect reflective tape on pulley wheel. Attach new reflective tape, if necessary.
- ☐ Install RPM sensor with laser pointed towards reflective tape.
- ☐ Route RPM sensor cable to location where engine sensor array will be housed.

III. MAP SENSOR

- ☐ Replace one air box cover with air box cover retrofitted with MAP sensor port.
- ☐ Attach MAP sensor to MAP sensor port.
- ☐ Connect MAP sensor cable to MAP sensor.
- ☐ Route MAP sensor cable to location where PEMS unit will be housed.

IV. IAT SENSOR

- ☐ Install IAT sensor to appropriate location.
- ☐ Route IAT sensor cable to location where engine sensor array will be housed.

V. ENGINE SENSOR ARRAY

- ☐ Connect RPM sensor cable to engine sensor array.
- ☐ Connect IAT sensor cable to engine sensor array.

DATE ________________ **INSTALLATION**

COMPUTATIONAL LABORATORY FOR ENERGY, AIR, AND RISK
LOCOMOTIVE EMISSIONS TESTING CHECKLIST

VI. GPS SENSOR

- ☐ Install GPS sensor to locomotive roof.
- ☐ Route GPS sensor cable to location where PEMS unit will be housed.

VII. PEMS UNIT

- ☐ Install vibration damping plate to location where PEMS unit will be housed.
- ☐ Route 110V power cable from electricity source to location where PEMS unit will be housed.
- ☐ Connect 12V power converter to 110V power cable.
- ☐ Place PEMS unit on vibration damping plate.
- ☐ Connect PEMS unit power cord to 12V power converter.
- ☐ Connect MAP sensor cable to PEMS unit.
- ☐ Connect engine sensor array to PEMS unit.
- ☐ Connect GPS sensor cable to PEMS unit.
- ☐ Connect engine exhaust sampling lines to PEMS unit.
- ☐ Connect exhaust and zeroing tubes to PEMS unit.
- ☐ Power PEMS unit and verify data acquisition of RPM, MAP, IAT and exhaust concentrations.
- ☐ PM flow meter set to 4 L/min.

VIII. HANDHELD GPS UNITS

- ☐ Recharge batteries to handheld GPS units.

IX. CERTIFICATION

I certify that I have completed the preinstallation of the PEMS unit as described above.

SIGNATURE ______________________________

DATE ____________________ **INSTALLATION**

COMPUTATIONAL LABORATORY FOR ENERGY, AIR, AND RISK

LOCOMOTIVE EMISSIONS TESTING CHECKLIST

LOCOMOTIVE	
RESEARCHER(S)	

Wearing personal protective equipment? ☐ Yes ☐ No

I. EQUIPMENT COLLECTION

- ☐ PEMS unit
- ☐ 12V power converter
- ☐ Engine exhaust sampling lines
- ☐ Air box cover retrofitted with MAP sensor port
- ☐ RPM sensor
- ☐ MAP sensor
- ☐ GPS sensor
- ☐ IAT sensor
- ☐ Sensor box
- ☐ Handheld GPS units

II. CERTIFICATION

I certify that I have collected the above equipment from uninstallation of the PEMS.

SIGNATURE ____________________

DATE ____________________ **DECOMMISSION**

COMPUTATIONAL LABORATORY FOR ENERGY, AIR, AND RISK

RAIL YARD LOCOMOTIVE EMISSIONS TESTING DATA LOG

DATE (MM-DD-YYYY)	
LOCOMOTIVE	
RESEARCHER(S)	

PEMS warm up start time: ____________ Warm up duration: _____ min

Wearing personal protective equipment? ☐ Yes ☐ No

PRIME MOVER ENGINE PEMS File ID

START TIME	THROTTLE POSITION	ENGINE RPM	TEST DURATION
	ENGINE WARM UP		
	NOTCH 8		
	NOTCH 7		
	NOTCH 6		
	NOTCH 5		
	NOTCH 4		
	NOTCH 3		
	NOTCH 2		
	NOTCH 1		
	HIGH IDLE		
	LOW IDLE		

