Measurement of Emissions of Passenger Rail Locomotives
Using a Portable Emission Measurement System

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The purpose of this study is to demonstrate a method for measurement of passenger railroad locomotive emissions using a Portable Emission Measurement System (PEMS) based on railyard load tests of three locomotives, including one GP40 and two F59PHIs. These locomotives have mechanically governed diesel prime mover engines (PMEs) with approximately 3,000 hp output. Each locomotive has a “head-end power” (HEP) engine that produces approximately 600 hp for generating electricity used in the passenger cars. The engines were measured using ultra-low sulfur diesel (ULSD) fuel. Each engine was instrumented to measure manifold absolute pressure (MAP), engine RPM, intake air temperature, and exhaust concentrations of selected gases and particles. These data are used to quantify exhaust and fuel flow. The exhaust concentrations of NO, CO, CO₂, hydrocarbons, and particulate matter were measured. The PMEs are operated at each of many throttle notch settings. For the HEP engines, three electrical loads were applied based on power usage for one, two and four passenger cars, respectively. Over 97 percent of the raw data survived a multi-step quality assurance process. The data obtained from the PEMS for the main engines were found to be comparable, on a fuel-basis, to data reported by others, particularly for NOₓ and CO. The key results from this work are establishment of a simplified methodology for future tests and development of baseline data.
INTRODUCTION

There were 23,732 Class I locomotives in the United States in 2006.¹ The U.S. Environmental Protection Agency (EPA) estimates that locomotives consume approximately 4 billion gallons of diesel fuel annually.² Locomotive diesel engines are significant sources of air pollution.³⁻⁵ However, there are relatively few data regarding the emission rates of this source category. Furthermore, although freight locomotives typically have one large prime mover engine (PME) that is used to generate direct current for use in traction motors, many passenger locomotives have a separate head end power engine (HEP) that is used to generate 60 Hz alternating current to provide hotel services in the passenger train consist. There are few data regarding HEP emissions. Freight locomotives include switchers and line-haul. Switchers tend to be smaller, with PMEs of 2,000 hp or less, whereas line-haul freight PMEs can be approximately 4,000 to 6,000 hp each. There are some exceptions to this, such as recent introductions of switcher locomotives with multiple smaller engine “gensets” that can be turned on or off individually in order to match power demand. Passenger locomotive PME may typically be approximately 3,000 hp. Passenger locomotive HEPs are approximately 600 hp, but are not certified under the locomotive emission standard. Instead, they are subject to nonroad diesel engine rules.

The main source of PME emissions factor data are certification tests conducted to demonstrate that a particular engine make and model complies with an applicable locomotive standard. U.S. locomotive PMEs are subject to emission standards promulgated in March 2008. The standards apply to new and remanufactured engines. The standards contain a tiered approach to more stringent emission limits depending on the engine model year or date of remanufacturing. PMEs are operated at discrete throttle notch settings, including low idle, high idle for power take-off,
and eight notches that enable variation in useful output. Certification that a PME complies with the applicable standard is based on Federal Reference Method (RFM) instrumentation and a test procedure in which the engine is run at steady state for each throttle notch position (40 CFR Part 92 Subpart B; CFR = Code of Federal Regulations). The notch position steady-state emission rates are weighted to represent a switcher or line-haul freight duty cycle, depending on the engine size and application. Such tests are expensive, conducted under steady state conditions, and take place at a very limited number of facilities. There is significant cost of transport of locomotives to the test facility, lost revenue service during transport and testing, and the test itself.

Owners and operators of locomotive fleets are under increasing scrutiny with regard to justification of operations based on environmental considerations. To quantify the real-world emissions of locomotives, there is a need for a more flexible, convenient, and less costly approach to obtaining emissions data. Such data can support evaluation of the effectiveness of engine remanufacture, alternative fuels, changes in operating practices, and comparisons of locomotives within a fleet. In turn, these data can support decisions regarding acquisition or remanufacturing of locomotives, selection of fuels, and improvement of operating procedures, in order to reduce emissions. The data quality objectives for such data are not as stringent as those for certification tests, since the former may only need to provide insight regarding relative difference whereas the latter must enable comparison to allowable emission rates.

The use of a Portable Emission Measurement System (PEMS) as a means to obtain data useful to a locomotive fleet owner is evaluated here. PEMS can be easily installed for static measurements at a railyard and can also be installed on-board a locomotive for over-the-rail
measurements (planned for a subsequent study). Although PEMS have been applied extensively for measurement of in-use emissions of cars, trucks, and nonroad vehicles such as construction equipment, they have not yet been widely applied to locomotives.

