Supporting Information

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

Brandon M. Graver, H. Christopher Frey*, and Jiangchuan Hu
Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Campus Box 7908, Raleigh, NC 27695-7908, Email: frey@ncsu.edu, Phone: (919) 515-1155, Fax: (919) 515-7908

59 pages, 13 tables, 15 figures

The supporting information include: (1) specifications of each locomotive model owned by the North Carolina Department of Transportation (NCDOT); (2) the Piedmont passenger rail service route map; (3) the average observed travel duration between rail stations on the Piedmont; (4) a discussion of the PEMS precision, accuracy, and calibration; (5) photographs of the installation of the PEMS on the prime mover engine (PME); (6) equations used to estimate locomotive fuel use and emission rates; (7) a discussion on the estimation of the PME volumetric efficiency based on dynamometer measurements; (8) notch average rail yard (RY) and over-the-rail (OTR) engine parameters and engine output-based emission rates for each locomotive; (9) cycle average RY and OTR engine output-based emission rates for each locomotive; and (10) lubrication oil analysis results.

Locomotive Specifications

Model Designation F59PH

Number Currently in NCDOT Locomotive Fleet 4

Prime Mover Diesel Engine... EMD

Model 12N-710G3

Type .... Turbocharged

Total Displacement .... 139.6 L (8,520 in^3)

Number of Cylinders...12

Cylinder Arrangement .... 45° "V"

Compression Ratio.. 16:1

Displacement per Cylinder .... 11,635 cm^3 (710 in^3)

Cylinder Bore...230.19 mm (9.06 in)

Cylinder Stroke ....279.4 mm (11.0 in)

Operating Principle ....2 Stroke Cycle

Rotation (Facing Flywheel End)...Counterclockwise

Full Speed ....904 RPM

Normal Idle Speed ....343 RPM

Low Idle Speed ....200 RPM

Weight.. 13,700 kg (30,200 lbs)

Speed and Performance Data

Maximum Speed based on Rated Speed of Traction Motors .... 83 mph

Overspeed Alarm and Penalty Setting .... 80 mph

Tractive Effort (Stall)... 29,300 kg (64,500 lbs)

Tractive Effort (Continuous)... 19,100 kg (42,000 lbs)

Peak Dynamic Brake Effort .... 12,100 kg (26,750 lbs)

Major Dimensions

Maximum Length.. 17.72 m (58 ft, 2 in)

Maximum Width... 3.20 m (10 ft, 6 in)

Maximum Height .... 4.81 m (15 ft, 8.19 in)

Loaded Weight on Rail .... 118,000 kg (260,000 lbs)

Fuel Tank Capacity .... 6,820 to 8,410 L (1,500 to 1,850 gal)

Model Designation F59PHI

Number Currently in NCDOT Locomotive Fleet 2

Prime Mover Diesel Engine........ EMD

Model 12N-710G3B-EC

Type .... Turbocharged

Total Displacement .... 139.6 L (8,520 in^3)

Number of Cylinders........ 12

Cylinder Arrangement .... 45° "V"

Compression Ratio........ 16:1

Displacement per Cylinder .... 11,635 cm^3 (710 in^3)

Cylinder Bore........ 230.19 mm (9.06 in)

Cylinder Stroke .... 279.4 mm (11.0 in)

Operating Principle .... 2 Stroke Cycle

Rotation (Facing Flywheel End)........ Counterclockwise

Full Speed .... 904 RPM

Normal Idle Speed .... 343 RPM

Low Idle Speed .... 200 RPM

Weight........ 13,700 kg (30,200 lbs)

Speed and Performance Data

Maximum Speed based on Rated Speed of Traction Motors .... 110 mph

Overspeed Alarm and Penalty Setting .... 83 mph

Tractive Effort (Stall)... 29,300 kg (64,500 lbs)

Tractive Effort (Continuous)... 19,100 kg (42,000 lbs)

Peak Dynamic Brake Effort .... 12,100 kg (26,750 lbs)

Major Dimensions

Maximum Length.. 17.9 m (58 ft, 7 in)

Maximum Width.. 3.2 m (10 ft, 7.5 in)

Maximum Height.. 4.9 m (15 ft, 11.75 in)

Loaded Weight on Rail .... 124,250 kg (270,000 lbs)

Fuel Tank Capacity..8,200 L (1,800 gal)

Piedmont Route Map and Timetable

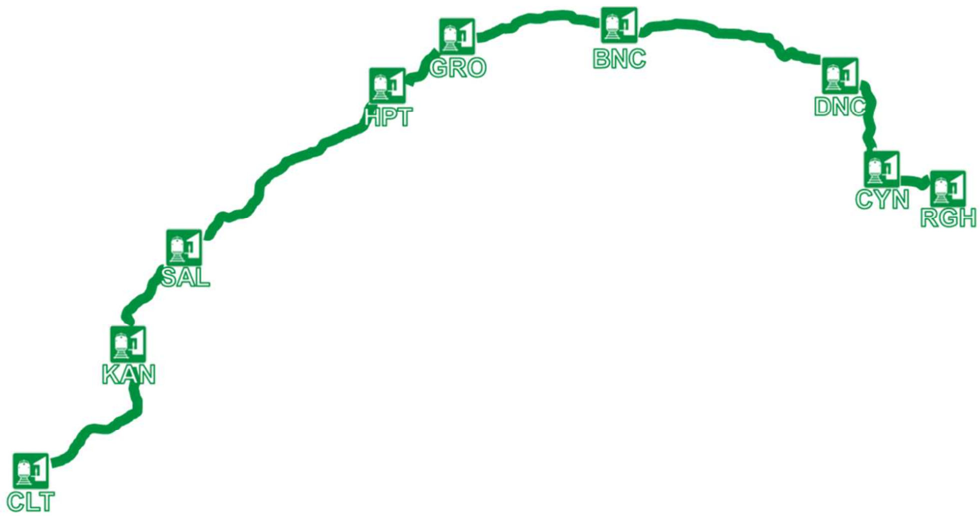


Figure S1. Route map of the North Carolina AMTRAK Piedmont passenger rail service.

Table S1. North Carolina AMTRAK Piedmont Passenger Rail Service Average Observed Duration of Travel between Rail Stations

(a) Southbound Trains

Station	Average Observed Travel Time (min)
Raleigh (RGH)	---
Cary (CYN)	11
Durham (DNC)	21
Burlington (BNC)	40
Greensboro (GRO)	22
High Point (HPT)	20
Salisbury (SAL)	35
Kannapolis (KAN)	17
Charlotte (CLT)	26

(b) Northbound Trains

Station	Average Observed Travel Time (min)
Charlotte (CLT)	---
Kannapolis (KAN)	26
Salisbury (SAL)	16
High Point (HPT)	35
Greensboro (GRO)	17
Burlington (BNC)	24
Durham (DNC)	38
Cary (CYN)	21
Raleigh (RGH)	14

PEMS Precision, Accuracy, and Calibration

The PEMS used here are the OEM-2100 Montana and OEM-2100AX Axion systems, manufactured by Clean Air Technologies International, Inc. These PEMS are comprised of two parallel five-gas analyzers, a particulate matter (PM) measurement system, and engine sensor array, a global positioning system (GPS), and an on-board computer (*1, 2*).

The two parallel gas analyzers simultaneously measure the volume percentage of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitric oxide (NO), and oxygen (O_2) in the vehicle exhaust. HC, CO, and CO_2 are measured using non-dispersive infrared (NDIR). The accuracy for CO and CO_2 are excellent. The accuracy of the HC measurement depends on the type of fuel used (*3, 4*). NO is measured using an electrochemical cell. Nitrogen oxides (NO_X) is typically comprised of approximately 95 volume percent NO; therefore, NO emissions converted to an equivalent NO_2 mass basis (using the molecular weight of NO_2) are a good indicator of total NO_X emissions. NO_X emissions are typically reported as equivalent NO_2. Prior to each set of measurements, the PEMS was calibrated with a California Bureau of Automotive Repair (BAR) certified calibration gas (BAR-97 Low). Each PEMS gas analyzer was re-calibrated using ambient air to "zero" values every 15 minutes on a staggered schedule, so that typically at least one gas analyzer was measuring while the other was "zeroing."

The PEMS reports the mass emission rates estimated using concentration and engine data as detailed elsewhere (*3, 5-6*). The precision of this PEMS is ±25ppm, ±4 ppm, ±0.02%, and ±0.3% for NO, HC, CO and CO_2, respectively (*7*). Comparison of the PEMS with a dynamometer laboratory shows that the Montana system has good precision and accuracy (*3, 8*). For example, the Montana system has been evaluated in the Environmental Technology Verification (ETV) program of the U.S. EPA. In an independent study by Battelle, emissions of several vehicles were measured simultaneously on a laboratory grade dynamometer facility and with the PEMS (*8*). The coefficients of determination (R^2) for the comparison for exceeded 0.86 for all pollutants, indicating good precision. The slopes of the parity plots for CO, CO_2 and NO ranged from 0.92 to 1.05, indicating good accuracy. NDIR is well known to respond only partially to the total loading of hydrocarbon species in the exhaust, because it responds well to alkanes but is less responsive for other types of S-3 compounds, such as aromatics (*9-11*).

Correction factors are used to adjust for biases associated with the PEMS emissions measurement methods. As noted earlier, NO_x is typically comprised of 90 to 95% NO by volume. A correction factor of 1.053 (1/0.95) is used to approximate for total NO_x, based on 95% NO in NO_x. If the actual share of NO in NO_x is slightly lower (e.g., by 5%), the estimate of total NO_x will be slightly low (e.g. by approximately 5%). The overall response to NDIR to a mixture of hydrocarbons in engine exhaust is approximately 23% to 68% of the actual total HC (*10*). A correction factor of 2.5 is used to approximate for total HC. An evaluation of the laser light scattering technique for measuring PM showed as much as an 80% difference in the emission measurement relative to the FRM (*12*). Thus, the PM emission rates are based on a correction factor of 5 to approximate total PM.

PEMS Calibration Accuracy Check Procedure

1. Inspect all portable emissions measurement system (PEMS) pumps for proper vacuum.

2. Clean the non-dispersive infrared (NDIR) chambers for both PEMS benches.

3. Warm up the PEMS for a minimum of sixty (60) minutes.

4. Calibrate both PEMS benches using BAR-97 LOW calibration gas.

5. Once calibration is complete, allow PEMS to run for ten (10) minutes to allow complete purging of system.

6. Run BAR-97 LOW calibration gas through system for two (2) minutes.

7. Allow PEMS to run for ten (10) minutes to allow complete purging of system.

8. Run BAR-97 HIGH calibration gas through system for two (2) minutes.

9. Allow PEMS to run for ten (10) minutes to allow complete purging of system.

10. Calibrate both PEMS benches using BAR-97 HIGH calibration gas.

11. Once calibration is complete, allow PEMS to run for ten (10) minutes to allow complete purging of system.

12. Run BAR-97 HIGH calibration gas through system for two (2) minutes.

13. Allow PEMS to run for ten (10) minutes to allow complete purging of system.

14. Run BAR-97 LOW calibration gas through system for two (2) minutes.

15. Allow PEMS to run for ten (10) minutes to allow complete purging of system.

16. Download the PEMS data and calculate average concentrations of each gas compound during Steps 6, 8, 12, and 14. Calculate the difference in measured average concentrations from calibration gas certification concentrations.

Table S2. PEMS Calibration Accuracy Check Results

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

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

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

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

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

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

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

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

PEMS Installation

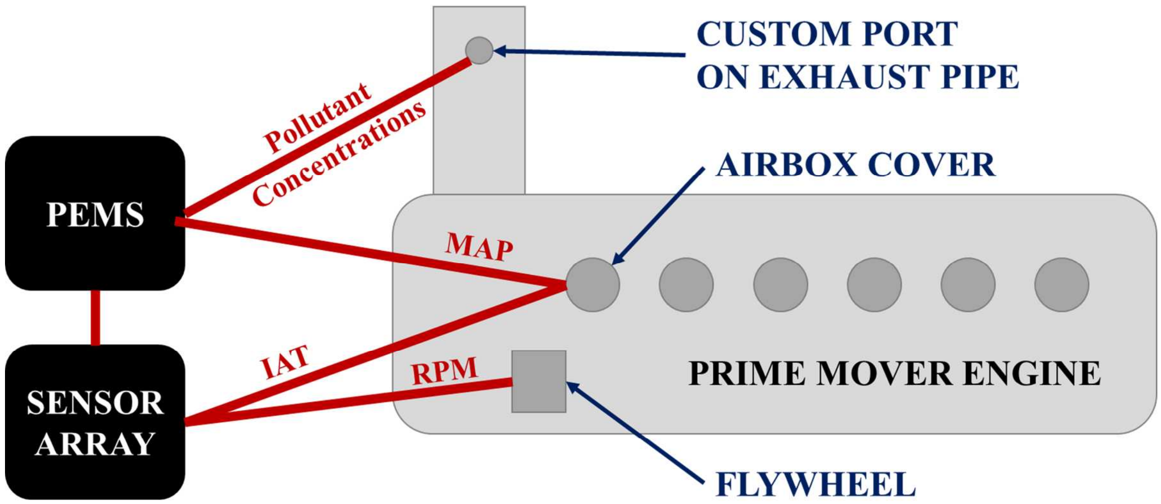


Figure S2. Diagram of PEMS Setup on Locomotive Prime Mover Engine

Figure S3. PEMS Placement for F59PH Locomotive Prime Mover Engine Measurement
(a) inside of the locomotive cab; (b) inside an air conditioned vehicle during extreme heat

Figure S4. 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 S5. Prime Mover Engine Activity Digital Display in F59PH Locomotive Cab

Figure S6. 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 S7. Installation of Sensors on an F59PHI Locomotive Prime Mover Engine
(a) RPM sensor; (b) manifold absolute pressure (MAP) sensor; (c) intake air temperature (IAT) sensor

Figure S8. 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

Estimation of Fuel Use and Emission Rates

Fuel-based emission rates are estimated based on exhaust gas and fuel compositions, independent of fuel flow rate data. This is due to the inability to accurately measure fuel use during rail yard and over-the-rail measurements, since fuel is taken from a large on-board tank and locomotive engines continuously return unspent fuel to the tank. 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 (*13*), and is widely used to estimate air flow through an engine. The intake air molar flow rate is calculated as:

$$M_a = \frac{\left(P_M - \frac{P_B}{ER}\right) \times EV \times \left(\frac{ES}{30 \times EC}\right) \times \eta_{ev}}{R \times (T_{int} + 273.15)} \quad \text{(S1)}$$