Data downloaded from PEMS? ☐ Yes ☐ No

Preliminary PEMS data QA with PQAS? ☐ Yes ☐ No

Data downloaded from locomotive? ☐ Yes ☐ No

Dr. Frey notified? ☐ Yes ☐ No

Additional notes: ____

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RAIL YARD **PAGE 1 OF 2**

COMPUTATIONAL LABORATORY FOR ENERGY, AIR, AND RISK

RAIL YARD LOCOMOTIVE EMISSIONS TESTING DATA LOG

TEST DATE	
LOCOMOTIVE	
RESEARCHER(S)	

PEMS warm up start time: ____________ Warm up duration: _____ min

Wearing personal protective equipment? ☐ Yes ☐ No

HEP ENGINE PEMS File ID

START TIME	# PASSENGER CARS	ELECTRIC LOAD	TEST DURATION
	ENGINE WARM UP		
	0		
	1		
	2		
	3		
	4		
	5		
	6		
	OTHER:		
	OTHER:		

Data downloaded from PEMS? ☐ Yes ☐ No

Preliminary PEMS data QA with PQAS? ☐ Yes ☐ No

Data downloaded from locomotive? ☐ Yes ☐ No

Dr. Frey notified? ☐ Yes ☐ No

Additional notes: ______________________________________

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RAIL YARD **PAGE 2 OF 2**

COMPUTATIONAL LABORATORY FOR ENERGY AIR AND RISK
Department of Civil, Construction, and Environmental Engineering
NC State University, Campus Box 7908, Raleigh, NC 27695-7908

OVER-THE-RAIL LOCOMOTIVE EMISSIONS TESTING DOCUMENTATION

LOCOMOTIVE	
TEST DATES	

The following forms must be completed and on-file within 24 hours of task completion:

- ☐ PEMS Maintenance Log
- ☐ Installation Checklist
- ☐ Over-the-Rail Testing Data Log for each day
- ☐ Decommission Checklist

SAFETY REQUIREMENTS: All researchers must wear the following personal protective equipment during testing:

- ☐ Safety glasses
- ☐ Earplugs or earmuffs
- ☐ Long pants
- ☐ Steel-toed boots

COMPUTATIONAL LABORATORY FOR ENERGY, AIR, AND RISK

OVER-THE-RAIL LOCOMOTIVE EMISSIONS TESTING DATA LOG

DATE (MM-DD-YYYY)	
LOCOMOTIVE	
ENGINEER	
RESEARCHER(S)	
WEATHER	RGH: GRO: CLT:

PEMS warm up start time: ____________ Warm up duration: _____ min

Wearing personal protective equipment? ☐ Yes ☐ No

GPS unit turned on at rail yard? ☐ Yes ☐ No

GPS unit altimeter calibrated? ☐ Yes ☐ No

PEMS PM flow meter set to 4 L/min? ☐ Yes ☐ No

PIEDMONT TRAIN PEMS File ID

ARRIVAL TIME	RAIL STATION	DEPARTURE TIME
	RALEIGH (RGH)	
	CARY (CYN)	
	DURHAM (DNC)	
	BURLINGTON (BNC)	
	GREENSBORO (GRO)	
	HIGH POINT (HPT)	
	SALISBURY (SAL)	
	KANNAPOLIS (KAN)	
	CHARLOTTE (CLT)	

Notes:____

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OVER-THE-RAIL **PAGE 1 OF 2**

COMPUTATIONAL LABORATORY FOR ENERGY, AIR, AND RISK
OVER-THE-RAIL LOCOMOTIVE EMISSIONS TESTING DATA LOG

DATE (MM-DD-YYYY)	
LOCOMOTIVE	
ENGINEER	
RESEARCHER(S)	
WEATHER	CLT: GRO: RGH:

PEMS PM flow meter set to 4 L/min? ☐ Yes ☐ No

PIEDMONT TRAIN PEMS File ID

ARRIVAL TIME	RAIL STATION	DEPARTURE TIME
	CHARLOTTE (CLT)	
	KANNAPOLIS (KAN)	
	SALISBURY (SAL)	
	HIGH POINT (HPT)	
	GREENSBORO (GRO)	
	BURLINGTON (BNC)	
	DURHAM (DNC)	
	CARY (CYN)	
	RALEIGH (RGH)	