The objectives of this paper are to: (1) develop and apply a methodology for assessment of the activity, fuel use, and emission rates for locomotive PMEs and HEPs; (2) measure emission levels of locomotive engines using PEMS; and (3) evaluate the use of PEMS as an alternative to engine dynamometer measurement and identify its comparative strengths and limitations.

TECHNICAL APPROACH

The technical approach includes: (1) study design; (2) Portable Emission Measurement System (PEMS) instrumentation; (3) field data collection; (4) quality assurance and quality control; (5) data analysis; and (6) benchmark comparisons.

Study Design

Field study design includes specifying which engines are to be tested, when they are to be tested, what fuel will be used, what type of duty cycle will be performed, and who will operate the locomotives. The study design depends on the study objectives. In this case, the objectives are to obtain a baseline characterization of PME and HEP emissions for three locomotives used in passenger rail service between Raleigh, NC and Charlotte, NC. The data are needed to assess whether and to what extent emissions differ when comparing the three locomotives and to identify priorities (if any) among the three locomotives for future emission reduction efforts.
The selected locomotives are a GP40, NC1792, and two F59PHIs, NC1755 and NC1797, owned by the North Carolina Department of Transportation (NCDOT). Each locomotive has a PME used to provide direct current electric power for propulsion, and a head-end power (HEP) engine used to generate alternating current power for “hotel services” in the passenger train.\textsuperscript{12}

Emissions for each engine from each locomotive were measured, for a total of six engines.

The specifications of the PMEs and HEPs of the three locomotives are summarized in Table 1. Measurements are based on ultra low sulfur diesel (ULSD). The three PMEs are two-stroke engines. Two-stroke engines are known to burn more lubricating oil than four-stroke engines, which may be a factor that influences emission rates.

**Portable Emission Measurement System**

The PEMS used is the OEM-2100 Montana system manufactured by Clean Air Technologies International, Inc.\textsuperscript{13} The Montana system is comprised of two parallel five-gas analyzers, a particulate matter (PM) measurement system, an engine sensor array, and an on-board computer.

The pollutants measured include \(O_2\), HC, CO, \(CO_2\), NO\textsubscript{x}, and PM using the following detection methods:

- HC, CO, and \(CO_2\) using non-dispersive infrared (NDIR).\textsuperscript{10, 14}
- NO measured using electrochemical cell. For diesel engines, NO\textsubscript{x} is comprised of approximately 92 volume percent NO.\textsuperscript{15, 16}
• PM is measured using laser light scattering, with measurement ranging from ambient levels to low double digits opacity.\textsuperscript{10,14}

The performance of the Montana system has been verified in comparison to a laboratory grade chassis dynamometer measurement system.\textsuperscript{17-20} The coefficients of determination ($R^2$) exceeded 0.86 for all pollutants, indicating good precision. The slopes of parity plots for CO, CO\textsubscript{2} and NO ranged from 0.92 to 1.05, indicating good accuracy, and ranged from 0.62 to 0.79 for HC. The bias for HC is a well-known result of the NDIR detection method.\textsuperscript{21} The PEMS is calibrated in the laboratory using a cylinder gas and in the field periodically recalibrates to ambient air to prevent instrument drift. The PEMS used here has been used for measurements of a wide variety of vehicles, including cars, trucks, and construction equipment, and for a variety of fuels, including gasoline, E85 ethanol, ultra low sulfur diesel, and biodiesel. Thus, the PEMS is applicable to a wide variety of vehicle and fuel types.\textsuperscript{8,9}

Intake airflow, exhaust flow, and mass emissions are estimated using a method reported by Vojtisek-Lom and Cobb.\textsuperscript{14} The data needed for these estimates include manifold absolute pressure (MAP), engine RPM, and intake air temperature (IAT). A temporarily mounted sensor array is used to measure these three parameters.