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

The exhaust molar flow rate on a dry basis (M_e) is needed to estimate the mass of pollutants in the exhaust, and is estimated based on the intake air molar flow rate (M_a) and the air-to-fuel ratio inferred from the exhaust gas composition. The relation between M_e and M_a is as follows:

$$M_{e,t} = \frac{2 \times 0.21 \times M_{a,t}}{\left(2+\frac{x}{2}-z\right) y_{CO_2,t,dry} + \left(1+\frac{x}{2}-z\right) y_{CO,t,dry} + 2y_{O_2,t,dry} + y_{NO,t,dry} + (3x-7-6z)\, y_{C_6H_{14},t,dry}} \quad \text{(S2)}$$

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:

$$E_{i,t} = y_{i,t,dry} \times M_{e,t} \times MW_i \quad \text{(S3)}$$

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:

$$f_C = \frac{y_{CO_2}}{y_{CO_2} + y_{CO} + 3\, y_{HC}} \tag{S4}$$

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:

$$\rho_C = \rho_f\, p_C \tag{S5}$$

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:

$$EF_{CO_2}^{f} = 44\, f_c \left(\frac{\rho_c}{12}\right) \tag{S6}$$

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

$$EF_{NO_x}^{f} = \left(\frac{y_{NO}}{y_{CO_2}}\right)\left(\frac{46}{44}\right) EF_{CO_2}^{f} \tag{S7}$$

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

$$EF_{CO}^{f} = \left(\frac{y_{CO}}{y_{CO_2}}\right)\left(\frac{28}{44}\right) EF_{CO_2}^{f} \tag{S8}$$

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

$$EF_{HC}^{f} = \left(\frac{y_{HC}}{y_{CO_2}}\right)\left(\frac{42}{44}\right) EF_{CO_2}^{f} \tag{S9}$$

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:

$$CH_yO_z + a\,O_2 + 3.76\,a\,N_2 \rightarrow b\,CO_2 + c\,H_2O + d\,N_2 + e\,O_2 \tag{S10}$$

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	$y_{CO_2} = \dfrac{b}{b+d+e}$	$e = b\left(\dfrac{1 - y_{CO_2}}{y_{CO_2}}\right) - d$

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

$$a = \left(\frac{1}{4.76}\right)\left\{b\left[1 + \left(\frac{1 - y_{CO_2}}{y_{CO_2}}\right)\right] + \frac{y}{4} - \frac{z}{2}\right\} \tag{S11}$$

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:

$$\left(\frac{m_a}{m_f}\right) = \frac{32a + 28\,(3.76)a}{MW_f} = 137.28\,\frac{a}{MW_f} \tag{S12}$$

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

$$m_f = \frac{454\,\dot{m}_f\,W_s}{3{,}600} \tag{S13}$$

The air flow rate (g/sec) is:

$$m_a = m_f\left(\frac{m_a}{m_f}\right) \tag{S14}$$

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

$$m_e = m_f + m_a \quad \text{(S15)}$$

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 S10. 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).

$$M_{e,dry} = (b + d + e)\,\frac{m_f}{MW_f} \quad \text{(S16)}$$

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

$$V_{e,dry} = M_{e,dry}\left(\frac{R\,T}{P}\right) \quad \text{(S17)}$$

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:

$$E_{PM}^{t} = C_{PM}^{dry}\,V_{e,dry} \quad \text{(S18)}$$

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

$$E_{PM}^{f} = \frac{E_{PM}^{t}\,\rho_f}{m_f} \quad \text{(S19)}$$

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

Volumetric Efficiency Estimation

The purpose of this section is to develop a relationship between locomotive prime mover engine parameters during dynamometer measurements and engine volumetric efficiency. Results will be used to estimate engine volumetric efficieny for use in rail yard and over-the-rail measurement analyses.

Dynamometer measurements were conducted on the prime mover engines of locomotives NC 1859 and NC 1869 at the American Motive Power, Inc. (AMP) facility in 2010. The prime mover engines in each locomotive are an EMD 12-710G3B.

The AMP facility contains 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, AMP's facility does not include emissions measurements capabilities. Therefore, a PEMS was used in conjunction with the dynamometer.

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

$$SFC = \frac{\Delta w_{fuel}}{(HP)\left(\frac{\Delta t}{3600}\right)} \quad (1)$$

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

For each prime mover engine, three replicate measurements were made on the water brake dynamometer. After a 45-minute warm-up period of the Axion system main unit and an approximately equal time of engine warm-up, the engine was operated at each throttle notch position for approximately 5 minutes, starting at Notch 8 and working down to Idle. Data for each throttle notch were collected by the PEMS in different bags. Time needed to transition the engine to the next notch position was not included in the PEMS bagging and are excluded from 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.

For each notch position, measurement replicate, and prime mover engine model, the estimated volumetric efficiency was plotted versus a multiplicative function of engine speed and manifold absolute pressure, since the product of these engine parameters are a good indicator of engine power demand, as shown in Figure SI-11 for the EMD 12-710G3B engines. A trendline was fit to derive a model that would describe the relationship between VE, RPM, and MAP. The models used to describe the relationship between VE, RPM, and MAP for the datasets have an R^2 value that exceeds 0.95, indicating that the model explains the variation in data very well. VE has been reported to range up to 1.90 for turbocharged 2-stroke diesel engines (*14*).

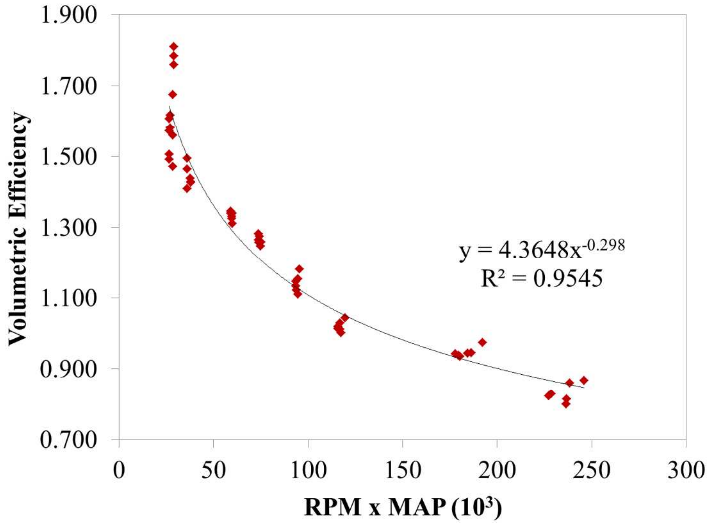


Figure S9. Model for volumetric efficiency based on engine speed and manifold absolute pressure of two EMD 12-710G3B prime mover engines measured on a dynamometer.

Rail Yard Measurement Engine Parameters

Table S3. Measured Notch Average Engine Performance Parameters from Rail Yard Measurement of Prime Mover Engines

(a) NC 1797 – F59PHI Locomotive

Fuel	Notch Position	Engine Output (kW)	Engine Speed (RPM)	IAT (K)	MAP (kPa)
ULSD (3 replicates)	Idle	7	343 (*0.00*)	314 (*0.00*)	107 (*0.01*)
	1	142	343 (*0.00*)	314 (*0.00*)	107 (*0.01*)
	2	261	343 (*0.00*)	313 (*0.01*)	107 (*0.01*)
	3	503	490 (*0.00*)	316 (*0.00*)	122 (*0.01*)
	4	746	651 (*0.00*)	314 (*0.00*)	146 (*0.01*)
	5	969	750 (*0.00*)	319 (*0.00*)	166 (*0.01*)
	6	1,193	750 (*0.00*)	318 (*0.00*)	168 (*0.01*)
	7	1,790	820 (*0.00*)	319 (*0.00*)	207 (*0.00*)
	8	2,013	903 (*0.00*)	321 (*0.00*)	230 (*0.01*)
B10 (3 replicates)	Idle	7	343 (*0.00*)	316 (*0.00*)	105 (*0.01*)
	1	142	343 (*0.00*)	317 (*0.01*)	105 (*0.00*)
	2	261	343 (*0.00*)	315 (*0.01*)	105 (*0.00*)
	3	503	490 (*0.00*)	318 (*0.00*)	119 (*0.01*)
	4	746	651 (*0.00*)	317 (*0.00*)	143 (*0.01*)
	5	969	750 (*0.00*)	321 (*0.01*)	163 (*0.01*)
	6	1,193	750 (*0.00*)	319 (*0.01*)	165 (*0.01*)
	7	1,790	820 (*0.00*)	319 (*0.00*)	204 (*0.01*)
	8	2,013	903 (*0.00*)	320 (*0.01*)	230 (*0.02*)
B20 (3 replicates)	Idle	7	343 (*0.00*)	318 (*0.00*)	104 (*0.00*)
	1	142	343 (*0.00*)	319 (*0.00*)	105 (*0.00*)
	2	261	343 (*0.00*)	319 (*0.00*)	105 (*0.00*)
	3	503	490 (*0.00*)	318 (*0.00*)	119 (*0.00*)
	4	746	651 (*0.00*)	318 (*0.00*)	143 (*0.00*)
	5	969	750 (*0.00*)	321 (*0.00*)	163 (*0.00*)
	6	1,193	750 (*0.00*)	321 (*0.00*)	165 (*0.00*)
	7	1,790	819 (*0.00*)	321 (*0.00*)	205 (*0.02*)
	8	2,013	903 (*0.00*)	322 (*0.01*)	224 (*0.01*)
B40 (3 replicates)	Idle	7	343 (*0.00*)	316 (*0.00*)	105 (*0.00*)
	1	142	343 (*0.00*)	316 (*0.00*)	105 (*0.00*)
	2	261	343 (*0.00*)	316 (*0.00*)	105 (*0.00*)
	3	503	490 (*0.00*)	317 (*0.00*)	119 (*0.00*)
	4	746	651 (*0.00*)	319 (*0.00*)	143 (*0.00*)
	5	969	750 (*0.00*)	322 (*0.00*)	163 (*0.00*)
	6	1,193	750 (*0.00*)	321 (*0.00*)	164 (*0.00*)
	7	1,790	820 (*0.00*)	322 (*0.00*)	203 (*0.00*)
	8	2,013	903 (*0.00*)	323 (*0.00*)	215 (*0.00*)

(b) NC 1810 – F59PH Locomotive

Fuel	Notch Position	Engine Output (kW)	Engine Speed (RPM)	IAT (K)	MAP (kPa)
ULSD (3 replicates)	Low Idle	7	238 (*0.00*)	331 (*0.00*)	101 (*0.00*)
	High Idle	7	386 (*0.02*)	341 (*0.00*)	110 (*0.01*)
	1	142	382 (*0.00*)	333 (*0.00*)	110 (*0.00*)
	2	261	382 (*0.00*)	335 (*0.00*)	110 (*0.00*)
	3	503	491 (*0.00*)	339 (*0.00*)	121 (*0.00*)
	4	746	566 (*0.00*)	340 (*0.00*)	132 (*0.00*)
	5	969	652 (*0.00*)	339 (*0.00*)	146 (*0.00*)
	6	1,193	729 (*0.00*)	341 (*0.00*)	162 (*0.00*)
	7	1,790	821 (*0.00*)	344 (*0.01*)	208 (*0.03*)
	8	2,013	906 (*0.00*)	346 (*0.00*)	237 (*0.00*)
B10 (1 replicate)	Low Idle	7	205	338	103
	High Idle	7	352	344	111
	1	142	352	342	111
	2	261	352	343	111
	3	503	496	346	125
	4	746	572	348	135
	5	969	654	348	148
	6	1,193	731	350	164
	7	1,790	827	353	212
	8	2,013	908	353	236
B20 (1 replicate)	Low Idle	7	207	330	103
	High Idle	7	353	342	112
	1	142	353	337	112
	2	261	353	339	112
	3	503	497	343	126
	4	746	573	345	137
	5	969	655	344	151
	6	1,193	732	346	167
	7	1,790	828	351	215
	8	2,013	909	349	236
B40 (3 replicates)	Low Idle	7	203 (*0.01*)	337 (*0.00*)	103 (*0.00*)
	High Idle	7	352 (*0.00*)	344 (*0.00*)	111 (*0.01*)
	1	142	351 (*0.00*)	339 (*0.00*)	111 (*0.00*)
	2	261	351 (*0.00*)	344 (*0.01*)	111 (*0.01*)
	3	503	496 (*0.00*)	347 (*0.01*)	124 (*0.00*)
	4	746	572 (*0.00*)	349 (*0.01*)	134 (*0.00*)
	5	969	653 (*0.00*)	348 (*0.01*)	147 (*0.00*)
	6	1,193	731 (*0.00*)	348 (*0.00*)	162 (*0.00*)
	7	1,790	826 (*0.00*)	350 (*0.00*)	187 (*0.02*)
	8	2,013	908 (*0.00*)	352 (*0.00*)	227 (*0.01*)

Fuel	Notch Position	Engine Output (kW)	Engine Speed (RPM)	IAT (K)	MAP (kPa)
B60 (5 replicates)	Low Idle	7	198 (*0.01*)	331 (*0.00*)	99 (*0.00*)
	High Idle	7	339 (*0.00*)	340 (*0.00*)	107 (*0.00*)
	1	142	339 (*0.00*)	333 (*0.00*)	106 (*0.00*)
	2	261	339 (*0.00*)	337 (*0.00*)	107 (*0.00*)
	3	503	488 (*0.00*)	340 (*0.00*)	120 (*0.00*)
	4	746	561 (*0.00*)	341 (*0.00*)	130 (*0.00*)
	5	969	650 (*0.00*)	340 (*0.01*)	144 (*0.00*)
	6	1,193	728 (*0.00*)	342 (*0.00*)	160 (*0.00*)
	7	1,790	821 (*0.00*)	345 (*0.00*)	189 (*0.03*)
	8	2,013	901 (*0.00*)	346 (*0.01*)	227 (*0.01*)
B80 (3 replicates)	Low Idle	7	197 (*0.00*)	333 (*0.00*)	101 (*0.00*)
	High Idle	7	339 (*0.00*)	343 (*0.01*)	108 (*0.00*)
	1	142	339 (*0.00*)	338 (*0.00*)	108 (*0.00*)
	2	261	339 (*0.00*)	341 (*0.00*)	108 (*0.00*)
	3	503	488 (*0.00*)	344 (*0.00*)	122 (*0.00*)
	4	746	563 (*0.00*)	346 (*0.00*)	131 (*0.00*)
	5	969	651 (*0.00*)	345 (*0.00*)	145 (*0.00*)
	6	1,193	728 (*0.00*)	346 (*0.00*)	160 (*0.00*)
	7	1,790	821 (*0.00*)	349 (*0.00*)	183 (*0.00*)
	8	2,013	901 (*0.00*)	349 (*0.00*)	223 (*0.01*)
B100 (3 replicates)	Low Idle	7	199 (*0.00*)	327 (*0.00*)	101 (*0.00*)
	High Idle	7	339 (*0.00*)	339 (*0.00*)	109 (*0.00*)
	1	142	339 (*0.00*)	330 (*0.00*)	109 (*0.00*)
	2	261	339 (*0.00*)	334 (*0.00*)	109 (*0.00*)
	3	503	489 (*0.00*)	338 (*0.00*)	124 (*0.00*)
	4	746	562 (*0.00*)	340 (*0.00*)	134 (*0.00*)
	5	969	651 (*0.00*)	339 (*0.00*)	150 (*0.00*)
	6	1,193	728 (*0.00*)	341 (*0.00*)	166 (*0.00*)
	7	1,790	821 (*0.00*)	347 (*0.01*)	215 (*0.03*)
	8	2,013	901 (*0.00*)	346 (*0.01*)	239 (*0.01*)