Data downloaded from PEMS? ☐ Yes ☐ No

Preliminary PEMS data QA with PQAS? ☐ Yes ☐ No

Data downloaded from locomotive? ☐ Yes ☐ No

Dr. Frey notified? ☐ Yes ☐ No

Notes:____

OVER-THE-RAIL **PAGE 2 OF 2**

APPENDIX B

Calculation of Fuel Use and Emission Rates

The intake air molar flow rate (M_a) is estimated based on engine data, including engine RPM, manifold absolute pressure (MAP), intake air temperature (IAT), engine displacement, engine compression ratio, and engine volumetric efficiency. This is known as the "speed density" method, and is widely used in vehicle electronic control systems to estimate air flow through and engine. The intake air molar flow rate is calculated as:

$$M_a = \frac{\left(P_M - \frac{P_B}{ER}\right) \times EV \times \left(\frac{ES}{30 \times EC}\right) \times \eta_{ev}}{R \times (T_{int} + 273.15)} \quad \text{(B1)}$$

Where,

EC	=	engine strokes per cycle (assumption: 2 for prime mover engine)
ER	=	engine compression ratio
ES	=	engine speed (RPM)
EV	=	engine displacement (L)
M_a	=	intake air molar flow rate (mole/sec) (assumption: air to be a mixture of 21 vol-% O_2 and 79 vol-% N_2)
P_B	=	barometric pressure (assumption: 101 kPa)
P_M	=	engine manifold absolute pressure (kPa)
T_{int}	=	intake air temperature (°C)
η_{ev}	=	engine volumetric efficiency (assumption: 0.95)

The exhaust molar flow rate on a dry basis (M_e) is estimated based on the intake air molar flow rate (M_a). The relation between M_e and M_a is as follows:

$$M_{e,t} = \frac{2 \times 0.21 \times M_{a,t}}{\left(2+\frac{x}{2}-z\right) y_{CO_2,t,dry} + \left(1+\frac{x}{2}-z\right) y_{CO,t,dry} + 2y_{O_2,t,dry} + y_{NO,t,dry} + (3x-7-6z)\, y_{C_6H_{14},t,dry}} \quad \text{(B2)}$$

Where,

$M_{e,t}$	=	dry exhaust molar flow rate for time *t* (mole/sec)
$y_{i,t,dry}$	=	mole fraction of pollutant species *i* on a dry basis for time *t* (gmol/gmol dry exhaust gases)
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, the PEMS estimates mass emission rates (g/sec) based upon the mole fraction on a dry basis, dry exhaust molar flow rate, and molar weight of exhaust gas as follows:

$$E_{i,t} = y_{i,t,dry} \times M_{e,t} \times MW_i \quad \text{(B3)}$$

Where,

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

Fuel-based emission factors are calculated based on the exhaust gas and fuel composition. 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. 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. Molar ratios of NO to CO_2 and HC to CO_2 are used to estimate the amount of NO and HC, respectively, emitted per gallon of fuel consumed. 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 fraction of carbon emitted as CO_2 is estimated as:

$$f_C = \frac{y_{CO_2}}{y_{CO_2} + y_{CO} + 3\, y_{HC}} \qquad \text{(B4)}$$

Where,

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

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

$$\rho_C = \rho_f\, p_C \qquad \text{(B5)}$$

Where,

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

The fuel-based CO_2 emission factor ($EF_f^{CO_2}$) is:

$$EF^f_{CO_2} = 44\, f_c \left(\frac{\rho_c}{12}\right) \qquad \text{(B6)}$$

The fuel-based NO emission factor (EF_f^{NO}) is:

$$EF^f_{NO_x} = \left(\frac{y_{NO}}{y_{CO_2}}\right)\left(\frac{46}{44}\right) EF^f_{CO_2} \qquad \text{(B7)}$$

The fuel-based CO emission factor (EF_f^{CO}) is:

$$EF^f_{CO} = \left(\frac{y_{CO}}{y_{CO_2}}\right)\left(\frac{28}{44}\right) EF^f_{CO_2} \qquad \text{(B8)}$$

The fuel-based HC emission factor (EF_f^{HC}) is:

$$EF_{HC}^{f} = \left(\frac{y_{HC}}{y_{CO_2}}\right)\left(\frac{42}{44}\right) EF_{CO_2}^{f} \quad \text{(B9)}$$

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 an 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:

$$CH_yO_z + a\,O_2 + 3.76\,a\,N_2 \rightarrow b\,CO_2 + c\,H_2O + d\,N_2 + e\,O_2 \quad \text{(B10)}$$