**Field Data Collection Procedure**

The measurements reported here were conducted under static conditions at a local railyard in Raleigh, NC. PEMS installation involves the following connections: (1) installing MAP, RPM, and IAT sensors; (2) connecting exhaust gas sample lines from the exhaust duct to the PEMS;
and (3) providing power to the PEMS. Installation is facilitated by identifying in advance the
details of these connections and providing sufficient time for railyard mechanics to fabricate an
MAP port and an exhaust sample line port for the duct of the PME, and to identify a source of
power. For railyard tests, shorepower can be used. The installation process on the day of the
tests takes about two hours for the PME. The MAP sensor is connected to a fabricated port on
the airbox of the engine. The RPM sensor is based on an optical device that detects the reflection
of light from reflective tape that is placed on a pulley wheel that rotates at the same RPM as the
engine. IAT is measured with a thermocouple. The key installation steps include removing an
airbox port and replacing with an identical one that has a barb fitting for the MAP sensor,
locating an appropriate position for the RPM sensor and reflective tape, finding a location in the
air intake path for the IAT sensor, connecting the exhaust duct port and the exhaust tubing,
routing wires and tubes between the locomotive and the PEMS unit, and connecting the PEMS to
shorepower. For the HEP engine, the procedure is similar. However, instead of an exhaust duct,
there is a tailpipe similar to that found on a truck for these three locomotives, and thus a standard
exhaust sample probe used routinely with trucks is easily installed in the tailpipe.

After installation, the PEMS and engine were warmed up for 45 minutes. After the warm-up, the
PME was run at notch position 8 for a period of approximately 3 minutes, after which the engine
was returned to idling. During testing under load, the electrical power produced by the DC
generator connected to the PME was 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 high electrical current. To
prevent overheating, operation at notches 6 through 8 was limited to 3 minutes. The load test at
each of these notches was immediately followed by a period of idling to allow the grid to cool for 5 minutes. Thereafter, testing occurred sequentially for notch positions 5, 4, 3, 2, 1, and idle without any intermediate idling.

The HEP was run at multiple electrical loads for a period of approximately 10 minutes per load. The electrical load conditions were none, low, medium, and high. The loads were imposed by attaching passenger rail cars and operating the lighting and air conditioning in each. Thus, the low, medium, and high loads correspond to the combined space conditioning and lighting loads for one, two, and four passenger cars, respectively. Voltages and currents were measured to estimate the electrical loads. During data collection, exhaust gas concentrations and engine data were recorded on a second-by-second basis.

The railyard testing is the first step in a series of longer-term research tasks. Later, we plan to make over-the-rail tests using PEMS, to enable comparison of results under railyard and over-the-rail conditions.

**Quality Assurance and Quality Control**

The measured data are screened to check for errors. If errors are identified, they are either corrected or the data set is not used for data analysis. Details of the quality assurance procedures are given by Frey et al. Three of the most common types of errors or problems are briefly described.
On occasion, an invalid reading is obtained for engine RPM from the optical sensor. The 2-stroke PMEs typically operate between 250 to 950 RPM. Values outside of this range are considered to be invalid and are removed prior to further data analysis.

“Freezing” refers to situations in which a value that is expected to change dynamically on a second-by-second basis remains constant over an implausibly long time period. On occasion, the gas analyzer output fails to update and appears to be “frozen” at a constant value.

Each gas analyzer is referred to as a “bench.” Most of the time, both benches are in use. Each gas analyzer bench is “zeroed” on a staggered schedule every 15 minutes. While zeroing, the gas analyzer will intake ambient air instead of tailpipe emissions. Therefore, most of the time, the concentration measurements from each of the two benches can be compared. When the relative error in the concentration measurement between both benches is within a predetermined “maximum allowable discrepancy” (MAD), and if no other errors are detected, then an average value is calculated based upon both of the benches. However, if the relative error exceeds the MAD due to problem such as leak in the sample line, overheating, or sampling pump failure, then only data obtained from the other bench is used.

Data Analysis

Measured data are analyzed to estimate average mass per time fuel use and emission rates for each throttle notch position. Emission rates for each throttle notch position were also estimated based on mass per gallon of fuel consumed. Weighted average emission factors were estimated.
for the line-haul freight locomotive cycle. The analysis method used here is similar to methods developed for other non-road vehicles, such as construction equipment.

RESULTS

The results include the field data collection schedule, quality assurance, comparison among engines, and comparison to independent data.

Field data collection occurred during 2008. The PMEs were tested for locomotives NC1755 and NC1792 in March. In July, the PME of locomotive NC1797 was tested. Measurements were made in July on the HEPs of all three locomotives. The time to install the PEMS, including the MAP, RPM, and IAT sensors, the exhaust sample line, and connections to shore power, was about two hours for the PME. The PME measurements occurred during a period of about one hour. After the PME tests, the sensors and exhaust lines were relocated to the HEP, which took about an hour. The HEP measurements occurred during a period of about an hour. Thus, tests on both the PME and HEP were completed within one day. Data analysis and reporting typically took about five days for each day of field measurements.

