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

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Abstract Avoided emissions attributable to the reduction in personal automobile trips for passenger rail riders are quantified based on real-world measurements. The North Carolina Department of Transportation (NCDOT) sponsors the Piedmont passenger rail service between Raleigh and Charlotte, NC. Per passenger-kilometer locomotive emissions were quantified based on portable emissions measurement system measured exhaust concentrations and duty cycles, or the fraction of trip time spent in each throttle notch setting of the prime mover engine, from 68 one-way trips of six Tier 0+ and Tier 1+ locomotives, and actual ridership data. Motor Vehicle Emissions Simulator (MOVES) software was used to estimate light-duty gasoline vehicle (LDGV) emission factors. Moving a passenger from an LDGV to a Piedmont train would lead to a net reduction in carbon dioxide (CO_2) and carbon monoxide (CO) emissions by 44–94 %, respectively, between Raleigh and Charlotte, based on the assumption that the driver is the only LDGV passenger. However, locomotive nitrogen oxides (NO_x), hydrocarbons (HC), and particulate matter (PM) emission factors were 4–11 times higher than for the LDGV, respectively. Delays for either the train or highway vehicles did not substantially alter the key findings. If a Tier 4 locomotive was used, NO_x, PM, and HC emission rates would be 90–99 % lower than current NCDOT locomotives. The use of real-world data representative of actual train operations provides an accurate basis for comparing rail and personal vehicle energy use and emissions and for identifying key factors affecting variability in the comparison.

Keywords Intercity rail · Energy intensity · Emissions · Carbon dioxide · Nitrogen oxides · Particulate matter

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1 Introduction

There are multiple motorized passenger transportation modes, including trains and automobiles. Each mode involves different technologies, fuels, and the number of passengers that can be transported. From 2003 to 2013, Amtrak's revenue passenger-kilometers (pkm) increased 1.8 %, while the energy intensity decreased by 2.8 % to approximately 1400 kJ/pkm. This is approximately 57 and 67 % lower than the energy intensity of passenger cars and passenger trucks, respectively [1]. The latter include pickup trucks, minivans, and sport utility vehicles.

Diesel engines, such as those used in locomotives, produce exhaust emissions that affect human health [2]. Significant amounts of nitrogen oxides (NO_x), a precursor to ozone (O_3), and secondary particulate matter (PM) formation, are produced by diesel engines [3]. Nitric oxide (NO) and nitrogen dioxide (NO_2) constitute NO_x. NO_2 and O_3 are both criteria pollutants regulated by the US Environmental Protection Agency (EPA) under the National Ambient Air Quality Standards (NAAQS) because of their impact on human health [4]. Inhalation of ground-level ozone can cause health problems such as damage to lung tissue, reduction of lung function, and sensitization of the lungs to other irritants [5]. Another criteria pollutant emitted significant amounts by diesel engines is primary PM. Inhalation of PM can cause cardiovascular disease and premature mortality in humans [2, 6].

A decrease in energy intensity correlates with a reduction in emissions. There have been many analyses that compare "avoided emissions" from shifting freight from one transport mode to another [7–14]. Freight locomotives are designed differently from passenger locomotives, having larger engines with more horsepower [15]. A few analyses compare passenger rail to other means of transport. One extensive study compares emission rates from numerous alternative land-based transportation modes and fuels, with passenger rail emission rates estimated from published emissions data [16]. However, the analysis is not based on measured real-world locomotive emission rates and there is no direct comparison of emission rates from highway and rail travel. Two studies focus on high-speed rail powered by electricity from renewable sources, which are not currently in operation in the U.S., but hypothesized to be in operation in future decades [17, 18]. One study compared emissions from commuter rail, using real-world duty cycles and notch-based emission factors from laboratory measurements of the same locomotive model, to automobile travel, using an automobile emissions model, and found that commuter rail emitted more NO_x and PM, but less HC and CO [19]. Tang et al. measured black carbon emissions from passing passenger locomotives and estimated mass per passenger-kilometer emission factors for black carbon and CO_2 [20]. Locomotive exhaust was measured using a sampling line hung above a track, rather than directly from the engine. CO_2 emission factors were based on estimated fuel economies, not actual measurements. Measured locomotive black carbon emissions were estimated to be ten times higher than for a light-duty vehicle. No studies were found that estimate trip-based per passenger emission factors from exhaust emissions measured directly from the locomotive engine during operation.