(c) NC 1859 – F59PH Locomotive

Fuel	Notch Position	Engine Output (kW)	Engine Speed (RPM)	IAT (K)	MAP (kPa)
ULSD (3 replicates)	Low Idle	7	238 (*0.00*)	335 (*0.01*)	100 (*0.00*)
	High Idle	7	370 (*0.00*)	346 (*0.00*)	108 (*0.00*)
	1	142	370 (*0.00*)	340 (*0.00*)	108 (*0.00*)
	2	261	370 (*0.00*)	342 (*0.00*)	109 (*0.00*)
	3	503	492 (*0.00*)	345 (*0.00*)	120 (*0.00*)
	4	746	565 (*0.00*)	346 (*0.00*)	129 (*0.01*)
	5	969	653 (*0.00*)	345 (*0.00*)	143 (*0.01*)
	6	1,193	731 (*0.00*)	348 (*0.00*)	158 (*0.01*)
	7	1,790	822 (*0.00*)	349 (*0.00*)	181 (*0.02*)
	8	2,013	904 (*0.00*)	351 (*0.00*)	228 (*0.01*)
B10 (3 replicates)	Low Idle	7	238 (*0.00*)	333 (*0.00*)	102 (*0.00*)
	High Idle	7	371 (*0.00*)	340 (*0.00*)	111 (*0.00*)
	1	142	370 (*0.00*)	334 (*0.00*)	111 (*0.00*)
	2	261	370 (*0.00*)	337 (*0.00*)	111 (*0.00*)
	3	503	493 (*0.00*)	339 (*0.00*)	124 (*0.00*)
	4	746	565 (*0.00*)	340 (*0.00*)	134 (*0.00*)
	5	969	653 (*0.00*)	339 (*0.00*)	149 (*0.00*)
	6	1,193	731 (*0.00*)	340 (*0.00*)	165 (*0.00*)
	7	1,790	822 (*0.00*)	344 (*0.00*)	208 (*0.01*)
	8	2,013	904 (*0.00*)	344 (*0.00*)	234 (*0.00*)
B20 (3 replicates)	Low Idle	7	238 (*0.00*)	333 (*0.00*)	100 (*0.00*)
	High Idle	7	371 (*0.00*)	343 (*0.00*)	109 (*0.00*)
	1	142	370 (*0.00*)	333 (*0.00*)	109 (*0.00*)
	2	261	370 (*0.00*)	336 (*0.00*)	109 (*0.00*)
	3	503	493 (*0.00*)	340 (*0.00*)	122 (*0.00*)
	4	746	565 (*0.00*)	342 (*0.00*)	132 (*0.00*)
	5	969	652 (*0.00*)	341 (*0.00*)	146 (*0.00*)
	6	1,193	729 (*0.00*)	343 (*0.00*)	163 (*0.00*)
	7	1,790	821 (*0.00*)	345 (*0.01*)	205 (*0.00*)
	8	2,013	904 (*0.00*)	345 (*0.00*)	233 (*0.00*)
B40 (3 replicates)	Low Idle	7	239 (*0.00*)	327 (*0.01*)	101 (*0.01*)
	High Idle	7	371 (*0.00*)	340 (*0.00*)	109 (*0.01*)
	1	142	370 (*0.00*)	330 (*0.00*)	109 (*0.01*)
	2	261	370 (*0.00*)	334 (*0.01*)	110 (*0.01*)
	3	503	492 (*0.00*)	337 (*0.00*)	122 (*0.00*)
	4	746	565 (*0.00*)	340 (*0.00*)	131 (*0.01*)
	5	969	653 (*0.00*)	337 (*0.00*)	146 (*0.01*)
	6	1,193	730 (*0.00*)	340 (*0.01*)	162 (*0.01*)
	7	1,790	822 (*0.00*)	344 (*0.00*)	191 (*0.02*)
	8	2,013	904 (*0.00*)	345 (*0.01*)	229 (*0.01*)

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

Rail Yard Measurement Emission Rates

Correction factors are used to adjust for biases associated with the PEMS emissions measurement methods for NO_x, HC, and PM (*15*). NO_x includes NO and NO_2. Only NO was measured. The overall response to NDIR to a mixture of hydrocarbons in engine exhaust is less than the actual total HC (*13, 16*). The cycle average NO_x/NO ratio and FID/NDIR ratio for HC were evaluated for the same locomotives measured here using a SEMTECH-DS PEMS (*10*). RY measurements were made with the Axion as well as a SEMTECH-DS PEMS that measures both NO and NO_2 and that measures HC with both NDIR and FID using a heated sample line. The NO_x/NO ratio for each notch position of each locomotive for various fuels were estimated from the SEMTECH-measured exhaust concentrations of NO and NO_2. The NO_x/NO ratios were used as the NO_x bias correction factor. The FID/NDIR ratio for HC was also estimated as a ratio of the HC exhaust concentrations measured by the SEMTECH for FID versus NDIR. The FID/NDIR ratios for each fuel, locomotive, and notch position were used as the HC bias correction factor. The NO_x/NO and FID/NDIR ratios are included below in Tables S4 and S5.

The trends in the data are significant and repeatable for NO_x, PM, and CO_2, based on the CVs shown below in Table S6 (for RY measurements). The trends in the emission rates for HC and CO are less significant and have more imprecision, given that a majority of the concentrations of these pollutants were at or below the detection limit of the PEMS. Since diesel engines typically emit relatively low CO and HC emission rates, it is not surprising that these engines also have relatively low CO and HC emission rates. In this regard, we have confidence in all of these data. An instrument with lower HC and CO detection limits would increase the precision of the HC and CO emission rate estimates but would not change the basic insight that these emissions are relatively low.

Table S4. NO_x Bias Correction Factors based on SEMTECH Measurements

(a) ULSD

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

(b) B10

<table>
<tr><th>Notch Position</th><th>NC 1797</th><th>NC 1810</th><th>NC 1859</th></tr>
<tr><td>Idle</td><td>1.082</td><td rowspan="10">No SEMTECH Measurements

Using NC 1859 Correction Factors</td><td>1.116</td></tr>
<tr><td>Dynamic Brake*</td><td>1.082</td><td>1.116</td></tr>
<tr><td>1</td><td>1.086</td><td>1.101</td></tr>
<tr><td>2</td><td>1.074</td><td>1.072</td></tr>
<tr><td>3</td><td>1.067</td><td>1.065</td></tr>
<tr><td>4</td><td>1.070</td><td>1.060</td></tr>
<tr><td>5</td><td>1.072</td><td>1.060</td></tr>
<tr><td>6</td><td>1.064</td><td>1.057</td></tr>
<tr><td>7</td><td>1.056</td><td>1.061</td></tr>
<tr><td>8</td><td>1.067</td><td>1.083</td></tr>
</table>

(c) B20

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

(d) B40

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

(e) B60

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

(f) B80

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

(g) B100

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

Table S5. NO_x Bias Correction Factors based on Ambient Temperature and Humidity

(a) NC 1797

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

(b) NC 1810

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

(c) NC 1859

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

NO_x correction factors were estimated for each day of OTR measurements using the following equations from Lindhjem *et al*. (*16*):

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

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

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

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

T = ambient temperature, °C

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

Table S6. HC Bias Correction Factors for Rail Yard Emission Rates based on SEMTECH and Axion Measurements

(a) ULSD

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

(b) B10

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

(c) B20

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

(d) B40

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

(e) B60

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

(f) B80

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

(g) B100

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

Table S7. Time-Based Notch Average Emission Rates from Rail Yard Measurement of Prime Mover Engines

(a) NC 1797 – F59PHI Locomotive

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
ULSD (3 replicates)	Idle	0.31 (*0.11*)	0.18 (*0.21*)	0.02 (*0.69*)	0.01 (*0.06*)	8.73 (*0.14*)
	1	0.81 (*0.09*)	0.06 (*0.68*)	0.02 (*0.90*)	0.02 (*0.03*)	29.0 (*0.05*)
	2	1.39 (*0.04*)	0.07 (*0.77*)	0.02 (*0.56*)	0.02 (*0.04*)	43.9 (*0.05*)
	3	1.90 (*0.01*)	0.06 (*0.25*)	0.01 (*1.24*)	0.02 (*0.03*)	79.4 (*0.01*)
	4	2.28 (*0.01*)	0.08 (*0.36*)	0.01 (*1.48*)	0.02 (*0.04*)	123 (*0.00*)
	5	3.18 (*0.02*)	0.11 (*0.14*)	0.00 (*1.23*)	0.03 (*0.03*)	167 (*0.01*)
	6	3.67 (*0.06*)	0.70 (*0.77*)	0.00 (*1.63*)	0.03 (*0.02*)	198 (*0.06*)
	7	4.57 (*0.00*)	0.35 (*0.33*)	0.06 (*0.57*)	0.12 (*0.02*)	324 (*0.02*)
	8	6.13 (*0.01*)	1.14 (*0.93*)	0.74 (*0.17*)	0.15 (*0.06*)	420 (*0.01*)
B10 (3 replicates)	Idle	0.43 (*0.01*)	0.86 (*0.62*)	0.06 (*0.44*)	0.01 (*0.09*)	13.5 (*0.01*)
	1	1.10 (*0.02*)	0.27 (*0.54*)	0.05 (*0.16*)	0.01 (*0.04*)	35.4 (*0.01*)
	2	1.91 (*0.03*)	0.40 (*0.37*)	0.07 (*0.41*)	0.01 (*0.03*)	53.9 (*0.01*)
	3	2.43 (*0.02*)	0.45 (*0.16*)	0.09 (*0.22*)	0.02 (*0.01*)	92.5 (*0.01*)
	4	2.86 (*0.03*)	0.62 (*0.35*)	0.16 (*0.57*)	0.03 (*0.03*)	140 (*0.00*)
	5	3.89 (*0.04*)	0.59 (*0.46*)	0.10 (*0.09*)	0.03 (*0.02*)	180 (*0.01*)
	6	4.55 (*0.01*)	0.75 (*0.36*)	0.11 (*0.92*)	0.03 (*0.01*)	219 (*0.02*)
	7	5.31 (*0.02*)	1.63 (*0.15*)	0.14 (*0.94*)	0.13 (*0.05*)	356 (*0.01*)
	8	7.36 (*0.02*)	3.55 (*0.16*)	0.55 (*0.19*)	0.18 (*0.12*)	433 (*0.00*)
B20 (3 replicates)	Idle	0.42 (*0.25*)	0.78 (*0.19*)	0.07 (*0.70*)	0.01 (*0.02*)	11.4 (*0.21*)
	1	0.95 (*0.04*)	0.30 (*0.13*)	0.01 (*1.36*)	0.01 (*0.04*)	26.0 (*0.09*)
	2	1.73 (*0.03*)	0.38 (*0.21*)	0.01 (*0.87*)	0.01 (*0.01*)	41.5 (*0.08*)
	3	2.20 (*0.03*)	0.54 (*0.21*)	0.01 (*0.98*)	0.02 (*0.02*)	71.1 (*0.06*)
	4	2.54 (*0.02*)	0.84 (*0.07*)	0.01 (*1.73*)	0.02 (*0.02*)	115 (*0.06*)
	5	3.55 (*0.01*)	0.49 (*0.58*)	0.00 (*n/a*)	0.02 (*0.02*)	146 (*0.00*)
	6	4.15 (*0.02*)	0.88 (*0.32*)	0.04 (*0.96*)	0.02 (*0.01*)	193 (*0.02*)
	7	5.09 (*0.04*)	0.87 (*0.92*)	0.13 (*0.97*)	0.10 (*0.06*)	311 (*0.01*)
	8	7.34 (*0.03*)	4.85 (*0.32*)	0.60 (*0.25*)	0.11 (*0.07*)	398 (*0.09*)

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

(b) NC 1810 – F59PH Locomotive

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
ULSD (3 replicates)	Low Idle	0.13 (*0.08*)	1.30 (*0.06*)	0.08 (*0.24*)	0.01 (*0.06*)	7.75 (*0.07*)
	High Idle	0.17 (*0.05*)	1.82 (*0.03*)	0.09 (*0.24*)	0.01 (*0.11*)	14.4 (*0.04*)
	1	0.36 (*0.05*)	1.21 (*0.08*)	0.06 (*0.37*)	0.01 (*0.01*)	31.6 (*0.03*)
	2	0.64 (*0.04*)	1.01 (*0.10*)	0.07 (*0.44*)	0.02 (*0.02*)	47.9 (*0.03*)
	3	1.21 (*0.01*)	1.23 (*0.16*)	0.07 (*0.33*)	0.03 (*0.01*)	85.6 (*0.01*)
	4	1.64 (*0.01*)	1.10 (*0.12*)	0.09 (*0.70*)	0.05 (*0.03*)	127 (*0.01*)
	5	2.03 (*0.02*)	0.84 (*0.10*)	0.08 (*0.67*)	0.06 (*0.03*)	170 (*0.01*)
	6	2.43 (*0.01*)	2.00 (*0.16*)	0.12 (*0.91*)	0.07 (*0.00*)	209 (*0.01*)
	7	3.02 (*0.04*)	2.66 (*0.46*)	0.72 (*0.33*)	0.22 (*0.11*)	317 (*0.02*)
	8	3.35 (*0.01*)	2.50 (*0.26*)	0.98 (*0.06*)	0.28 (*0.15*)	391 (*0.01*)
B10 (1 replicate)	Low Idle	0.16	0.16	0.01	0.01	7.98
	High Idle	0.24	0.12	0.01	0.01	14.8
	1	0.51	0.11	0.04	0.02	31.6
	2	0.88	0.12	0.04	0.03	48.6
	3	1.59	0.13	0.04	0.04	85.3
	4	2.17	0.04	0.11	0.06	127
	5	2.54	0.00	0.13	0.09	170
	6	3.04	0.01	0.12	0.11	204
	7	3.75	0.23	0.88	0.17	316
	8	3.78	0.09	1.40	0.26	416