Quality Assurance

On average, 97 percent of the raw second-by-second data were valid. Unusual engine RPM (which occurred only for one engine), gas analyzer freezing, and inter-analyzer discrepancy accounted for, on average, loss of 0.8, 0.7, and 1.2 percent of the raw data, respectively.
The engine RPM for each of the three PMEs were approximately the same for a given notch position. At idle, the engines operate at approximately 250 RPM, while at notch 8 they operate at approximately 900 RPM. MAP varies from approximately 103 to 276 kPa, depending on the notch positions and engine.

The exhaust concentrations for NO and CO\textsubscript{2} tend to increase as notch position increases. For example, as shown in Figure 1, the NO concentration for the GP40’s EMD16-645 engine increases monotonically from 164 to 1,555 ppm between idle and notch 8. McKanna \textit{et al.} reported similar NO emission concentrations for each notch position for an EMD16-645 engine.\textsuperscript{22} The NO and CO\textsubscript{2} concentrations for the EMD12-710 engines of the F59PHIs increase from idle to notch 7 and are lower at notch 8 than notch 7. NO\textsubscript{x} formation strongly depends on a combustion temperature.\textsuperscript{23} NO concentration of NC1755, which has an EMD12-710 engine, increases from 160 to 1,360 ppm between idle and notch 7. At notch 8, the NO concentration is 1,170 ppm. The observed concentrations for HC and CO are less sensitive to notch positions in part because they are often at or below the detection limit of gas analyzers. The observed levels were between 0.6 to 19 ppm for HC and 0.0008 to 0.085 vol-\% for CO. However, the detection limit is sensitive enough to make inferences as to whether the emission rates are at or above Tier 0+ or Tier 1+ levels that would be required to be achieved as a result of a later engine rebuild.

Diesel engines typically have very low emissions of CO and HC because they operate with high air-to-fuel ratios. CO and HC mass emission rates are not usually a main point of concern when evaluating diesel engines: rather, the focus is on NO\textsubscript{x} and PM.
The NO emission rates increase monotonically between idle and notch 8. For example, the average NO emission rates for NC1755 range from 0.13 to 11 g/sec between idle and notch 8. The NO emission rates for the older EMD16-645 engine are generally higher than for the two EMD12-710 engines; for example, the NO emission rate at notch 8 is 22 to 28 percent higher than for the EMD12-710 engines.

Fuel-based emission factors, given in Table 2, were calculated based on a carbon balance of the exhaust components, molar ratio of exhaust components to CO₂, and fuel carbon content. Cycle average emission factors were estimated based on the line-haul freight locomotive duty cycle. The EPA duty cycle includes a mode for dynamic braking which was not part of the stationary load test procedure. The percentage of time assigned to dynamic braking in the EPA cycle was assigned to the idle mode. The cycle average emission rate is based on total emissions divided by total fuel use for the cycle.

The NOx emission rate for the NC1755 F59PHI locomotive varies from approximately 170 to 240 g/gallon among the notch positions. Although a large percentage of time for the freight line haul cycle occurs in the idle mode, the majority of the fuel consumed (65 to 67 percent, depending on the engine) is estimated to occur at notch 8. The mass per time rate of fuel consumption at notch position 8 is approximately two orders-of-magnitude higher than at idle. Given the high fuel consumption rate at high engine load, the fuel-based cycle average emission factors are most influenced by the modal emission factors at high engine load. The cycle weighted average NO emission rate is 220 g/gallon.
The two F59PHI locomotives have similar cycle average NO\textsubscript{x} and opacity-based PM emission rates. Apparent differences in cycle average HC and CO emission rates are not significant. The average concentrations are below the detection limit of 13 ppm for HC and 0.012 \textit{vol}-% for CO.

The GP40 has a similar average opacity-based PM emission rate compared to the F59PHIs, and a somewhat higher average NO emission rate. The average HC and CO emissions rates for the GP40 are within the range of those for the F59PHIs.