The National Cooperative Rail Research Program (NCRRP) of the Transportation Research Board commissioned a model to compare energy consumption and greenhouse gas emissions from passenger rail to that of highway and air travel [21]. The resulting Multi-Modal Passenger Simulation model (MMPASSIM) allows users to specify rail equipment and route parameters to estimate energy and greenhouse gas (GHG) emission intensities per passenger-distance. The model did not include criteria air contaminants, such as NO_x, CO, HC, and PM. MMPASSIM simulates rail energy intensity using a traditional train energy and resistance methodology, and estimates GHG emission intensity using EPA-published GHG emission rates by fuel type. The model accounts for energy consumption and greenhouse gas emissions associated with operation of the transport vehicle, as well as for the fuel cycle for gasoline, diesel, or electricity.

The NCRRP report cites a strong influence of load factor on emissions intensities, with daily and seasonal ridership variations affecting the comparison of passenger rail to other transport modes [21]. The report states that the average load factor for Amtrak system-wide intercity service is 47 %. Another study indicates that for regional intercity rail, such as the Piedmont, the average load factor is 35 % [18]. For the estimation of Piedmont energy and emissions intensities, the NCRRP report characterized the typical consist configuration as one locomotive with 4 trailing passenger cars with a total seating capacity of 336 seats, and a load factor of 42 % [21].

Available data regarding locomotive emissions are typically from engine dynamometer measurements [15]. Portable emissions measurement systems (PEMS) have previously been used to measure engine exhaust concentrations during dynamometer measurements [23], static rail yard measurements [23], and passenger service [24]. PEMS can be deployed onboard a locomotive, enabling assessment of engine activity, fuel use, and emission factors without removing locomotives from service. Furthermore, PEMS can be used to obtain representative trip-based emission factors during revenue-generating service.

Locomotive emissions are affected by age, emission standard, emissions controls, and duty cycles. The age of the locomotive determines the emission standards the locomotive must meet when manufactured or remanufactured, and the emission controls used to achieve those standards [3]. Variations in duty cycle may lead to variations in trip total emissions [25]. Numerous factors can lead to variations in observed duty cycles and travel time, including: (1) differences in operating behavior among engineers; (2) longer than scheduled periods at the rail station to load and unload passengers; (3) slow orders because of weather or track repair; and (4) allowing other rail traffic to pass by changing tracks or stopping on a siding [24]. Stopping in the siding or remaining at a station longer than scheduled increases trip duration and the duration and percentage of time spent in idle. Delays in rail travel time could lead to a less favorable comparison of the train versus avoided highway emissions.

Conversely, delays in highway travel time could lead to a more favorable comparison of the train versus highway emissions. Highway vehicle emission rates are affected by vehicle type, time of day, travel time, and trip average speed [26, 27]. Passenger trucks, on average, have higher energy intensities than passenger cars, which lead to higher emissions [1]. The time of day can have an effect on roadway congestion, such as during rush hour commutes to and from work. Idling in highway congestion decreases trip average speed and increases travel time. In one study, decreased congestion, during non-rush hours, approximately doubled trip average speed and decreased NO_x, CO, and HC emission rates by up to 60 % [27]. CO_2 emission rates typically increase as trip average speed decreases [28].

In a previous report, Frey and Graver compared emissions from passenger rail and highway vehicles in North Carolina using the same methodology introduced here [22]. The report estimated emission rates for three F59PH, one F59PH, and one GP40 locomotives for five origin and destination rail station pairs. Additional emissions and duty cycle measurements and more recent passenger rail ridership data have been collected, and are included here. The locomotive fleet composition has also changed since the report, and this research represents the current fleet. In addition, the effect of delay with respect to rail and highway vehicle emissions is now considered.

1.1 Objectives

The objectives here are to determine: (1) if rail travel has lower per passenger-kilometer emission factors compared to travel with a highway vehicle; (2) if rail travel emission factors are sensitive to where on the route a rider boards the train; (3) if rail travel delays significantly increase per passenger-kilometer emission factors; and (4) if highway travel delays significantly increase per passenger-kilometer emission factors. Compared to previous literature, this paper is based on real-world measurements of the actual locomotive emissions, and is not based on an estimate or a model. To achieve this, methods to measure locomotive exhaust emissions, and estimate locomotive and highway vehicle emission factors were derived, as described in Sect. 2. The results of the emissions measurement and modeling are presented and discussed in Sect. 3, while Sect. 4 provides final conclusions of the research.