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):

$$a = \left(\frac{1}{4.76}\right)\left\{b\left[1 + \left(\frac{1 - y_{CO_2}}{y_{CO_2}}\right)\right] + \frac{y}{4} - \frac{z}{2}\right\} \quad \text{(B11)}$$

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:

$$\left(\frac{m_a}{m_f}\right) = \frac{32a + 28\,(3.76)a}{MW_f} = 137.28\,\frac{a}{MW_f} \quad \text{(B12)}$$

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

$$m_f = \frac{454\, \dot{m}_f\, W_s}{3{,}600} \tag{B13}$$

The air flow rate (g/sec) is:

$$m_a = m_f \left(\frac{m_a}{m_f}\right) \tag{B14}$$

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

$$m_e = m_f + m_a \tag{B15}$$

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 B10. 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).

$$M_{e,dry} = (b + d + e)\, \frac{m_f}{MW_f} \tag{B16}$$

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

$$V_{e,dry} = M_{e,dry} \left(\frac{R\,T}{P}\right) \tag{B17}$$

Where,

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

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

$$E^t_{PM} = C^{dry}_{PM}\, V_{e,dry} \tag{B18}$$

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

$$E^f_{PM} = \frac{E^t_{PM}\, \rho_f}{m_f} \tag{B19}$$

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

APPENDIX C

Calculation of Oxygen Concentrations Based on Carbon Dioxide Concentrations

Invalid PEMS O_2 concentrations in the prime mover engine exhaust were observed for the June 27, 2011 testing of NC 1810 and the June 28, 2011 testing of NC 1859. However, exhaust O_2 concentrations can be calculated based on the exhaust CO_2 concentrations.

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

$$CH_yO_z + a\,O_2 + 3.76\,a\,N_2 \rightarrow b\,CO_2 + c\,H_2O + d\,N_2 + e\,O_2 \qquad \text{(C1)}$$

From the fuel properties of diesel, the values of *y* and *z* are known:

y	=	1.889 gmol H / gmol C in fuel
z	=	0 gmol O / gmol C in fuel

From exhaust measurements, the mole fraction of CO_2 (y_{CO_2}), on a dry basis, is known. Thus, the unknowns are:

a	=	gmol inlet O_2 / gmol C in fuel
b	=	gmol CO_2 in exhaust / gmol C in fuel
c	=	gmol H_2O in exhaust / gmol C in fuel
d	=	gmol N_2 in exhaust / gmol C in fuel
e	=	gmol O_2 in exhaust / gmol C in fuel

These can be calculated using a system of equations based on elemental mass balances and the observed mole fraction of CO_2:

Atom Balance for C:	b	=	1 gmol CO_2 in exhaust / gmol C in fuel	
Atom Balance for H:	y	=	$2c$	(C2)
	c	=	$y / 2$	(C3)
	c	=	0.9445 gmol H_2O in exhaust / gmol C in fuel	
Atom Balance for O:	$2a + z$	=	$2b + c + 2e$	(C4)
	a	=	$b + (c / 2) + e - (z / 2)$	(C5)
Atom Balance for N:	$7.52a$	=	$2d$	(C6)
	d	=	$3.76a$	(C7)
Mole Fraction of CO_2:	y_{CO_2}	=	$\frac{b}{b+d+e}$	(C8)
	e	=	$b\left(\frac{1-y_{CO_2}}{y_{CO_2}}\right) - d$	(C9)

Substituting into the equation for *a*:

$$a = \left(\frac{1}{4.76}\right)\left\{b\left[1 + \left(\frac{1-y_{CO_2}}{y_{CO_2}}\right)\right] + \frac{y}{4} - \frac{z}{2}\right\} \tag{C10}$$

Hence, *a* can be solved based on the observed mole fraction for CO_2 on a dry basis.

$$a = \left(\frac{1}{4.76}\right)\left\{\left[1 + \left(\frac{1-y_{CO_2}}{y_{CO_2}}\right)\right] + \frac{1.889}{4}\right\} \tag{C11}$$

Unknowns *d* and *e* can be solved using Equations C7 and C9.