A comparison of the fuel-based emission factors from the three locomotives versus the range and average of values reported by EPA\textsuperscript{7,24} is given in Table 2. For NO\textsubscript{x}, the measured emission factors are comparable to the range reported by EPA, although they tend to be at the low end of the range. The PEMS measures NO but not total NO\textsubscript{x}. Thus, if an adjustment were made to account for this, the measured emission factor would be increased by a ratio of 1.087 (1/0.92), leading to values of 230 to 260 g/gallon. These values are within the range of the EPA data.

Overall, the NO emission measurements are deemed to be reasonable.

For HC, the measured emission factors are low compared to the weighted average from the EPA reported data. For one F59PHI, the measured average emission factor is less than the minimum value estimated based on EPA’s data. However, the measured average emission factors for the GP40 and the other F59PHI are slightly higher than the minimum value. The HC measurement is based on NDIR, which is known to be accurate for straight chain hydrocarbons but is less accurate for more complex molecules (such as aromatics). Typically, NDIR HC measurements may need to be adjusted with a bias correction of 2 or more to correspond to the actual total hydrocarbon load in the exhaust.\textsuperscript{21} If a factor of 2 adjustment is applied here, then the measured
emission factors would be 3.8 to 9.4 g/gal. While still at the low end of the range of data inferred from EPA’s report, these values are consistent with the benchmark data.

As noted earlier, the CO exhaust gas concentrations are typically below the detection limit of the gas analyzers, and thus are subject to uncertainty. Nonetheless, the average emission factors estimated from the measurements are comparable to the data reported by EPA.

The opacity-based PM measurements are clearly lower than the benchmark data. As noted earlier, these measurements are based on a light scattering laser photometer detection method. These measurements are useful for relative comparisons of data obtained using the same method, but are not appropriate for characterization of the absolute total emissions. The data here suggest that the three locomotives have comparable PM emission rates. The data showed that the opacity-based PM emission rates are approximately a factor of 4 lower than the average estimated fuel-based rate based on data reported by EPA.

The brake-specific fuel consumption for these locomotives is not known because there is no measurement of shaft torque nor is there an electronic control module that reports estimates of such data based on engine maps. Thus, it is not possible to directly estimate emission factors in units of g/bhp-hr. However, it is possible to make an estimate of g/bhp-hr emission factors for notch 8 using a typical value for brake specific fuel consumption (BSFC). EPA reports a typical BSFC of 0.048 gal/bhp-hr.\textsuperscript{7,24} Measured BSFC at notch 8 is reported as 0.048 gal/bhp-hr for EMD16-645 and EMD12-710 engines.\textsuperscript{22,25} Based on this value of BSFC, estimated brake specific emission factors for notch 8 position are shown in Table 3.
EPA reported 14 and 11 g/bhp-hr of line-haul duty cycle average NO\textsubscript{x} emission rates for EMD16-645 and EMD12-710 engines, respectively.\textsuperscript{7} Based on other data, NO\textsubscript{x} emission rates for EMD16-645 have been reported in a range from 12 to 13 g/bhp-hr.\textsuperscript{26} The estimated Notch 8 emission rate for the EMD16-645 is slightly less than these values, and varies for the two measured EMD12-710 engines between 9 and 11 g/bhp-hr. The older engines are not required to comply with the new standards until such time as they would undergo engine rebuilds. Furthermore, the measurements conducted here are intended to evaluate relative differences among notches and engines, and are not a Federal Reference Method (FRM).

For HC, NC1792 and NC1797 have emission rates that are comparable to the Tier 3 standard of 0.3 g/bhp-hr, taking into account the known bias in NDIR measurements of total HC. For CO, it is likely that all three locomotives can comply with any of the Tiers of the locomotive standards. For PM, there is considerable uncertainty given the semi-qualitative nature of the measurement method. There is not yet a standardized method for measuring particulate matter using portable instruments. This is an area of active and ongoing research among PEMS developers.

Rebuilds of these engines, which were planned as of the date that these measurements were made, would need to focus on significantly reducing NO\textsubscript{x} emissions to achieve the requirement for Tier 0+ compliance that would be triggered by a rebuild.
Table 4 shows the fuel rate and fuel-based emission rates for the HEP engines versus electrical load. 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. At a load of “none,” some power was consumed to maintain battery charge of the locomotive’s batteries.