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

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

(c) NC 1859 – F59PH Locomotive

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
ULSD (3 replicates)	Low Idle	0.17 (*0.02*)	0.23 (*0.26*)	0.07 (*0.29*)	0.02 (*0.04*)	9.20 (*0.02*)
	High Idle	0.20 (*0.00*)	1.42 (*0.37*)	0.73 (*0.46*)	0.02 (*0.02*)	13.8 (*0.02*)
	1	0.45 (*0.02*)	0.47 (*0.15*)	0.10 (*0.31*)	0.03 (*0.02*)	35.5 (*0.01*)
	2	0.79 (*0.04*)	0.78 (*0.08*)	0.16 (*0.04*)	0.03 (*0.01*)	53.7 (*0.01*)
	3	1.42 (*0.03*)	1.25 (*0.08*)	0.27 (*0.09*)	0.05 (*0.02*)	93.7 (*0.00*)
	4	1.84 (*0.02*)	1.56 (*0.18*)	0.41 (*0.34*)	0.07 (*0.02*)	126 (*0.03*)
	5	2.25 (*0.03*)	0.91 (*0.87*)	0.23 (*0.91*)	0.09 (*0.02*)	171 (*0.01*)
	6	2.78 (*0.06*)	0.00 (*n/a*)	0.30 (*0.25*)	0.13 (*0.02*)	226 (*0.02*)
	7	3.23 (*0.09*)	2.01 (*1.12*)	1.36 (*0.85*)	0.21 (*0.05*)	304 (*0.03*)
	8	3.79 (*0.04*)	2.99 (*0.13*)	1.50 (*0.04*)	0.28 (*0.02*)	392 (*0.00*)
B10 (3 replicates)	Low Idle	0.15 (*0.04*)	0.22 (*0.55*)	0.05 (*0.56*)	0.01 (*0.05*)	9.07 (*0.03*)
	High Idle	0.19 (*0.05*)	0.36 (*0.14*)	0.09 (*0.25*)	0.02 (*0.10*)	14.7 (*0.01*)
	1	0.44 (*0.06*)	0.11 (*0.54*)	0.04 (*0.46*)	0.01 (*0.02*)	35.8 (*0.01*)
	2	0.77 (*0.06*)	0.09 (*0.40*)	0.03 (*0.66*)	0.02 (*0.01*)	53.2 (*0.01*)
	3	1.40 (*0.05*)	0.09 (*0.67*)	0.02 (*0.00*)	0.02 (*0.01*)	91.8 (*0.00*)
	4	1.89 (*0.06*)	0.07 (*0.40*)	0.01 (*0.87*)	0.03 (*0.07*)	130 (*0.00*)
	5	2.38 (*0.04*)	0.09 (*0.47*)	0.02 (*0.00*)	0.04 (*0.03*)	173 (*0.00*)
	6	2.82 (*0.04*)	0.16 (*0.07*)	0.03 (*0.00*)	0.04 (*0.05*)	212 (*0.00*)
	7	3.64 (*0.04*)	0.19 (*0.34*)	0.15 (*0.27*)	0.10 (*0.06*)	310 (*0.00*)
	8	3.93 (*0.03*)	0.09 (*0.33*)	0.22 (*0.51*)	0.18 (*0.22*)	372 (*0.00*)
B20 (3 replicates)	Low Idle	0.13 (*0.05*)	0.32 (*0.46*)	0.07 (*0.46*)	0.01 (*0.04*)	7.55 (*0.13*)
	High Idle	0.17 (*0.06*)	0.47 (*0.14*)	0.09 (*0.21*)	0.01 (*0.09*)	12.9 (*0.14*)
	1	0.40 (*0.03*)	0.33 (*0.37*)	0.08 (*0.43*)	0.02 (*0.03*)	30.8 (*0.02*)
	2	0.71 (*0.02*)	0.41 (*0.30*)	0.09 (*0.28*)	0.02 (*0.04*)	46.7 (*0.04*)
	3	1.30 (*0.02*)	0.53 (*0.30*)	0.09 (*0.43*)	0.03 (*0.03*)	80.8 (*0.03*)
	4	1.76 (*0.02*)	0.57 (*0.40*)	0.09 (*0.44*)	0.04 (*0.02*)	118 (*0.02*)
	5	2.23 (*0.02*)	0.36 (*0.40*)	0.02 (*0.87*)	0.05 (*0.03*)	158 (*0.01*)
	6	2.65 (*0.03*)	0.96 (*0.38*)	0.09 (*0.88*)	0.06 (*0.01*)	194 (*0.01*)
	7	3.46 (*0.03*)	2.12 (*0.40*)	0.27 (*0.77*)	0.12 (*0.02*)	286 (*0.01*)
	8	3.66 (*0.04*)	0.27 (*0.63*)	0.22 (*0.20*)	0.16 (*0.15*)	374 (*0.03*)

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
B40 (3 replicates)	Low Idle	0.19 (*0.05*)	0.23 (*0.19*)	0.08 (*0.07*)	0.01 (*0.09*)	7.79 (*0.06*)
	High Idle	0.23 (*0.02*)	0.31 (*0.29*)	0.15 (*0.47*)	0.01 (*0.16*)	12.6 (*0.09*)
	1	0.56 (*0.03*)	0.07 (*0.47*)	0.11 (*0.35*)	0.02 (*0.04*)	34.1 (*0.01*)
	2	0.98 (*0.02*)	0.06 (*0.33*)	0.10 (*0.30*)	0.02 (*0.02*)	49.9 (*0.02*)
	3	1.78 (*0.03*)	0.07 (*0.30*)	0.11 (*0.33*)	0.03 (*0.02*)	88.0 (*0.01*)
	4	2.28 (*0.01*)	0.06 (*0.23*)	0.11 (*0.49*)	0.04 (*0.06*)	119 (*0.03*)
	5	2.91 (*0.02*)	0.06 (*0.89*)	0.09 (*0.18*)	0.05 (*0.06*)	163 (*0.02*)
	6	3.45 (*0.06*)	0.59 (*1.12*)	0.18 (*0.27*)	0.06 (*0.01*)	199 (*0.04*)
	7	4.35 (*0.03*)	0.48 (*0.66*)	0.35 (*0.15*)	0.11 (*0.05*)	294 (*0.03*)
	8	4.89 (*0.04*)	0.22 (*0.34*)	0.45 (*0.25*)	0.15 (*0.08*)	386 (*0.02*)

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

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

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

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

Table S8. Weights Used to Estimate Time-Based Fleet Average Emission Rates

Fuel	Locomotive	Rail Yard		Over-the-Rail	
		Number of Measurements	Weighting of Each Measurement[a]	Number of Measurements	Weighting of Each Measurement[a]
ULSD	NC 1797	3	1/9	6	1/18
	NC 1810	3	1/9	6	1/18
	NC 1859	3	1/9	6	1/18
B10	NC 1797	3	1/9	6	1/18
	NC 1810	1	1/3	6	1/18
	NC 1859	3	1/9	6	1/18
B20	NC 1797	3	1/9	5	1/15
	NC 1810	1	1/3	6	1/18
	NC 1859	3	1/9	15 *PM: 9*[b]	1/45 *PM: 1/27*
B40	NC 1797	3	1/9	6	1/18
	NC 1810	1	1/3	5	1/15
	NC 1859	3	1/9	6	1/18

[a] *For a given fuel, the sum of the weights for each locomotive is 1/3. This ensures that each locomotive is accounted for evenly in the fleet average emission rate.*

[b] *Only 9 measurements of PM were valid during over-the-rail measurements of NC 1859 on B20. There were 15 measurements of all other pollutants.*

Table S9. Time-Based Cycle Average Emission Rates from Rail Yard Measurement of Prime Mover Engines

Locomotive	Fuel	Cycle Average Emission Rate (g/s)									
		NO_x[a]		HC[b]		CO		PM[c]		CO_2	
NC 1797 (F59PHI)	ULSD	1.85	(*0.01*)	0.31	(*0.49*)	0.13	(*0.19*)	0.04	(*0.09*)	106	(*0.06*)
	B10	2.29	(*0.02*)	1.10	(*0.30*)	0.14	(*0.05*)	0.04	(*0.08*)	118	(*0.01*)
	B20	2.20	(*0.03*)	1.27	(*0.15*)	0.13	(*0.17*)	0.03	(*0.10*)	101	(*0.04*)
	B40	2.23	(*0.00*)	0.39	(*0.28*)	0.14	(*0.42*)	0.04	(*0.20*)	116	(*0.05*)
NC 1810 (F59PH)	ULSD	1.05	(*0.01*)	1.35	(*0.10*)	0.24	(*0.06*)	0.07	(*0.10*)	107	(*0.00*)
	B10	1.19		0.40		0.28		0.07		111	
	B20	1.17		0.28		0.14		0.03		97.1	
	B40	1.59		0.25		0.13		0.08		86.1	
	B60	1.32	(*0.07*)	0.16	(*1.00*)	0.16	(*0.55*)	0.04	(*0.15*)	110	(*0.05*)
	B80	1.24	(*0.01*)	0.10	(*0.89*)	0.15	(*0.04*)	0.11	(*0.11*)	105	(*0.05*)
	B100	1.22	(*0.02*)	0.89	(*0.47*)	0.08	(*0.08*)	0.06	(*0.34*)	116	(*0.00*)
NC 1859 (F59PH)	ULSD	1.21	(*0.02*)	2.57	(*0.15*)	0.50	(*0.18*)	0.07	(*0.06*)	105	(*0.05*)
	B10	1.24	(*0.04*)	0.28	(*0.41*)	0.08	(*0.37*)	0.05	(*0.16*)	105	(*0.00*)
	B20	1.16	(*0.03*)	0.35	(*0.41*)	0.10	(*0.09*)	0.05	(*0.09*)	101	(*0.02*)
	B40	1.54	(*0.04*)	0.25	(*0.21*)	0.16	(*0.30*)	0.04	(*0.09*)	101	(*0.04*)
Fleet Average[d]	ULSD	1.37	(*9%*)	1.41	(*24%*)	0.29	(*20%*)	0.06	(*9%*)	106	(*1%*)
	B10	1.60	(*12%*)	0.49	(*38%*)	0.17	(*21%*)	0.05	(*9%*)	111	(*2%*)
	B20	1.53	(*13%*)	0.57	(*37%*)	0.12	(*7%*)	0.03	(*11%*)	99.8	(*1%*)
	B40	1.70	(*9%*)	0.24	(*23%*)	0.14	(*10%*)	0.06	(*15%*)	101	(*5%*)

Italicized values in parentheses for each locomotive are coefficients of variation (standard deviation divided by the mean) on the mean emission rate. For the fleet average emission rates, the italicized values in parentheses are relative standard errors (standard error divided by the mean). Fleet average emission rate means and standard errors derived from one sample weighted t-tests.

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

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

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

[d] Fleet average emission rates based on equal weighting of each locomotive.

Over-the-Rail Measurement Engine Parameters

Table S10. Measured Notch Average Engine Performance Parameters from Over-the-Rail Measurement of Prime Mover Engines

(a) NC 1797 – F59PHI Locomotive

Fuel	Notch Position	Engine Output (kW)	Engine Speed (RPM)	IAT (K)	MAP (kPa)
ULSD (6 replicates)	Idle	7	343 (*0.00*)	320 (*0.00*)	106 (*0.01*)
	DB	7	343 (*0.00*)	320 (*0.01*)	106 (*0.01*)
	1	142	343 (*0.00*)	321 (*0.00*)	106 (*0.00*)
	2	261	343 (*0.00*)	321 (*0.00*)	106 (*0.01*)
	3	503	490 (*0.00*)	321 (*0.01*)	120 (*0.01*)
	4	746	651 (*0.00*)	321 (*0.00*)	144 (*0.01*)
	5	969	750 (*0.00*)	321 (*0.01*)	164 (*0.01*)
	6	1,193	750 (*0.00*)	321 (*0.00*)	165 (*0.01*)
	7	2,013	819 (*0.00*)	321 (*0.00*)	185 (*0.01*)
	8	2,237	903 (*0.00*)	322 (*0.00*)	216 (*0.01*)
B10 (6 replicates)	Idle	7	343 (*0.00*)	317 (*0.01*)	104 (*0.01*)
	DB	7	340 (*0.02*)	317 (*0.01*)	105 (*0.01*)
	1	142	343 (*0.00*)	317 (*0.01*)	105 (*0.01*)
	2	261	343 (*0.00*)	317 (*0.01*)	105 (*0.01*)
	3	503	490 (*0.00*)	317 (*0.01*)	119 (*0.02*)
	4	746	651 (*0.00*)	318 (*0.01*)	143 (*0.02*)
	5	969	749 (*0.00*)	318 (*0.01*)	164 (*0.03*)
	6	1,193	749 (*0.00*)	317 (*0.01*)	164 (*0.02*)
	7	2,013	819 (*0.00*)	317 (*0.01*)	185 (*0.04*)
	8	2,237	903 (*0.00*)	319 (*0.01*)	217 (*0.04*)
B20 (5 replicates)	Idle	7	343 (*0.00*)	318 (*0.01*)	104 (*0.02*)
	DB	7	343 (*0.00*)	318 (*0.01*)	104 (*0.02*)
	1	142	343 (*0.00*)	318 (*0.01*)	104 (*0.02*)
	2	261	343 (*0.00*)	318 (*0.01*)	104 (*0.02*)
	3	503	490 (*0.00*)	318 (*0.01*)	119 (*0.02*)
	4	746	651 (*0.00*)	319 (*0.01*)	143 (*0.03*)
	5	969	749 (*0.00*)	319 (*0.01*)	163 (*0.03*)
	6	1,193	749 (*0.00*)	318 (*0.01*)	164 (*0.03*)
	7	2,013	821 (*0.00*)	319 (*0.01*)	186 (*0.03*)
	8	2,237	903 (*0.00*)	319 (*0.01*)	214 (*0.04*)
B40 (6 replicates)	Idle	7	343 (*0.00*)	326 (*0.01*)	101 (*0.01*)
	DB	7	343 (*0.00*)	326 (*0.01*)	102 (*0.01*)
	1	142	342 (*0.00*)	326 (*0.00*)	101 (*0.01*)
	2	261	343 (*0.00*)	327 (*0.01*)	101 (*0.01*)
	3	503	490 (*0.00*)	326 (*0.01*)	115 (*0.01*)
	4	746	651 (*0.00*)	326 (*0.01*)	138 (*0.01*)
	5	969	750 (*0.00*)	326 (*0.00*)	157 (*0.01*)
	6	1,193	750 (*0.00*)	327 (*0.00*)	158 (*0.01*)
	7	2,013	819 (*0.00*)	326 (*0.00*)	174 (*0.00*)
	8	2,237	903 (*0.00*)	327 (*0.01*)	202 (*0.01*)