For the June 27, 2011 test of NC 1810:

Notch	***a***	***d***	***e***	**Exhaust CO_2 [%]**	y_{CO_2}
Low Idle	29.69	111.63	28.22	0.71	0.0071
High Idle	11.39	42.84	9.92	1.86	0.0186
1	10.55	39.67	9.08	2.01	0.0201
2	7.29	27.42	5.82	2.92	0.0292
3	5.81	21.84	4.34	3.68	0.0368
4	4.78	17.97	3.31	4.49	0.0449
5	4.23	15.92	2.76	5.08	0.0508
6	3.83	14.40	2.36	5.63	0.0563
7	3.22	12.11	1.75	6.73	0.0673
8	3.05	11.48	1.58	7.11	0.0711

For the June 28, 2011 test of NC 1859:

Notch	***a***	***d***	***e***	**Exhaust CO_2 [%]**	y_{CO_2}
Low Idle	26.69	100.36	25.22	0.79	0.0079
High Idle	15.00	56.40	13.53	1.41	0.0141
1	10.40	39.09	8.93	2.04	0.0204
2	7.50	28.19	6.02	2.84	0.0284
3	5.98	22.50	4.51	3.57	0.0357
4	4.78	17.97	3.31	4.49	0.0449
5	4.25	15.98	2.78	5.06	0.0506
6	4.03	15.14	2.55	5.35	0.0535
7	3.35	12.60	1.88	6.46	0.0646
8	3.35	12.58	1.87	6.47	0.0647

The percentage of O_2 in the exhaust can be calculated as:

$$\frac{(e)(y_{CO_2})}{b} \times 100 \tag{C12}$$

Comparing tests of NC 1810:

Notch	May 23, 2011			June 27, 2011	
	Measured Exhaust CO_2 [%]	**Measured Exhaust O_2 [%]**	**Estimated Exhaust O_2[a] [%]**	**Measured Exhaust CO_2 [%]**	**Estimated Exhaust O_2 [%]**
Low Idle	---	---	---	0.71	20.03
High Idle	2.10	18.20	18.13	1.86	18.45
1	3.03	17.11	16.85	2.01	18.25
2	3.09	16.58	16.77	2.92	17.00
3	3.88	14.43	15.68	3.68	15.96
4	4.75	13.91	14.49	4.49	14.84
5	5.45	13.68	13.53	5.08	14.03
6	5.91	13.22	12.89	5.63	13.28
7	6.05	12.66	12.70	6.73	11.77
8	6.84	11.74	11.62	7.11	11.25

Comparing tests of NC 1859:

Notch	March 8, 2011			June 28, 2011	
	Measured Exhaust CO_2 [%]	**Measured Exhaust O_2 [%]**	**Estimated Exhaust O_2[a] [%]**	**Measured Exhaust CO_2 [%]**	**Estimated Exhaust O_2 [%]**
Low Idle	0.76	19.85	19.96	0.79	19.92
High Idle	0.81	19.72	19.90	1.41	19.07
1	1.99	18.29	18.28	2.04	18.21
2	2.93	16.97	16.99	2.84	17.11
3	3.69	15.99	15.94	3.57	16.11
4	4.36	15.07	15.02	4.49	14.84
5	5.00	14.31	14.14	5.06	14.06
6	5.31	13.79	13.72	5.35	13.66
7	6.61	12.33	11.93	6.46	12.14
8	6.78	12.25	11.70	6.47	12.12

[a] Estimated exhaust O_2 concentrations for tests where exhaust O_2 concentrations were measured (March 8, 2011 and May 23, 2011) are used for comparative purposes only. Measured exhaust O_2 concentrations are used in all emissions and fuel use calculations.

Based on the results from the four locomotive tests, the comparisons of exhaust CO_2 and O_2 concentrations are relatively similar. This suggests that the estimated exhaust O_2 concentrations are valid.

APPENDIX D

Observed Over-the-Rail Duty Cycles

This appendix contains the observed duty cycles for all 41 over-the-rail tests of the NCDOT locomotive fleet. An explanation of any major train delays are also noted for each applicable duty cycle. The tables depict the percent time spent in each notch position.