The rate of fuel use, CO₂ emissions, and NO emissions increase as electrical load increases. HC emission rates for diesel engines typically depend less on load and more on air-to-fuel ratio. The CO emission rate tends to be highest at no load, which is a relatively inefficient operating condition. Fuel-based PM emission rates are approximately similar among various loads. While the Cummins KTA19 engine, which was rebuilt in 2005, has higher electrical loads than the CAT 3412 engines, the fuel use and emission rates were lower.

As expected, the fuel use and CO₂ emission rates of the two CAT3412 engines are similar for comparable loads. The NO emission rates are of similar magnitude but appear to be slightly higher for NC1755 than for NC1797. The HC, CO, and PM emission rates are comparable in magnitude.

We have not been able to identify published data on the same make and model of HEP engines. As a benchmark, EPA certification data for similar size engines manufactured by Cummins and
CAT in 2003 were compared to fuel-based emission factors here. Non-road engine emission data reported by EPA for 2003 was the most recently available. Since EPA data were reported in gram per brake-horsepower-hour, gram per gallon emission factors were calculated based on engine-specific BSFC.

The Cummins 3CEXL019 is 19 liter non-road diesel engine with BSFC of 0.0427 gal/bhp-hr. The certification emission rates are 140, 9, 36, and 5.2 g/gal for NO$_x$, HC, CO, and PM. Generally, these values are approximately similar to or higher than rail-yard emission factors. At no electrical load, railyard HC and CO emission rates are 7 and 14 percent higher, respectively, than the certification data.

For comparison to CAT3412 engine, certification data for a CAT 3CPXL27 engine are used. The later is a 27 liter non-road diesel engine with BSFC of 0.0515 gal/bhp-hr. The emission rates for CAT 3CPXL27 are 123, 3.2, 32, and 4.7 g/gal for for NO$_x$, HC, CO, and PM. The railyard emission factors for NO$_x$, HC, and CO are higher than the certification data during load tests. The railyard opacity-based PM emission factors are less than those of certification data.

Fuel-based HEP NO emission rates are substantially lower than those of the much larger PMEs. The fuel-based HC emission rates were of comparable magnitude for the HEP and PMEs. For CO, the fuel-based rates ranged from 38 to 82 g/gallon for the CAT3412 engines. These rates tend to be higher than those for the PMEs. The CO emission rates for the Cummins engine are comparable to those of the PMEs. The fuel-based PM emission rates for all three HEP engines
were approximately similar and appear to be higher than for the substantially larger PMEs. There is not a strong trend of fuel-based PM emission rate with respect to load.

CONCLUSIONS

The use of PEMS to conduct railyard tests has been demonstrated in this work based on applications to three locomotives. Railyard tests are a relatively low cost method for benchmarking and comparison of locomotive emissions. They are significantly cheaper than centralized FRM tests that require sending a locomotive to a test facility, which would involve significant time out of service and lost revenue. For a local railyard test, the locomotive is typically kept in the railyard for a day. The total duration of preparation, testing of the PME, and testing of the HEP is approximately six hours. For each day of testing, there are typically about four to five days of work for analyzing and reporting data.

The railyard exhaust concentrations for NO and CO$_2$ for the PMEs were comparable to other static test results for each notch position. The HC and CO concentrations were often below the detection limit of gas analyzers. The opacity-based PM showed low concentrations compared to PM concentrations based on FRM.

The fuel-based NO$_x$ emission rates for EMD16-645 engine were generally higher than those for EMD12-710 engine. The fuel-based opacity was similar for both engines.
The line haul cycle average fuel-based emission rates for NO\textsubscript{x} and CO were comparable to benchmark data based on federal reference methods. HC measurements using NDIR have a known bias. When this bias is considered, the measurement results are comparable to benchmark data. For PM, the semi-qualitative laser light scattering measurements are useful for relative comparisons to data obtained with the same method, but are not accurate in terms of absolute magnitude.

For HEP engines, the exhaust concentrations for Cummins KTA19 and CAT3412 increased as electrical load increased. Whereas the fuel-based emission rates for NO, HC, CO, and opacity for Cummins KTA19 engine were lower than the benchmark data, those for CAT 3412 were higher than the benchmark data except opacity.