(b) NC 1810 – F59PH Locomotive

Fuel	Notch Position	Engine Output (kW)	Engine Speed (RPM)	IAT (K)	MAP (kPa)
ULSD (6 replicates)	Low Idle	7	238 (*0.00*)	339 (*0.01*)	98 (*0.01*)
	High Idle	7	381 (*0.00*)	342 (*0.01*)	107 (*0.01*)
	DB	7	389 (*0.05*)	341 (*0.01*)	108 (*0.01*)
	1	142	380 (*0.00*)	341 (*0.01*)	108 (*0.01*)
	2	261	380 (*0.00*)	342 (*0.01*)	108 (*0.01*)
	3	503	489 (*0.00*)	342 (*0.01*)	119 (*0.01*)
	4	746	565 (*0.00*)	343 (*0.01*)	130 (*0.02*)
	5	969	654 (*0.00*)	344 (*0.01*)	147 (*0.03*)
	6	1,193	730 (*0.00*)	344 (*0.01*)	159 (*0.01*)
	7	2,013	826 (*0.00*)	346 (*0.01*)	195 (*0.03*)
	8	2,237	907 (*0.00*)	346 (*0.01*)	244 (*0.03*)
B10 (6 replicate)	Low Idle	7	200 (*0.01*)	344 (*0.00*)	101 (*0.01*)
	High Idle	7	350 (*0.00*)	350 (*0.01*)	109 (*0.00*)
	DB	7	374 (*0.08*)	351 (*0.01*)	110 (*0.02*)
	1	142	350 (*0.00*)	350 (*0.01*)	108 (*0.01*)
	2	261	348 (*0.00*)	351 (*0.01*)	110 (*0.01*)
	3	503	493 (*0.00*)	352 (*0.01*)	122 (*0.01*)
	4	746	568 (*0.00*)	353 (*0.00*)	131 (*0.01*)
	5	969	650 (*0.00*)	354 (*0.01*)	144 (*0.02*)
	6	1,193	728 (*0.00*)	355 (*0.01*)	159 (*0.01*)
	7	2,013	823 (*0.00*)	355 (*0.01*)	182 (*0.01*)
	8	2,237	904 (*0.00*)	357 (*0.01*)	228 (*0.03*)
B20 (6 replicate)	Low Idle	7	200 (*0.01*)	342 (*0.01*)	101 (*0.01*)
	High Idle	7	352 (*0.00*)	347 (*0.00*)	108 (*0.00*)
	DB	7	371 (*0.09*)	348 (*0.01*)	110 (*0.02*)
	1	142	351 (*0.00*)	348 (*0.01*)	109 (*0.01*)
	2	261	347 (*0.00*)	349 (*0.01*)	109 (*0.01*)
	3	503	494 (*0.00*)	350 (*0.01*)	123 (*0.01*)
	4	746	569 (*0.00*)	350 (*0.01*)	133 (*0.01*)
	5	969	651 (*0.00*)	352 (*0.01*)	148 (*0.02*)
	6	1,193	729 (*0.00*)	351 (*0.01*)	162 (*0.02*)
	7	2,013	823 (*0.00*)	355 (*0.01*)	192 (*0.06*)
	8	2,237	905 (*0.00*)	355 (*0.01*)	236 (*0.03*)
B40 (5 replicates)	Low Idle	7	202 (*0.00*)	338 (*0.00*)	101 (*0.01*)
	High Idle	7	352 (*0.00*)	342 (*0.01*)	110 (*0.01*)
	DB	7	361 (*0.02*)	342 (*0.01*)	110 (*0.01*)
	1	142	352 (*0.00*)	342 (*0.00*)	111 (*0.01*)
	2	261	347 (*0.01*)	342 (*0.01*)	111 (*0.01*)
	3	503	495 (*0.00*)	344 (*0.01*)	124 (*0.02*)
	4	746	569 (*0.00*)	343 (*0.01*)	134 (*0.01*)
	5	969	652 (*0.00*)	347 (*0.01*)	149 (*0.02*)
	6	1,193	730 (*0.00*)	346 (*0.01*)	164 (*0.01*)
	7	2,013	822 (*0.00*)	348 (*0.00*)	190 (*0.03*)
	8	2,237	905 (*0.00*)	349 (*0.00*)	233 (*0.01*)

Fuel	Notch Position	Engine Output (kW)	Engine Speed (RPM)	IAT (K)	MAP (kPa)
B60 (6 replicates)	Low Idle	7	199 (*0.01*)	341 (*0.01*)	99 (*0.01*)
	High Idle	7	347 (*0.02*)	344 (*0.01*)	106 (*0.01*)
	DB	7	376 (*0.09*)	345 (*0.00*)	109 (*0.03*)
	1	142	347 (*0.02*)	345 (*0.01*)	107 (*0.01*)
	2	261	346 (*0.02*)	346 (*0.01*)	108 (*0.01*)
	3	503	490 (*0.01*)	346 (*0.01*)	122 (*0.02*)
	4	746	567 (*0.01*)	345 (*0.01*)	131 (*0.02*)
	5	969	650 (*0.00*)	349 (*0.01*)	145 (*0.03*)
	6	1,193	729 (*0.00*)	348 (*0.01*)	160 (*0.03*)
	7	2,013	820 (*0.01*)	350 (*0.02*)	195 (*0.09*)
	8	2,237	903 (*0.00*)	350 (*0.01*)	219 (*0.05*)
B80 (6 replicates)	Low Idle	7	197 (*0.00*)	336 (*0.01*)	100 (*0.01*)
	High Idle	7	339 (*0.00*)	342 (*0.01*)	108 (*0.01*)
	DB	7	364 (*0.09*)	343 (*0.01*)	111 (*0.02*)
	1	142	338 (*0.00*)	342 (*0.01*)	109 (*0.01*)
	2	261	338 (*0.00*)	344 (*0.01*)	109 (*0.01*)
	3	503	488 (*0.00*)	343 (*0.01*)	123 (*0.01*)
	4	746	562 (*0.00*)	344 (*0.01*)	133 (*0.01*)
	5	969	650 (*0.00*)	345 (*0.01*)	147 (*0.01*)
	6	1,193	726 (*0.00*)	345 (*0.01*)	162 (*0.02*)
	7	2,013	821 (*0.00*)	346 (*0.01*)	188 (*0.02*)
	8	2,237	900 (*0.00*)	347 (*0.01*)	226 (*0.03*)
B100 (4 replicates)	Low Idle	7	197 (*0.00*)	337 (*0.00*)	99 (*0.00*)
	High Idle	7	338 (*0.00*)	340 (*0.00*)	107 (*0.01*)
	DB	7	351 (*0.07*)	340 (*0.00*)	109 (*0.02*)
	1	142	338 (*0.00*)	340 (*0.01*)	107 (*0.01*)
	2	261	338 (*0.00*)	338 (*0.00*)	107 (*0.01*)
	3	503	488 (*0.00*)	340 (*0.00*)	121 (*0.01*)
	4	746	562 (*0.00*)	339 (*0.01*)	131 (*0.01*)
	5	969	649 (*0.00*)	342 (*0.00*)	146 (*0.01*)
	6	1,193	725 (*0.00*)	343 (*0.01*)	162 (*0.01*)
	7	2,013	820 (*0.00*)	344 (*0.01*)	191 (*0.01*)
	8	2,237	901 (*0.00*)	346 (*0.00*)	227 (*0.04*)

(c) NC 1859 – F59PH Locomotive

Fuel	Notch Position	Engine Output (kW)	Engine Speed (RPM)	IAT (K)	MAP (kPa)
ULSD (6 replicates)	Low Idle	7	237 (*0.00*)	343 (*0.01*)	100 (*0.00*)
	High Idle	7	369 (*0.00*)	348 (*0.01*)	108 (*0.01*)
	DB	7	386 (*0.04*)	348 (*0.01*)	109 (*0.01*)
	1	142	369 (*0.00*)	349 (*0.00*)	110 (*0.01*)
	2	261	369 (*0.00*)	347 (*0.01*)	110 (*0.01*)
	3	503	491 (*0.00*)	348 (*0.01*)	122 (*0.02*)
	4	746	564 (*0.00*)	349 (*0.01*)	132 (*0.02*)
	5	969	651 (*0.00*)	350 (*0.01*)	146 (*0.02*)
	6	1,193	728 (*0.00*)	350 (*0.01*)	160 (*0.01*)
	7	2,013	819 (*0.00*)	350 (*0.01*)	179 (*0.01*)
	8	2,237	902 (*0.00*)	352 (*0.01*)	227 (*0.02*)
B10 (6 replicates)	Low Idle	7	238 (*0.00*)	334 (*0.01*)	101 (*0.01*)
	High Idle	7	371 (*0.00*)	338 (*0.01*)	110 (*0.02*)
	DB	7	382 (*0.04*)	337 (*0.01*)	111 (*0.02*)
	1	142	370 (*0.00*)	337 (*0.01*)	110 (*0.02*)
	2	261	371 (*0.00*)	337 (*0.01*)	111 (*0.02*)
	3	503	493 (*0.00*)	338 (*0.01*)	123 (*0.02*)
	4	746	565 (*0.00*)	340 (*0.01*)	134 (*0.02*)
	5	969	653 (*0.00*)	341 (*0.01*)	151 (*0.04*)
	6	1,193	730 (*0.00*)	343 (*0.01*)	167 (*0.03*)
	7	2,013	820 (*0.00*)	345 (*0.01*)	198 (*0.06*)
	8	2,237	903 (*0.00*)	343 (*0.01*)	235 (*0.05*)
B20 (15 replicates)	Low Idle	7	238 (*0.00*)	336 (*0.01*)	100 (*0.02*)
	High Idle	7	371 (*0.00*)	339 (*0.01*)	109 (*0.02*)
	DB	7	377 (*0.03*)	339 (*0.01*)	110 (*0.02*)
	1	142	371 (*0.00*)	338 (*0.01*)	110 (*0.02*)
	2	261	372 (*0.01*)	339 (*0.01*)	110 (*0.02*)
	3	503	493 (*0.00*)	339 (*0.01*)	123 (*0.02*)
	4	746	564 (*0.00*)	340 (*0.01*)	133 (*0.02*)
	5	969	653 (*0.00*)	341 (*0.01*)	148 (*0.03*)
	6	1,193	729 (*0.00*)	342 (*0.01*)	164 (*0.02*)
	7	2,013	820 (*0.00*)	344 (*0.01*)	194 (*0.05*)
	8	2,237	903 (*0.00*)	343 (*0.00*)	233 (*0.03*)
B40 (6 replicates)	Low Idle	7	237 (*0.00*)	338 (*0.01*)	99 (*0.01*)
	High Idle	7	370 (*0.00*)	342 (*0.00*)	107 (*0.00*)
	DB	7	378 (*0.03*)	341 (*0.00*)	109 (*0.01*)
	1	142	370 (*0.00*)	342 (*0.01*)	108 (*0.01*)
	2	261	369 (*0.00*)	340 (*0.01*)	109 (*0.01*)
	3	503	491 (*0.00*)	341 (*0.01*)	120 (*0.01*)
	4	746	564 (*0.00*)	342 (*0.01*)	130 (*0.01*)
	5	969	651 (*0.00*)	343 (*0.01*)	145 (*0.01*)
	6	1,193	729 (*0.00*)	344 (*0.01*)	160 (*0.01*)
	7	2,013	819 (*0.00*)	346 (*0.01*)	187 (*0.05*)
	8	2,237	902 (*0.00*)	346 (*0.00*)	225 (*0.03*)

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

Over-the-Rail Measurement Emission Rates

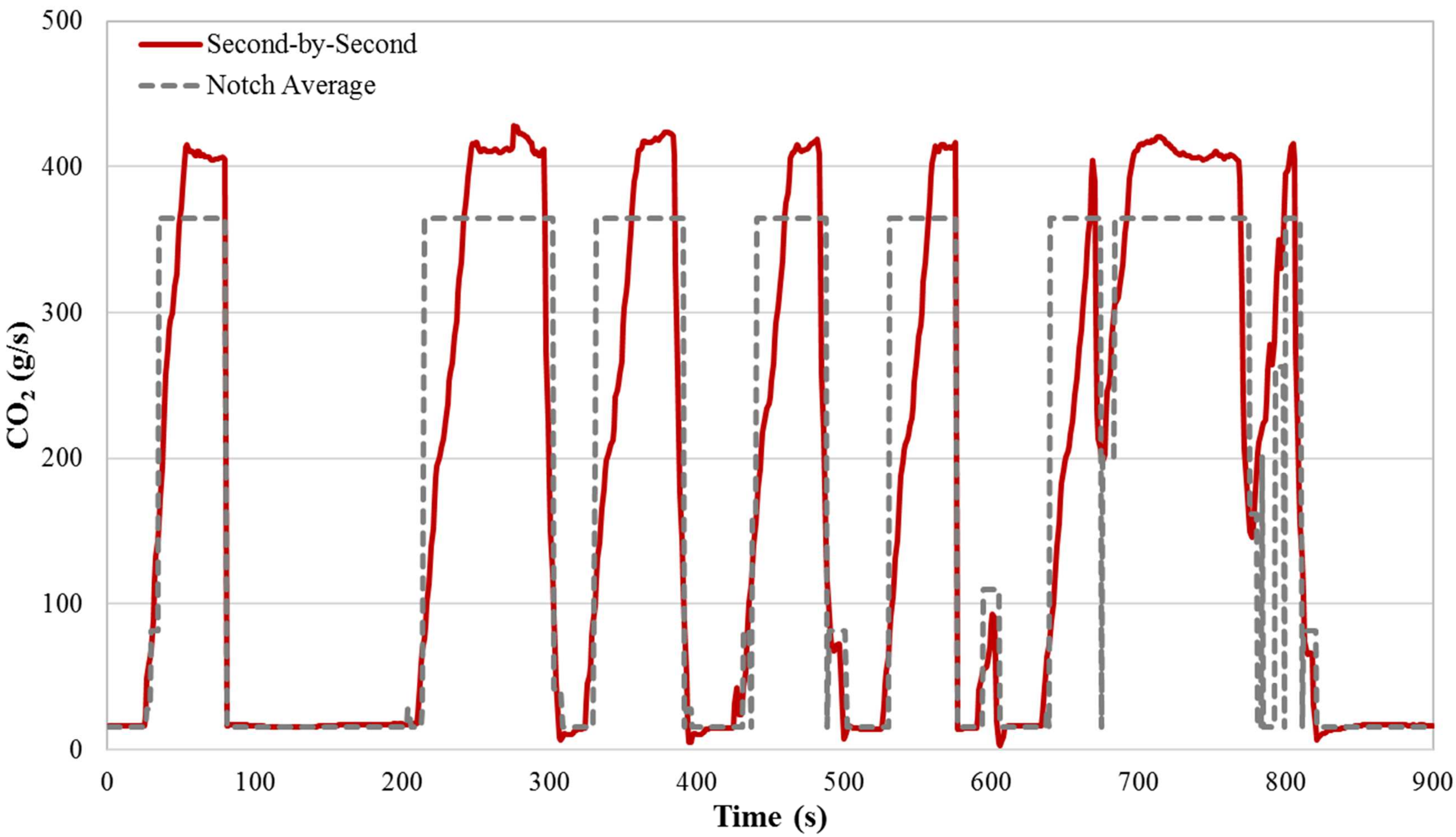


Figure S10. Time Trace of PEMS-Measured Time-Based CO_2 Emission Rate for a 900-Second Segment of a One-Way Piedmont Trip by Locomotive NC 1859 on Ultra-Low Sulfur Diesel