Date	12/6/2009	12/6/2009	12/7/2009	12/13/2009	12/13/2009	12/14/2009	12/14/2009	4/29/2010	4/29/2010
Locomotive	**NC 1792**	**NC 1792**	**NC 1792**	**NC 1792**	**NC 1792**	**NC 1792**	**NC 1792**	**NC 1792**	**NC 1792**
Train	**73**	**76**	**73**	**73**	**76**	**73**	**76**	**73**	**76**
Idle	26.35	27.81	22.92	25.00	24.06	20.74	25.91	25.26	29.51
Dyn. Brake	18.90	18.83	17.44	20.27	12.84	14.94	17.87	10.50	11.78
1	3.00	1.93	1.99	4.67	9.64	2.60	2.62	5.08	4.12
2	2.15	3.35	6.62	3.10	8.89	7.25	5.78	3.80	4.79
3	3.53	3.14	6.19	3.33	5.57	8.28	5.31	2.26	3.28
4	1.96	3.25	5.55	4.18	5.40	8.20	6.54	3.89	5.66
5	2.55	2.69	2.73	2.89	4.60	3.14	3.06	3.14	2.16
6	3.28	2.22	3.24	2.10	6.65	3.42	2.62	2.66	2.51
7	2.38	3.18	1.68	1.94	2.59	1.36	1.63	2.24	0.77
8	35.90	33.60	31.64	32.53	19.76	30.07	28.67	41.17	35.41
Note									

Date	4/30/2010	4/30/2010	5/1/2010	5/1/2010	6/13/2010	6/13/2010	6/14/2010	6/15/2010
Locomotive	**NC 1792**	**NC 1792**	**NC 1792**	**NC 1792**	**NC 1755**	**NC 1755**	**NC 1755**	**NC 1755**
Train	**73**	**76**	**73**	**76**	**73**	**76**	**73**	**76**
Idle	32.59	29.89	29.58	30.05	25.84	40.89	31.44	33.65
Dyn. Brake	11.30	17.36	13.61	15.64	5.85	4.87	6.90	5.88
1	8.03	8.55	1.85	2.61	9.76	4.15	3.18	2.67
2	4.57	5.05	3.96	4.28	5.77	2.94	1.89	4.30
3	2.20	1.59	2.59	4.07	2.02	1.82	1.58	3.27
4	1.09	2.51	2.37	2.76	1.29	1.60	1.09	2.75
5	0.88	1.58	3.47	2.16	1.18	0.40	1.04	0.88
6	1.21	1.60	2.94	1.56	1.25	1.24	1.64	2.08
7	0.27	0.56	1.57	1.31	1.17	0.20	0.39	0.08
8	37.86	31.31	38.05	35.57	45.87	41.89	50.85	44.45
Note								

Date	4/14/2011	4/14/2011	4/15/2011	4/15/2011	4/16/2011	4/16/2011	5/24/2011	5/24/2011	5/25/2011
Locomotive	**NC 1859**	**NC 1859**	**NC 1859**	**NC 1859**	**NC 1859**	**NC 1859**	**NC 1810**	**NC 1810**	**NC 1810**
Train	**73**	**76**	**73**	**74**	**73**	**74**	**73**	**74**	**73**
Idle	27.97	71.04	36.35	41.91	34.04	44.42	50.39	58.26	40.93
Dyn. Brake	---	---	---	---	---	---	---	---	---
1	1.71	1.14	2.06	4.48	1.12	8.97	9.94	1.27	4.66
2	10.68	1.78	3.36	2.85	9.01	6.28	6.26	2.22	6.40
3	4.47	1.57	2.77	2.23	3.27	5.37	2.95	2.71	2.49
4	4.03	1.18	2.15	2.20	4.29	2.15	1.42	2.19	1.11
5	0.71	1.53	3.34	3.31	0.49	2.75	1.98	1.72	2.29
6	0.40	0.52	3.09	2.35	1.25	1.57	0.92	0.57	1.14
7	0.02	0.08	0.46	0.18	0.07	0.20	0.11	0.07	0.19
8	50.02	23.42	46.43	40.50	46.49	30.70	26.02	30.99	40.78
Note		1				2	3	4	

Date	5/25/2011	5/26/2011	5/26/2011	5/27/2011	5/27/2011	6/7/2011	6/7/2011	6/8/2011	6/8/2011
Locomotive	**NC 1810**	**NC 1810**	**NC 1810**	**NC 1810**	**NC 1810**	**NC 1859**	**NC 1859**	**NC 1859**	**NC 1859**
Train	**74**	**73**	**74**	**73**	**74**	**73**	**74**	**73**	**74**
Idle	35.61	40.60	37.89	37.08	51.06	34.36	30.57	38.77	35.53
Dyn. Brake	---	---	---	---	---	---	---	---	---
1	1.57	10.29	5.74	4.03	10.41	10.47	8.17	8.38	4.62
2	13.44	5.56	10.12	6.64	14.62	5.49	8.16	5.25	9.31
3	4.51	2.41	5.49	3.39	4.15	2.19	6.11	4.81	3.15
4	4.19	0.60	6.90	1.49	2.41	1.54	5.34	3.84	3.42
5	1.57	1.93	4.61	2.67	0.46	2.13	4.32	2.34	1.38
6	0.60	1.61	6.86	2.21	0.22	0.72	8.42	2.52	0.26
7	0.05	0.70	1.46	1.06	0.02	0.10	2.47	0.06	0.34
8	38.45	36.30	20.94	41.41	16.65	42.99	26.43	34.03	42.00
Note					5				