2 Methods

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

2.1 Field Study Design

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

2.1.1 *Locomotives*

One of the fastest growing routes for Amtrak, in terms of relative change in ridership, is the Piedmont in North Carolina. Through a joint effort between the North Carolina Department of Transportation (NCDOT) and Amtrak, daily passenger rail service is provided between Raleigh and Charlotte, and seven cities in between, as shown in Fig. 1. Currently, two trains operate in both directions each day. Typically, each train is comprised of one locomotive, one baggage/lounge car, and two passenger cars. Additional passenger cars are added, if warranted by ridership figures, such as during the weekends. The capacity of each passenger car varies between 56 and 66 seats.

The NCDOT owns two Electro-Motive Diesel (EMD) F59PHI model and four EMD F59PH model locomotives and associated rolling stock. Each locomotive has a 12-cylinder, 140-L, 2237-kW EMD 12–710 prime mover engine (PME) used to provide direct current electric power for propulsion. A smaller 671-kW head-end power (HEP) engine is used to generate alternating current power for "hotel services" in the passenger cars, such as lighting, heating, and cooling. All locomotives were remanufactured within the last 4 years to meet the Tier 0+ and Tier 1+ emission standards for the F59PH and F59PHI locomotives, respectively. New locomotives manufactured in 2015 must meet Tier 4 emission standards, which have NO_x emission rates 82–86 % lower than the Tier 0+ and Tier 1+ standards, respectively. Tier 4 PM emission rate standards are 86 % lower than the Tier 0+ and Tier 1+ standards [29].

PME notch position was inferred from engine solenoid operation data archived by an onboard data recorder. Real-time engine output data was provided on a digital display in the locomotive cab, but was not archived by the data recorder. An analyst recorded engine output at each notch from the digital display for at least one measurement of each locomotive.

2.1.2 *Portable Emissions Measurement System*

A PEMS was used to measure PME and HEP exhaust CO_2, CO, HC, NO, and PM concentrations. The PEMS used were the Montana and Axion systems, both manufactured by Clean Air Technologies, Inc. (now GlobalMRV) [30]. Each PEMS was comprised of two parallel five-gas analyzers, a PM measurement system, and an engine sensor array with sensors to measure engine speed (RPM), manifold absolute pressure (MAP), and intake air temperature (IAT). Nondispersive infrared (NDIR) detection was used for CO_2, CO, and HC measurement, and laser light scattering was used to measure PM. A less biased HC measurement method, flame ionization detection (FID), was

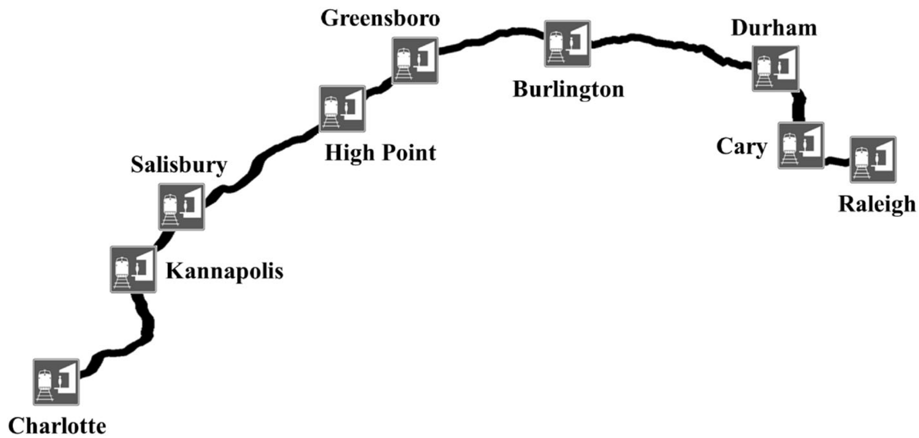

Fig. 1 Route map of the North Carolina AMTRAK Piedmont passenger rail service

not used in this study because FID requires the use of hydrogen as a "fuel" to burn the HC sample without contributing carbon to the sample. However, transporting a hydrogen gas mixture onboard the locomotive is prohibited. For measurement of NO, electrochemical sensing was used. RPM, MAP, and IAT were used to quantify engine air flow using the speed density method, which is based on the ideal gas law with empirical adjustment [31, 32].

To measure MAP, a pressure sensor was installed on the PME via a port on the intake air manifold. An optical RPM sensor was used in combination with reflective tape to measure the time interval of revolutions of a flywheel that rotates at the same speed as the engine crankshaft. The IAT sensor is a thermistor that is installed in the PME intake air flow path. For the HEPs, engine load was measured based on voltage and current delivered to passenger cars. Engine speed was displayed on an electronic screen on the HEP.