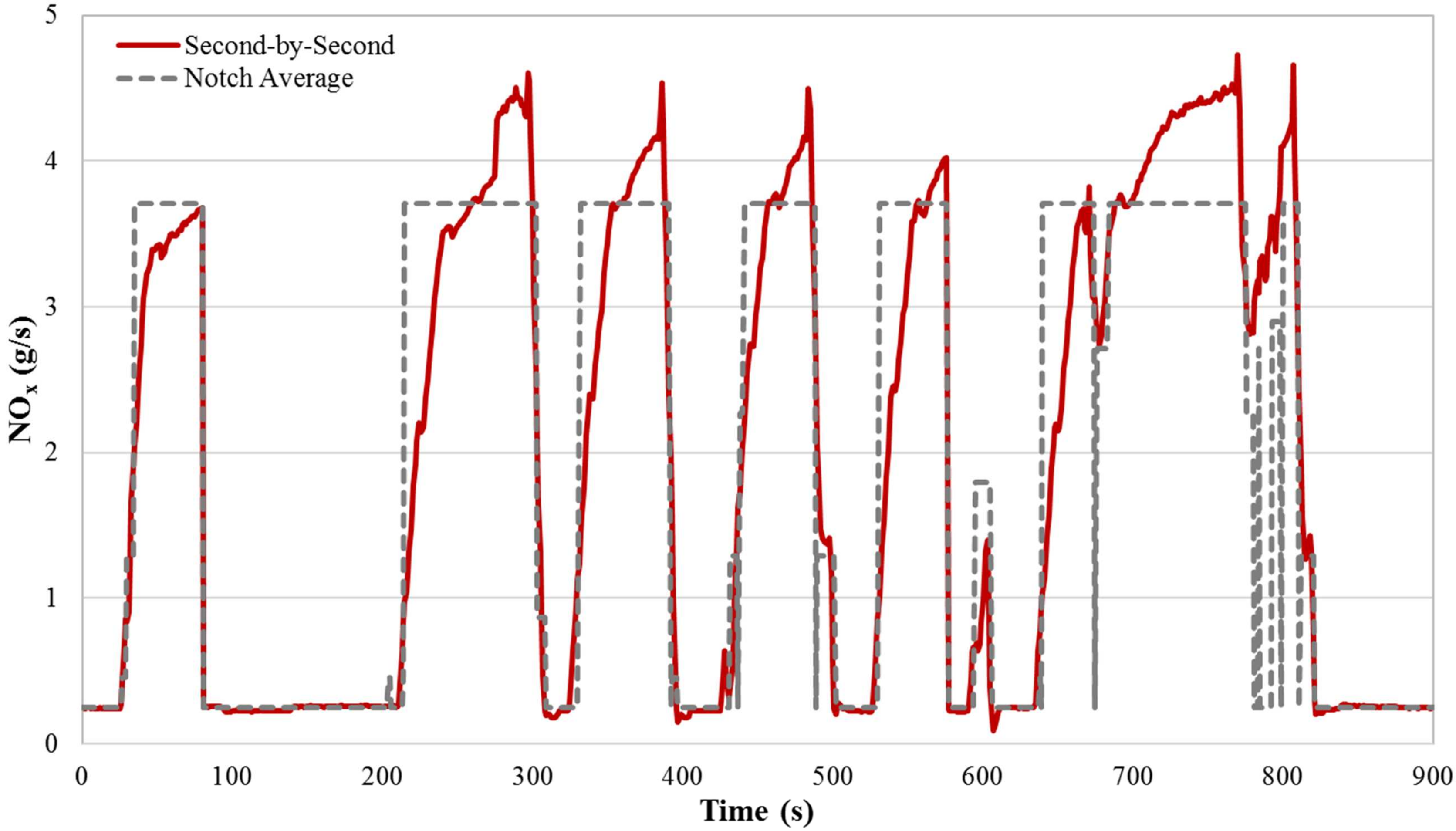


Figure S11. Time Trace of PEMS-Measured Time-Based NO_x Emission Rate for a 900-Second Segment of a One-Way Piedmont Trip by Locomotive NC 1859 on Ultra-Low Sulfur Diesel

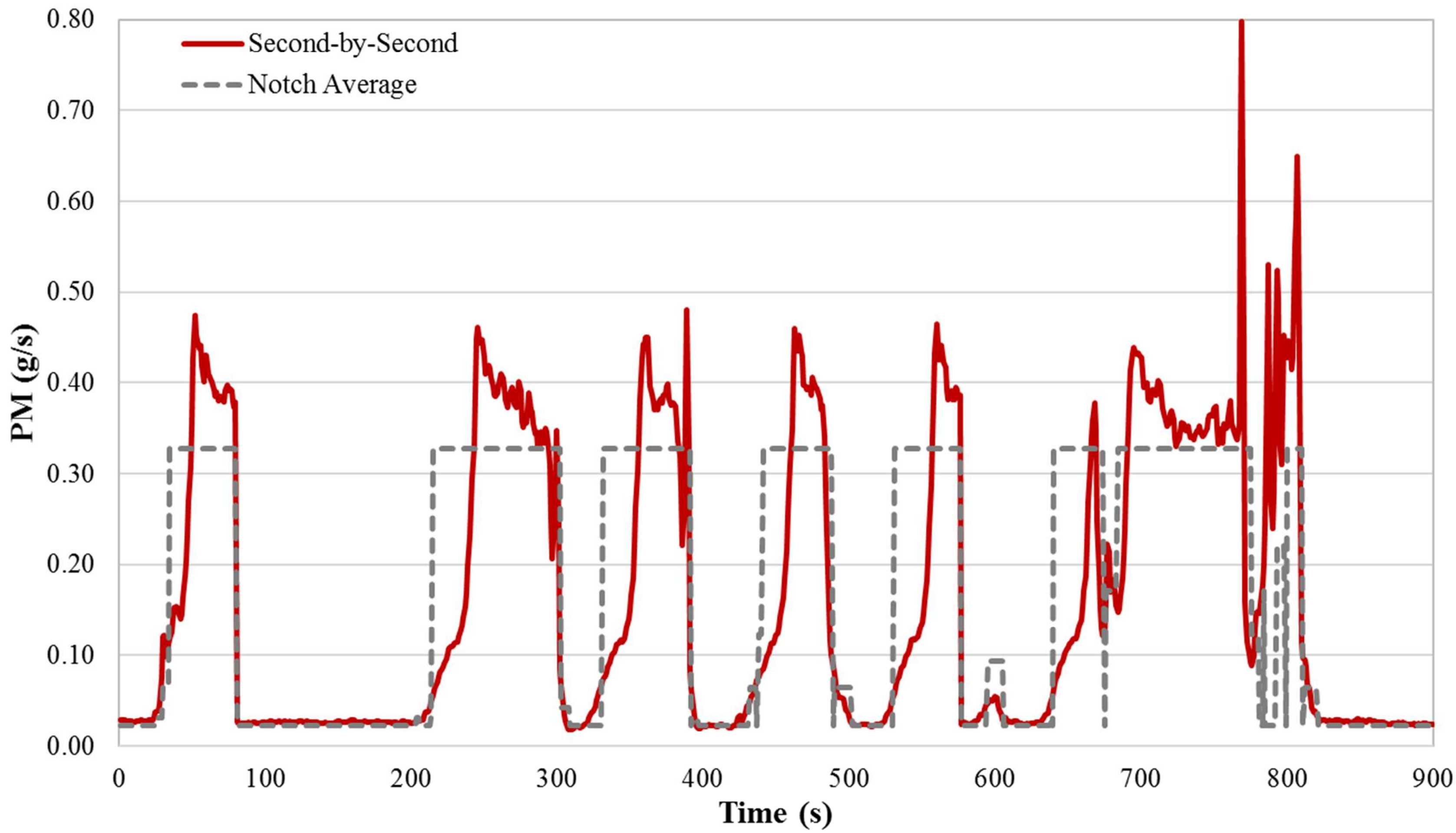


Figure S12. Time Trace of PEMS-Measured Time-Based PM Emission Rate for a 900-Second Segment of a One-Way Piedmont Trip by Locomotive NC 1859 on Ultra-Low Sulfur Diesel

Table S11. Time-Based Notch Average Emission Rates from Over-the-Rail Measurements of Prime Mover Engines

(a) NC 1797 – F59PHI Locomotive

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

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
B20 (5 replicates)	Idle	0.38 (*0.06*)	0.02 (*0.98*)	0.02 (*0.98*)	0.01 (*0.09*)	12.4 (*0.11*)
	Dynamic Brake	0.35 (*0.13*)	0.02 (*1.78*)	0.02 (*1.78*)	0.01 (*0.08*)	11.8 (*0.14*)
	1	0.80 (*0.10*)	0.01 (*1.50*)	0.01 (*1.50*)	0.01 (*0.07*)	25.8 (*0.18*)
	2	1.35 (*0.09*)	0.01 (*1.09*)	0.01 (*1.09*)	0.01 (*0.07*)	41.6 (*0.16*)
	3	2.65 (*0.09*)	0.01 (*1.76*)	0.01 (*1.76*)	0.02 (*0.07*)	77.6 (*0.14*)
	4	3.79 (*0.07*)	0.01 (*1.44*)	0.02 (*1.44*)	0.02 (*0.05*)	112 (*0.10*)
	5	4.90 (*0.09*)	0.01 (*1.20*)	0.01 (*1.20*)	0.02 (*0.10*)	153 (*0.12*)
	6	4.91 (*0.05*)	0.01 (*1.70*)	0.01 (*1.70*)	0.02 (*0.06*)	174 (*0.11*)
	7	5.85 (*0.07*)	0.01 (*0.88*)	0.02 (*0.88*)	0.09 (*0.16*)	285 (*0.15*)
	8	6.28 (*0.03*)	0.20 (*0.30*)	0.13 (*0.30*)	0.10 (*0.21*)	347 (*0.05*)
B40 (6 replicates)	Idle	0.69 (*0.13*)	0.17 (*0.76*)	0.16 (*0.76*)	0.01 (*0.37*)	16.2 (*0.03*)
	Dynamic Brake	0.63 (*0.09*)	0.27 (*0.58*)	0.26 (*0.58*)	0.01 (*0.33*)	16.0 (*0.05*)
	1	1.41 (*0.15*)	0.05 (*0.62*)	0.09 (*0.62*)	0.01 (*0.19*)	35.4 (*0.11*)
	2	2.05 (*0.15*)	0.06 (*0.60*)	0.11 (*0.60*)	0.01 (*0.25*)	49.1 (*0.12*)
	3	4.24 (*0.05*)	0.07 (*0.72*)	0.12 (*0.72*)	0.02 (*0.26*)	93.6 (*0.03*)
	4	5.86 (*0.11*)	0.09 (*0.76*)	0.16 (*0.76*)	0.03 (*0.38*)	137 (*0.06*)
	5	7.12 (*0.11*)	0.09 (*0.68*)	0.15 (*0.68*)	0.05 (*0.51*)	182 (*0.06*)
	6	7.42 (*0.14*)	0.08 (*1.03*)	0.11 (*1.03*)	0.05 (*0.51*)	208 (*0.07*)
	7	8.24 (*0.04*)	0.18 (*0.60*)	0.14 (*0.60*)	0.25 (*1.05*)	254 (*0.06*)
	8	8.29 (*0.05*)	0.91 (*0.24*)	0.46 (*0.24*)	0.22 (*0.23*)	389 (*0.02*)

(b) NC 1810 – F59PH Locomotive

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

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
B20 (6 replicate)	Low Idle	0.13 (*0.11*)	0.01 (*0.64*)	0.01 (*0.64*)	0.01 (*0.30*)	6.71 (*0.18*)
	High Idle	0.24 (*0.08*)	0.03 (*0.24*)	0.03 (*0.24*)	0.01 (*0.20*)	14.8 (*0.10*)
	Dynamic Brake	0.22 (*0.12*)	0.03 (*0.22*)	0.03 (*0.22*)	0.01 (*0.19*)	15.8 (*0.15*)
	1	0.47 (*0.12*)	0.02 (*0.37*)	0.04 (*0.37*)	0.02 (*0.10*)	28.0 (*0.14*)
	2	0.61 (*0.15*)	0.02 (*0.19*)	0.04 (*0.19*)	0.03 (*0.15*)	37.1 (*0.19*)
	3	1.06 (*0.17*)	0.04 (*0.36*)	0.07 (*0.36*)	0.04 (*0.11*)	67.4 (*0.23*)
	4	1.50 (*0.12*)	0.05 (*0.66*)	0.09 (*0.66*)	0.07 (*0.10*)	97.3 (*0.17*)
	5	2.04 (*0.07*)	0.09 (*0.43*)	0.16 (*0.43*)	0.09 (*0.08*)	146 (*0.10*)
	6	2.45 (*0.07*)	0.15 (*0.63*)	0.28 (*0.63*)	0.11 (*0.19*)	181 (*0.08*)
	7	3.22 (*0.13*)	0.38 (*0.16*)	0.51 (*0.52*)	0.18 (*0.55*)	282 (*0.08*)
	8	3.52 (*0.08*)	1.93 (*0.21*)	1.22 (*0.21*)	0.21 (*0.20*)	370 (*0.06*)
B40 (5 replicates)	Low Idle	0.17 (*0.15*)	0.02 (*0.60*)	0.01 (*0.60*)	0.01 (*0.30*)	8.64 (*0.32*)
	High Idle	0.29 (*0.20*)	0.03 (*0.25*)	0.03 (*0.25*)	0.02 (*0.25*)	20.4 (*0.23*)
	Dynamic Brake	0.24 (*0.16*)	0.03 (*0.53*)	0.02 (*0.53*)	0.03 (*0.24*)	18.6 (*0.24*)
	1	0.38 (*0.08*)	0.03 (*0.47*)	0.04 (*0.47*)	0.03 (*0.09*)	28.7 (*0.29*)
	2	0.46 (*0.13*)	0.03 (*0.23*)	0.03 (*0.23*)	0.02 (*0.27*)	36.7 (*0.18*)
	3	0.92 (*0.11*)	0.05 (*0.51*)	0.06 (*0.51*)	0.04 (*0.21*)	65.2 (*0.19*)
	4	1.35 (*0.21*)	0.06 (*0.33*)	0.08 (*0.33*)	0.05 (*0.09*)	90.0 (*0.19*)
	5	1.90 (*0.13*)	0.10 (*0.24*)	0.13 (*0.24*)	0.08 (*0.12*)	134 (*0.18*)
	6	2.38 (*0.09*)	0.10 (*0.42*)	0.13 (*0.42*)	0.10 (*0.13*)	166 (*0.27*)
	7	2.99 (*0.05*)	0.23 (*0.67*)	0.19 (*0.92*)	0.11 (*0.65*)	256 (*0.09*)
	8	3.09 (*0.13*)	1.70 (*0.16*)	0.76 (*0.16*)	0.23 (*0.06*)	364 (*0.12*)