Date	6/9/2011	6/9/2011	6/10/2011	6/10/2011	8/2/2011	8/2/2011
Locomotive	**NC 1859**	**NC 1859**	**NC 1859**	**NC 1859**	**NC 1869**	**NC 1869**
Train	**73**	**74**	**73**	**74**	**75**	**76**
Idle	45.45	31.70	37.60	43.25	36.22	37.43
Dyn. Brake	---	---	---	---	---	---
1	2.63	8.01	7.05	5.80	4.64	7.11
2	2.61	9.89	4.90	2.44	2.35	4.91
3	3.72	4.80	2.22	1.57	3.77	3.44
4	2.13	6.59	1.68	1.13	2.48	2.38
5	1.61	4.61	1.66	1.04	2.82	2.54
6	1.15	7.84	2.61	0.73	2.99	1.34
7	0.09	2.10	0.18	0.29	1.60	0.73
8	40.61	24.45	42.09	43.75	43.14	40.12
Note						

Notes:

1. Train stopped in siding at Superior due to dead AMTRAK Carolinian Train 79 (Total delay: 2 hr, 27 min)
2. Train stopped four times: two signals down, two trees down due to tornado (Total delay: 0 hr, 57 min)
3. Train stopped due to oncoming freight train in emergency (Total delay: 0 hr, 24 min)
4. Train stopped in siding at Superior due to oncoming AMTRAK Piedmont Train 75 (Total delay: 0 hr, 17 min)
5. Train speed restricted to 15 mph due to flash flood warning from Mile Post H18 to H65; crew change at DNC

APPENDIX E

MOVES Input Data for Wake County, NC

The following vehicle type, vehicle age, fuel type, and inspection and maintenance data for Wake County, NC was used in the EPA Motor Vehicle Emissions Simulator (MOVES) model to calculate per passenger-mile emission factors for light duty gasoline vehicles traveling between the five pairs of origin and destination rail stations. Data was obtained from the Division of Air Quality at the North Carolina Department of Environment and Natural Resources.

Vehicle Types

Passenger Cars	57.98% of total passenger vehicles
Passenger Trucks	42.02% of total passenger vehicles

Vehicle Age Distribution

Age	% of Passenger Cars	% of Passenger Trucks
New (0 years old)	5.91	2.99
1 year old	4.40	2.45
2 years old	6.21	6.14
3 years old	7.71	7.99
4 years old	7.41	7.15
5 years old	7.61	5.89
6 years old	7.51	7.03
7 years old	7.11	6.70
8 years old	6.71	5.47
9 years old	6.01	5.65
10 years old	6.11	5.87
11 years old	5.21	5.10
12 years old	4.30	4.29
13 years old	3.60	4.20
14 years old	2.70	2.87
15 years old	2.60	3.04
16 years old	1.90	2.87
17 years old	1.40	1.88
18 years old	1.10	1.44
19 years old	0.80	1.13
20 years old	0.60	1.08
21 years old	0.50	1.28
22 years old	0.40	1.12
23 years old	0.30	0.92
24 years old	0.23	0.78
25 years old	0.17	0.68
26 years old	0.13	0.63

27 years old	0.10	0.35
28 years old	0.07	0.23
29 years old	0.05	0.18
30 years or older	1.16	2.55

Fuel Type

Conventional Gasoline	100% of total passenger vehicles

Meteorology Data

Hourly temperature and relative humidity measurements for every day in 2010 for Wake County, NC

Inspection and Maintenance Data

Emissions standards compliance of during yearly vehicle inspection in Wake County, NC

Passenger Cars with Conventional Gasoline	90.25% compliance
Passenger Trucks with Conventional Gasoline	84.84% compliance