Emission factors based on PEMS measurements are useful for comparing engines. The data are reasonable and a useful benchmark to data that will be collected in future measurement campaigns. Examples of factors that will be assessed in future comparative studies include the effect of substitution of alternative fuel, such as B20 biodiesel, for ultra low sulfur diesel. Furthermore, the effect of hardware or operational modifications to the engines on emissions will be assessed. The same or similar methodology can be applied to other locomotives. The methodology will be adapted for in-use measurement of locomotives in over-the-rail service. The advantage of this type of measurement will be to obtain real-world duty cycles that may be unique to passenger rail service, as opposed to the national average freight duty cycles provided by EPA.
DISCLAIMER

The contents of this paper reflect the views of the authors and not necessarily the views of the University. The authors are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the North Carolina Department of Transportation, the Federal Highway Administration, or the Institute for Transportation Research and Education at the time of publication. This report does not constitute a standard, specification, or regulation.

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Dr. H. Christopher Frey is a professor in the civil, construction, and environmental engineering at North Carolina State University. Hyung-Wook Choi participated in this work as a postdoctoral research associate at NCSU and is now with the Greenhouse Gas Inventory & Research Center of Korea. Dr. Kangwook Kim participated in this work as a postdoctoral research associate at NCSU and is now with the Department of Sanitation of the City of New York.
REFERENCES


Table 1. Specifications of the prime mover and head-end power (HEP) engines of the tested locomotives.

<table>
<thead>
<tr>
<th>Item</th>
<th>NC1792 (GP40)</th>
<th>NC1755 and NC1797 (F59PHI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prime Mover</td>
<td>Head-End Power</td>
</tr>
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<td>Engine Make</td>
<td>EMD</td>
<td>Cummins</td>
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<tr>
<td>Engine Model</td>
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<td>KTA19</td>
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<tr>
<td>NO. Cylinders</td>
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<td>6</td>
</tr>
<tr>
<td>Displacement (L)</td>
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<tr>
<td>Horsepower (hp)</td>
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<td>600</td>
</tr>
</tbody>
</table>

Note: NC1755 and NC1797 are model F59PHI locomotives that were built in 1998 and 1997, respectively. NC1792 is model GP40 locomotive that was built in 1968. The prime mover engine and head-end power (HEP) engines of the GP40 were rebuilt in 1992 and 2005, respectively.
Table 2. Fuel-based emission factors based on notch position for the GP40 and F59PHI locomotive PMEs.

<table>
<thead>
<tr>
<th>Locomotive No, Model, and Engine</th>
<th>Notch Position</th>
<th>Fuel Use Percentage (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>NO as NO&lt;sub&gt;2&lt;/sub&gt; (g/gal)</th>
<th>HC&lt;sup&gt;d&lt;/sup&gt; (g/gal)</th>
<th>CO&lt;sup&gt;d&lt;/sup&gt; (g/gal)</th>
<th>Opacity-based PM (g/gal)</th>
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</thead>
<tbody>
<tr>
<td>NC1792, GP40, EMD16-645</td>
<td>Idle</td>
<td>2.8</td>
<td>240</td>
<td>14</td>
<td>52</td>
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<td>260</td>
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<td>260</td>
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<td>NC1755, F59PHI, EMD12-710</td>
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<td>240</td>
<td>1.7</td>
<td>13</td>
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<td>230</td>
<td>2.7</td>
<td>19</td>
<td>1.5</td>
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<td>65</td>
<td>220</td>
<td>1.8</td>
<td>12</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Cycle Average&lt;sup&gt;b&lt;/sup&gt;</td>
<td>220</td>
<td>1.9</td>
<td>11</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>NC1797, F59PHI, EMD12-710</td>
<td>Idle</td>
<td>2.5</td>
<td>250</td>
<td>14</td>
<td>5.5</td>
<td>9.4</td>
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<td>1.4</td>
<td>190</td>
<td>7.8</td>
<td>13</td>
<td>4.2</td>
</tr>
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<td>230</td>
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<td>1.2</td>
<td>14</td>
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<td>200</td>
<td>2.8</td>
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<tr>
<td></td>
<td>8</td>
<td>65</td>
<td>200</td>
<td>5.1</td>
<td>16</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>Cycle Average&lt;sup&gt;b&lt;/sup&gt;</td>
<td>210</td>
<td>4.7</td>
<td>15</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>EPA&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Minimum</td>
<td></td>
<td>220</td>
<td>3.1</td>
<td>11</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td></td>
<td>320</td>
<td>15</td>
<td>51</td>
<td>8.5</td>
</tr>
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<td></td>
<td>Fleet Average</td>
<td></td>
<td>260</td>
<td>10</td>
<td>32</td>
<td>6.3</td>
</tr>
</tbody>
</table>

<sup>a</sup> The fraction of fuel use for freight line-haul cycle is calculated based on time-based fuel use rate and line-haul duty cycle. The fraction of fuel use is adjusted in that dynamic braking is assigned to the idle mode.