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

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
B100 (4 replicates)	Low Idle	0.15 (*0.14*)	0.12 (*0.27*)	0.05 (*0.27*)	0.01 (*0.08*)	8.53 (*0.09*)
	High Idle	0.25 (*0.11*)	0.21 (*0.20*)	0.08 (*0.20*)	0.01 (*0.13*)	15.9 (*0.07*)
	Dynamic Brake	0.26 (*0.16*)	0.26 (*0.33*)	0.10 (*0.33*)	0.01 (*0.19*)	16.8 (*0.17*)
	1	0.47 (*0.15*)	0.28 (*0.32*)	0.10 (*0.32*)	0.01 (*0.17*)	32.5 (*0.12*)
	2	0.62 (*0.24*)	0.20 (*0.42*)	0.09 (*0.42*)	0.02 (*0.20*)	42.8 (*0.20*)
	3	1.36 (*0.12*)	0.13 (*0.30*)	0.09 (*0.30*)	0.03 (*0.27*)	92.2 (*0.07*)
	4	1.79 (*0.04*)	0.17 (*0.40*)	0.11 (*0.40*)	0.04 (*0.18*)	130 (*0.01*)
	5	2.30 (*0.04*)	0.21 (*0.64*)	0.13 (*0.64*)	0.05 (*0.05*)	179 (*0.01*)
	6	2.79 (*0.03*)	0.20 (*0.31*)	0.14 (*0.31*)	0.07 (*0.08*)	227 (*0.02*)
	7	3.32 (*0.10*)	0.48 (*0.37*)	0.24 (*0.37*)	0.15 (*0.06*)	299 (*0.10*)
	8	3.88 (*0.06*)	1.50 (*0.32*)	0.36 (*0.32*)	0.27 (*0.15*)	404 (*0.01*)

(c) NC 1859 – F59PH Locomotive

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
ULSD (6 replicates)	Low Idle	0.16 (*0.11*)	0.05 (*1.13*)	0.02 (*1.13*)	0.02 (*0.08*)	7.73 (*0.24*)
	High Idle	0.22 (*0.11*)	0.22 (*0.82*)	0.09 (*0.82*)	0.02 (*0.11*)	13.4 (*0.18*)
	Dynamic Brake	0.24 (*0.08*)	0.18 (*1.03*)	0.08 (*1.03*)	0.02 (*0.09*)	15.5 (*0.15*)
	1	0.45 (*0.10*)	0.22 (*0.60*)	0.09 (*0.60*)	0.03 (*0.08*)	27.7 (*0.18*)
	2	0.70 (*0.03*)	0.15 (*0.63*)	0.10 (*0.63*)	0.04 (*0.09*)	41.7 (*0.09*)
	3	1.27 (*0.03*)	0.30 (*1.64*)	0.22 (*1.64*)	0.06 (*0.10*)	81.4 (*0.08*)
	4	1.77 (*0.06*)	0.16 (*0.73*)	0.12 (*0.73*)	0.09 (*0.17*)	110 (*0.07*)
	5	2.24 (*0.03*)	0.17 (*0.98*)	0.14 (*0.98*)	0.12 (*0.13*)	162 (*0.05*)
	6	2.68 (*0.08*)	0.22 (*0.68*)	0.19 (*0.68*)	0.17 (*0.29*)	201 (*0.08*)
	7	2.87 (*0.07*)	0.23 (*0.97*)	0.19 (*0.97*)	0.22 (*0.25*)	263 (*0.09*)
	8	3.66 (*0.04*)	1.87 (*0.11*)	0.66 (*0.11*)	0.33 (*0.13*)	365 (*0.01*)

Fuel	Notch Position	NO as NO_2 (g/s)	HC (g/s)	CO (g/s)	Opacity-based PM (g/s)	CO_2 (g/s)
B10 (6 replicates)	Low Idle	0.14 (*0.24*)	0.15 (*0.47*)	0.07 (*0.47*)	0.01 (*0.20*)	8.36 (*0.21*)
	High Idle	0.21 (*0.19*)	0.20 (*0.37*)	0.09 (*0.37*)	0.01 (*0.18*)	16.8 (*0.05*)
	Dynamic Brake	0.23 (*0.22*)	0.22 (*0.36*)	0.10 (*0.36*)	0.01 (*0.19*)	20.9 (*0.47*)
	1	0.41 (*0.21*)	0.09 (*0.63*)	0.08 (*0.63*)	0.01 (*0.20*)	32.0 (*0.05*)
	2	0.61 (*0.23*)	0.09 (*0.71*)	0.08 (*0.71*)	0.02 (*0.19*)	45.8 (*0.07*)
	3	1.23 (*0.23*)	0.11 (*0.50*)	0.09 (*0.50*)	0.02 (*0.17*)	86.0 (*0.04*)
	4	1.66 (*0.24*)	0.11 (*0.66*)	0.10 (*0.66*)	0.03 (*0.21*)	121 (*0.01*)
	5	2.13 (*0.24*)	0.15 (*0.61*)	0.13 (*0.61*)	0.04 (*0.17*)	161 (*0.03*)
	6	2.61 (*0.22*)	0.16 (*0.55*)	0.13 (*0.55*)	0.05 (*0.14*)	201 (*0.03*)
	7	3.28 (*0.20*)	0.23 (*0.85*)	0.13 (*0.83*)	0.12 (*0.19*)	284 (*0.03*)
	8	3.62 (*0.20*)	0.64 (*0.50*)	0.23 (*0.50*)	0.19 (*0.20*)	351 (*0.05*)
B20 (15 replicates)	Low Idle	0.13 (*0.78*)	0.10 (*0.76*)	0.09 (*0.45*)	0.02 (*0.47*)	7.24 (*0.11*)
	High Idle	0.33 (*0.26*)	0.16 (*0.90*)	0.15 (*0.35*)	0.02 (*0.53*)	22.9 (*0.18*)
	Dynamic Brake	0.21 (*0.30*)	0.16 (*0.77*)	0.14 (*0.36*)	0.02 (*0.53*)	14.8 (*0.10*)
	1	0.40 (*0.41*)	0.07 (*0.75*)	0.12 (*0.35*)	0.02 (*0.52*)	29.1 (*0.08*)
	2	0.60 (*0.52*)	0.07 (*0.96*)	0.11 (*0.58*)	0.03 (*0.49*)	41.9 (*0.08*)
	3	1.17 (*0.54*)	0.08 (*0.89*)	0.14 (*0.64*)	0.03 (*0.44*)	79.6 (*0.05*)
	4	1.60 (*0.57*)	0.07 (*0.69*)	0.12 (*0.57*)	0.05 (*0.38*)	112 (*0.05*)
	5	2.09 (*0.55*)	0.10 (*0.88*)	0.18 (*0.85*)	0.06 (*0.43*)	156 (*0.04*)
	6	2.49 (*0.40*)	0.10 (*1.05*)	0.17 (*0.63*)	0.06 (*0.39*)	186 (*0.04*)
	7	3.27 (*0.30*)	0.19 (*0.91*)	0.26 (*0.65*)	0.14 (*0.36*)	287 (*0.06*)
	8	3.60 (*0.31*)	0.54 (*1.36*)	0.34 (*0.42*)	0.18 (*0.18*)	355 (*0.04*)

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

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

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

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

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

Table S12. Time-Based Cycle Average Emission Rates from Over-the-Rail Measurement of Prime Mover Engines

Locomotive	Fuel	Cycle Average Emission Rate (g/s)									
		NO_x[a]		HC[b]		CO		PM[c]		CO_2	
NC 1797 (F59PHI)	ULSD	3.61	(*0.05*)	0.53	(*0.21*)	0.77	(*0.46*)	0.04	(*0.09*)	98.3	(*0.09*)
	B10	3.22	(*0.13*)	0.26	(*0.45*)	0.61	(*0.32*)	0.04	(*0.10*)	108	(*0.05*)
	B20	3.25	(*0.15*)	0.09	(*0.36*)	0.45	(*0.34*)	0.03	(*0.13*)	93.4	(*0.09*)
	B40	4.34	(*0.13*)	0.45	(*0.32*)	0.92	(*0.31*)	0.05	(*0.30*)	105	(*0.04*)
NC 1810 (F59PH)	ULSD	1.80	(*0.15*)	1.38	(*0.22*)	0.83	(*0.32*)	0.06	(*0.09*)	110	(*0.05*)
	B10	1.63	(*0.10*)	2.42	(*0.22*)	0.25	(*1.33*)	0.10	(*0.07*)	104	(*0.05*)
	B20	1.81	(*0.12*)	0.81	(*0.20*)	0.18	(*0.30*)	0.06	(*0.17*)	97.7	(*0.10*)
	B40	1.26	(*0.20*)	0.52	(*0.29*)	0.03	(*0.36*)	0.06	(*0.09*)	96.1	(*0.08*)
	B60	2.18	(*0.14*)	0.75	(*0.37*)	0.32	(*0.60*)	0.10	(*0.42*)	100	(*0.10*)
	B80	1.84	(*0.26*)	0.54	(*0.49*)	0.46	(*0.37*)	0.06	(*0.12*)	101	(*0.09*)
	B100	1.91	(*0.13*)	0.72	(*0.35*)	0.57	(*0.26*)	0.06	(*0.14*)	110	(*0.05*)
NC 1859 (F59PH)	ULSD	1.90	(*0.09*)	0.90	(*0.21*)	0.88	(*0.71*)	0.09	(*0.14*)	97.9	(*0.06*)
	B10	1.70	(*0.24*)	0.32	(*0.48*)	0.71	(*0.31*)	0.05	(*0.16*)	102	(*0.02*)
	B20	1.65	(*0.11*)	0.26	(*0.79*)	0.62	(*0.78*)	0.05	(*0.22*)	98.8	(*0.08*)
	B40	2.05	(*0.12*)	0.32	(*0.33*)	0.38	(*0.35*)	0.04	(*0.07*)	98.8	(*0.04*)
Fleet Average[d]	ULSD	2.44	(*9%*)	0.94	(*10%*)	0.83	(*12%*)	0.06	(*9%*)	102	(*2%*)
	B10	2.18	(*9%*)	1.00	(*25%*)	0.52	(*14%*)	0.06	(*11%*)	105	(*1%*)
	B20	2.24	(*7%*)	0.39	(*18%*)	0.42	(*16%*)	0.05	(*8%*)	96.6	(*2%*)
	B40	2.55	(*13%*)	0.43	(*9%*)	0.45	(*22%*)	0.05	(*6%*)	100	(*2%*)

Italicized values in parentheses for each locomotive are coefficients of variation (standard deviation divided by the mean) on the mean emission rate. For the fleet average emission rates, the italicized values in parentheses are relative standard errors (standard error divided by the mean). Fleet average emission rate means and standard errors derived from one sample weighted t-tests.

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

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

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

[d] Fleet average emission rates based on equal weighting of each locomotive.

Discussion: Evaluation of intra- and inter-locomotive trends in PM measurement results

With regard to the possibility of some experimental artifact, particularly with respect to PM emission rates, which seem to be highly variable especially for NC 1810, we consider an engineering perspective. The same measurement procedures were used for all locomotives for all rail yard (RY) measurements, and the same procedures were used for all locomotives for all over-the-rail (OTR) measurements. The order of measurements was somewhat randomized, in that measurements of one locomotive were interspersed with those of another locomotive in terms of the order in which the measurements were done. Thus, if there were, say, some random error introduced by the measurement method, it should manifest across the board. However, in contrast, we see distinctive patterns for each of the three locomotives with regard to PM emissions. This suggests that the measurement method was unlikely to be the source of the patterns in the data.

We note that the comparison of PM emission rates for biofuel blends to ULSD is approximately consistent (similar percentage differences) for OTR and RY measurements for NC 1859. For NC 1797, both OTR and RY measurements indicate that the most favorable comparison is for B20. For NC 1810, the results are highly variable for both rail yard and over-the-rail. NC 1810 tends to be a higher PM emitter than the other two locomotives.

For NC 1810, the RY notch average PM emission rates (shown in Table S7 of the Supporting Information) are internally consistent for each fuel blend in that they are lowest at low engine load and increase with increasing engine load. The notch average PM emission rates are 0.10 g/sec or lower for Idle through Notch 5 for all fuel blends. There are large variations in the Notch 8 average emission rates: 0.28 g/sec for ULSD, 0.26 g/sec for B10, 0.11 g/sec for B20, 0.43 g/sec for B40, 0.18 g/sec for B60, 0.46 g/sec for B80, and 0.30 g/sec for B100. The cycle average rates (shown in Table S8 of the Supporting Information) for these cases fluctuate between 0.03 g/sec (B20) to 0.11 g/s (B80). In contrast, the RY cycle average PM emission rates vary only between 0.03 g/sec and 0.04 g/sec for NC 1797 and between 0.04 g/sec and 0.07 g/sec for NC 1859. Thus, NC 1810 is a higher emitting and "noisier" locomotive, with more inherent variability in emission rates than for the other two engines. However, for individual measurements, the trends in emission rates versus engine load are reasonable.

For the OTR measurements, we find that the trend in PM emission rate versus engine load is also as expected for each fuel blend in that it increases with increasing engine load. There are large variations in the Notch 8 emission rates (shown in Table S10 in the Supporting Information): 0.25 g/sec for ULSD, 0.38 g/sec for B10, 0.21 g/sec for B20, 0.23 g/sec for B40, 0.39 g/sec for B60, 0.25 g/sec for B80, and 0.27 g/sec for B100. Similar to the RY results, the OTR cycle average rates are more variable for NC 1810 than for the other two locomotives. For example, the NC 1810 cycle average emission rates vary from 0.06 g/sec to 0.10 g/sec among the fuel blends, which is generally higher than for the other two locomotives. NC 1859 cycle average rates vary between 0.04 g/sec to 0.09 g/sec among the fuel blends, whereas NC 1979 cycle average rates vary only between 0.03 g/sec and 0.05 g/sec. Thus, for both the OTR and RY results, NC 1810 typically has higher PM emission rates and more variability in the PM emissions rates.