<sup>b</sup> This is a cycle average emission factor based on adjusted line-haul cycle. The emission factors based on passenger cycle are similar to those for line-haul cycle within 5 percent difference.

<sup>c</sup> Source: Data based on EPA reports converted to a fuel basis.<sup>7, 24</sup>

<sup>d</sup> Italic numbers indicate emission rates based on exhaust concentrations that are below the detection limit of gas analyzers. The detection limits for HC and CO are 13 ppm and 0.012 vol.%, respectively.
Table 3. Average brake specific emission factors for throttle notch 8.

<table>
<thead>
<tr>
<th>Locomotive No, Model, and Engine</th>
<th>NO (g/bhp-hr)</th>
<th>HC (g/bhp-hr)</th>
<th>CO (g/bhp-hr)</th>
<th>Opacity based PM (g/bhp-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC1792, GP40, EMD16-645</td>
<td>11</td>
<td>0.17</td>
<td>0.65</td>
<td>0.073</td>
</tr>
<tr>
<td>NC1755, F59PHI, EMD12-710</td>
<td>11</td>
<td>0.09</td>
<td>0.58</td>
<td>0.060</td>
</tr>
<tr>
<td>NC1797, F59PHI, EMD12-710</td>
<td>8.8</td>
<td>0.25</td>
<td>0.76</td>
<td>0.054</td>
</tr>
</tbody>
</table>

Note: Brake specific emission factors were estimated based on fuel-based emission factors in Table 2 and brake specific fuel consumption (BSFC) of 0.048 gal/bhp-hr.\textsuperscript{7, 22, 24, 25}
### Table 4. Fuel-Based Emission Factors for Head-End Power Engines for the GP40 and F59PHI Locomotives for Selected Electrical Loads.

<table>
<thead>
<tr>
<th>Locomotive No (Model, Engine)</th>
<th>Electrical Load Level</th>
<th>Electrical Load (kW)</th>
<th>Fuel Use (g/sec)</th>
<th>NO as NO₂ (g/gal)</th>
<th>HCᵇ (g/gal)</th>
<th>COᵇ (g/gal)</th>
<th>Opacity-based PM (g/gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC1792 (GP40, Cummins KTA19)</td>
<td>None</td>
<td>1</td>
<td>4.1</td>
<td>39</td>
<td>9.6</td>
<td>41</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>14</td>
<td>4.8</td>
<td>43</td>
<td>3.7</td>
<td>19</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>27</td>
<td>5.8</td>
<td>50</td>
<td>3.6</td>
<td>11</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>53</td>
<td>7.7</td>
<td>63</td>
<td>3.4</td>
<td>9.4</td>
<td>1.6</td>
</tr>
<tr>
<td>NC1755 (F59PHI, CAT 3412)</td>
<td>None</td>
<td>1</td>
<td>5.2</td>
<td>130</td>
<td>12</td>
<td>82</td>
<td>2.4</td>
</tr>
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<td></td>
<td>Low</td>
<td>8</td>
<td>6.0</td>
<td>150</td>
<td>8.9</td>
<td>60</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>13</td>
<td>6.8</td>
<td>150</td>
<td>8.0</td>
<td>52</td>
<td>2.1</td>
</tr>
<tr>
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<td>High</td>
<td>26</td>
<td>9.2</td>
<td>170</td>
<td>6.5</td>
<td>38</td>
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</tr>
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<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
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<tr>
<td></td>
<td>Medium</td>
<td>18</td>
<td>7.4</td>
<td>130</td>
<td>9.1</td>
<td>50</td>
<td>2.6</td>
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<tr>
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<td>High</td>
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<td>9.3</td>
<td>140</td>
<td>6.3</td>
<td>39</td>
<td>2.3</td>
</tr>
</tbody>
</table>

ᵃ For each car, all lights were turned on and the air conditioning was run at daytime thermostat setting (72 °F).

ᵇ Italic numbers indicate emission rates based on exhaust concentrations that are below the detection limit of gas analyzers. The detection limits for HC and CO are 13 ppm and 0.012 vol-%, respectively.
Figure 1. Average NO concentration and emission rate for the PMEs of G40 and F59PHIs versus throttle notch position.