Given that consistent results were obtained when comparing OTR vs. RY in terms of engine operational parameters, and that the PM emission rates follow the expected trend with engine load for each individual measurement, it seems likely that the observed variability in emission rates is related to the engine itself (or the characteristics of its emissions).

Our experience is that there can be considerable inter-engine variability in emission rates, and in comparisons of fuels, when comparing engines of the same make and model. We have seen this in prior studies of highway vehicles (*17-18*).

Lube Oil Analysis Results

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

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

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

Table S13. Summary of Oil Analyses of Prime Mover Engines in NCDOT Locomotive Fleet

(a) NC 1797 (F59PHI)

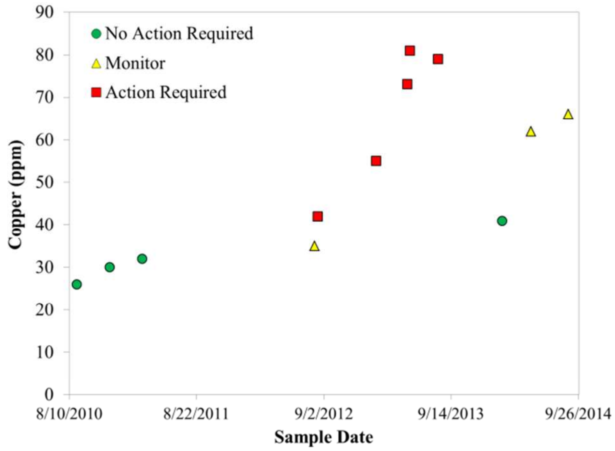
Date	**Summary**	**Fuel**
9/1/2010	No Action Required	ULSD
12/8/2010	No Action Required	ULSD
3/14/2011	No Action Required	ULSD
8/6/2012	Monitor: Wear metals and oil additives have changed a great deal; silicon levels may indicate some dirt entry or may be residue from a recent repair; iron, tin, and lead have increase and may indicate some crank and bearing wear	ULSD
8/15/2012	Action Required: Copper, iron, tin, and lead have increased and may indicate some crank and bearing wear	ULSD
2/14/2013	Action Required: Copper, lead and tin remains elevated. Possible bearing wear.	ULSD
5/7/2013	Action Required: Copper, lead and tin are increasing. Possible bearing wear.	ULSD
5/15/2013	Action Required: Copper, lead and tin are increasing. Possible bearing wear.	ULSD
8/6/2013	Action Required: Copper, lead and tin remain elevated. Possible bearing wear.	ULSD
11/8/2013	No Action Required	ULSD
2/12/2014	No Action Required	ULSD
5/9/2014	Monitor: Lead and tin are elevated. Possible bearing wear.	B40
8/28/2014	Monitor: Copper, lead, and tin are elevated. Possible bearing wear.	B10/B20

(b) NC 1810 (F59PH)

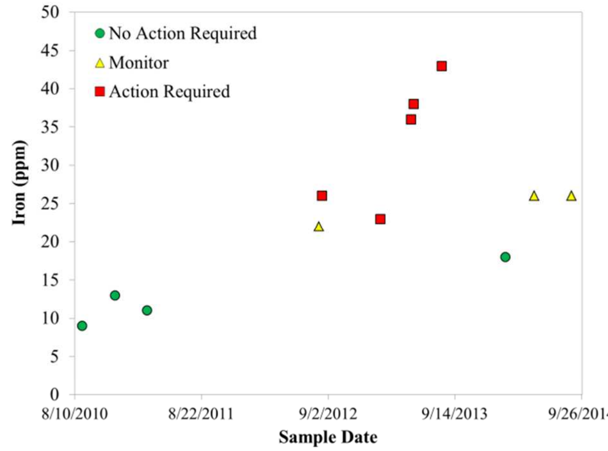
Date	**Summary**	**Fuel**
12/21/2010	No Action Required	ULSD
8/21/2011	No Action Required	ULSD
3/8/2012	No Action Required	ULSD
6/4/2012	No Action Required	ULSD
8/15/2012	Monitor: Iron and lead continue to increase and may indicate some crank and bearing wear	B10
2/22/2013	No Action Required	B10/B20/B40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

(c) NC 1859 (F59PH)

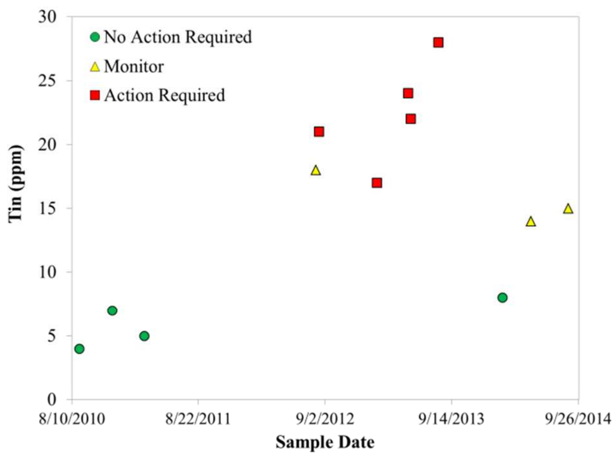
Date	**Summary**	**Fuel**
12/20/2011	Monitor: Copper, tin, and lead are higher than normal and may indicate some bearing wear	ULSD
3/18/2012	Monitor: No significant increase in wear detected	ULSD
6/19/2012	No Action Required	ULSD
9/14/2012	No Action Required	ULSD
12/25/2012	No Action Required	ULSD
3/27/2013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



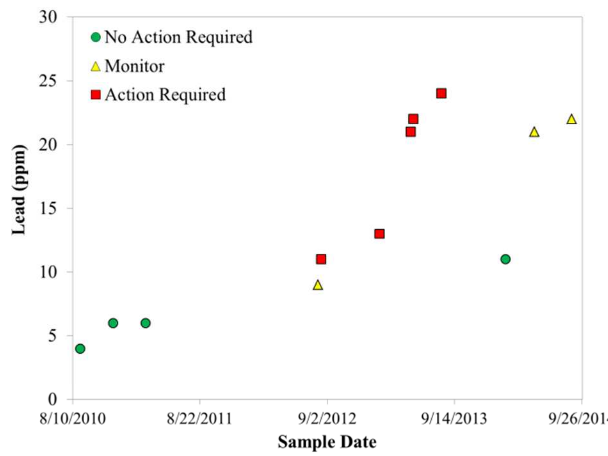
(a) Copper (Cu)



(b) Iron (Fe)

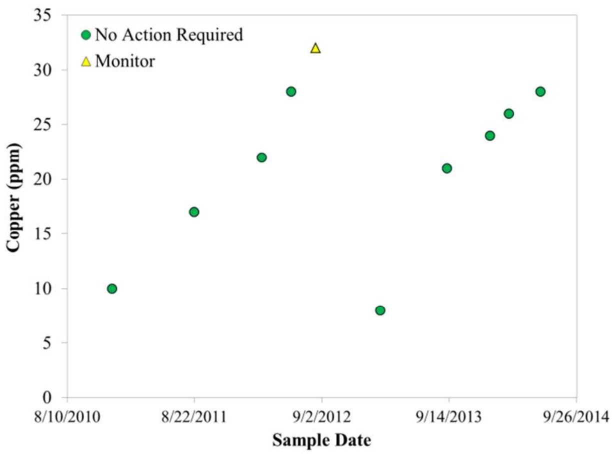


(c) Tin (Sn)

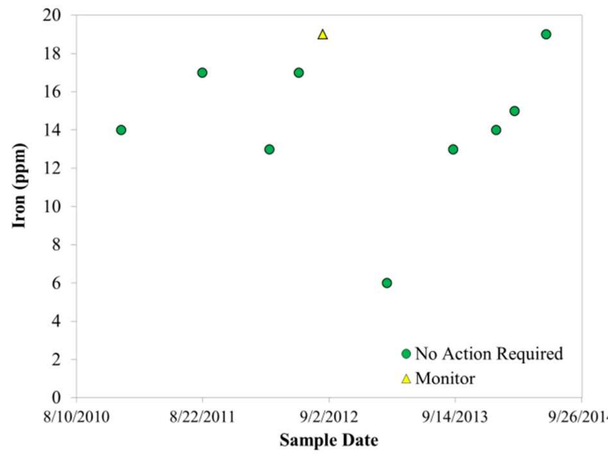


(d) Lead (Pb)

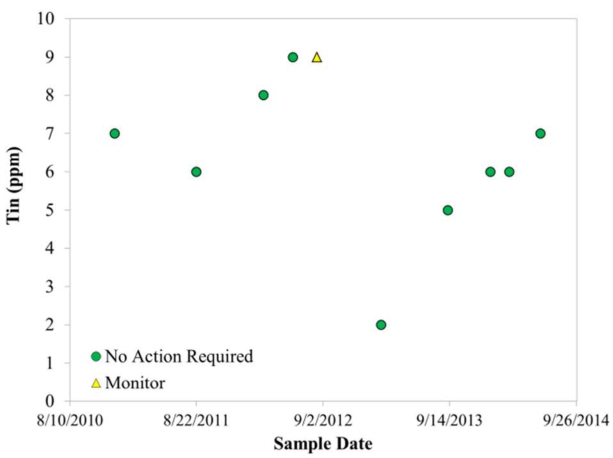
Figure S13. Wear Metal Concentrations in Oil Samples from NC 1797 Prime Mover Engine



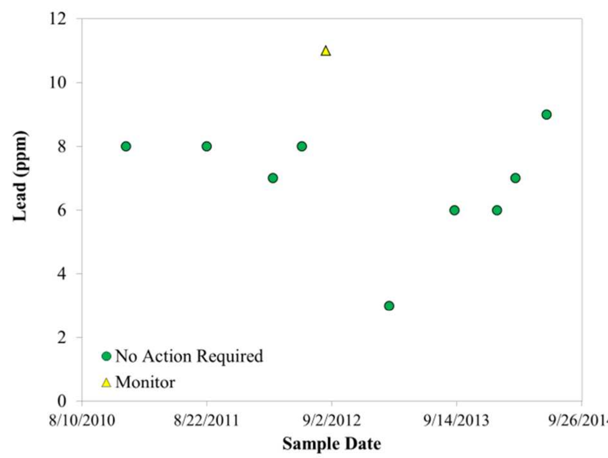
(a) Copper (Cu)



(b) Iron (Fe)

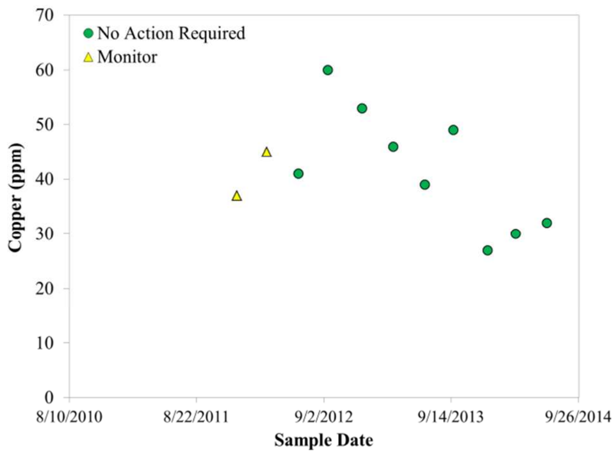


(c) Tin (Sn)

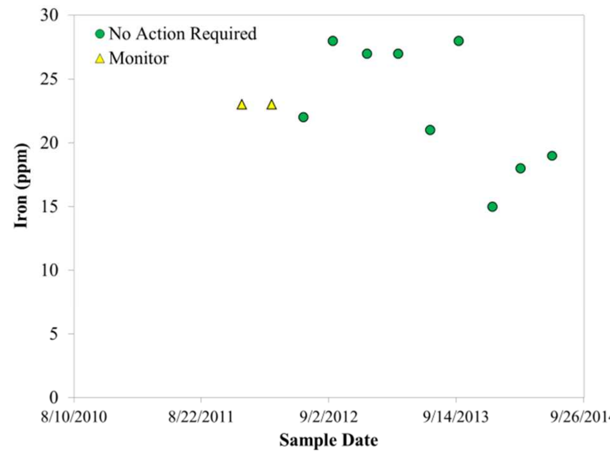


(d) Lead (Pb)

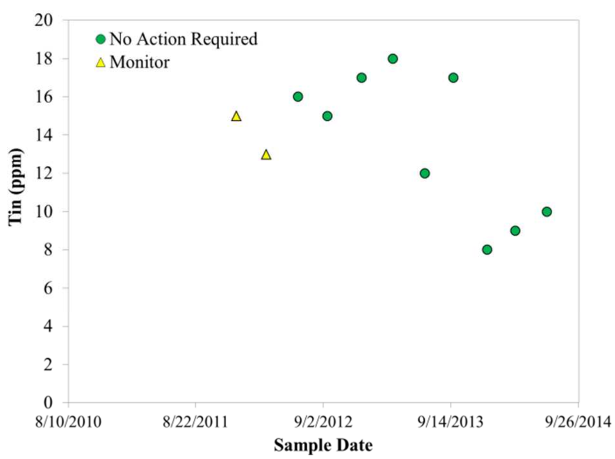
Figure S14. Wear Metal Concentrations in Oil Samples from NC 1810 Prime Mover Engine



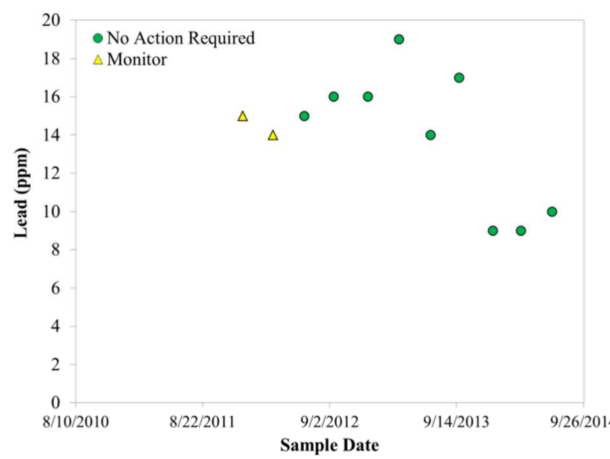
(a) Copper (Cu)



(b) Iron (Fe)



(c) Tin (Sn)



(d) Lead (Pb)

Figure S15. Wear Metal Concentrations in Oil Samples from NC 1859 Prime Mover Engine

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