The PEMS has been validated by an EPA Environmental Technology Verification assessment which indicated that the PEMS has good covariation and precision in measuring pollutant concentrations [33]. The same PEMS has been used in prior measurements of the same or similar locomotives [23, 24]. Emission rates measured using the PEMS are comparable to those reported elsewhere [15].

The PEMS was calibrated with a calibration gas (BAR-97 Low) which has pollutant concentrations that are in the range of what would be emitted from a diesel engine. To test the linearity of the PEMS sensor response, an experiment was conducted in our lab. The PEMS was calibrated with the Low blend, and both BAR-97 Low and BAR-97 High (with pollutant concentrations that are in the range of what would be emitted from a gasoline engine) blends were passed through the PEMS and pollutant concentrations measured. The PEMS was then calibrated with the High blend, and both Low and High blends were passed through the PEMS and pollutant concentrations measured. Differences between the pollutant concentration of the calibration gas measured by the PEMS and the labeled calibration gas pollutant concentration were within 6 % of the average of the two PEMS benches.

Correction factors were used to adjust for biases associated with the PEMS emissions measurement methods. In a previous study, rail yard measurements were made with a SEMTECH-DS PEMS that measures both NO and NO_2, as well as HC with FID and NDIR [34]. 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 calculated NO_x/NO ratios were used as the NO_x bias correction factor. The ratio of FID to NDIR, measured using the SEMTECH, was used to bias correct Axion HC concentrations to a total HC basis. An evaluation of the light scattering PM measurement technique showed emission measurement as much as 80 % lower versus the Federal Reference Method [35]. Thus, opacity-based PM emission factors were based on a correction factor of 5 to approximate total PM.

2.1.3 Data Collection Procedure

The locomotive engines were instrumented and exhaust concentration and engine activity data were measured continuously over-the-rail (OTR) for the PMEs and in the rail yard (RY) for the HEPs. The PME of each locomotive was measured OTR since it better reflects real-world locomotive operation than RY measurements [24]. RY HEP measurements were conducted since HEP operation typically remains constant regardless of locomotive operation.

For OTR PME measurements, the locomotives were operated normally during revenue-generating Piedmont passenger service by Amtrak engineers. The twice-daily Piedmont rail service covers a distance of 278 km, with a scheduled duration of 3 h and 10 min. Typically, each train is composed of one locomotive, one baggage/lounge car, and two passenger cars. Sixty-eight one-way OTR measurements were conducted on six locomotives. All of the locomotives operated on the same route. Therefore, they were subject to the same rail grade.

For RY HEP measurements, the HEP engine was run at multiple electrical loads for a period of 5–10 min for each load. Electrical loads were created by coupling passenger cars to the locomotive and operating the lighting and air condition/heating systems in each car. The electrical load conditions correspond to the number of passenger cars, from zero to four, being powered by the HEP. Because of variability in availability of passenger cars in the rail yard on a given measurement day, there was some measurement-to-measurement variability in the number of cars used. During the measurements, voltages and currents for each load were measured to estimate the electrical loads.

2.2 Data Quality Assurance

Data for PEMS exhaust concentrations, engine activity data from the sensor array, and locomotive activity data were time-aligned. From previous dynamometer and RY measurements, it is known that as notch position increases, RPM, MAP, and CO_2, NO_x, and PM concentrations typically increase [23]. Exhaust concentrations were time-synchronized with sensor array data by ensuring that any change in RPM and MAP corresponds to the appropriate change in measured exhaust concentrations. Sensor array and locomotive activity data were synchronized based on a change in notch inferred from activity recorder data and the corresponding change in RPM observed from the sensor array.

Measured data were screened for errors. Emission concentrations from one gas analyzer were compared to the other, and if the difference did not exceed a maximum allowable difference (MAD) threshold, then the concentrations were averaged. However, if the inter-analyzer discrepancy exceeded the MAD, either the data were not used or data from an analyzer suspected of producing invalid measurements were excluded and only data from the valid analyzer were used. HC and CO concentrations in diesel engine exhaust tend to be low, because these engines operate with excess air and have efficient combustion [3]. Negative values for these pollutants that were within the precision of the instrument were assumed to be zero. Additional details on data processing and quality assurance procedures are given elsewhere [36–38].

2.3 Locomotive Emission Factors

The base case PME and HEP emission factors are based on on-time travel, which is defined as within 10 min of the scheduled travel time between Raleigh and Charlotte. PME emission factors are dependent on various engine parameters, pollutant exhaust concentrations, route distance, and train ridership. HEP emission factors are dependent on pollutant exhaust concentrations, route distance, and train ridership.

2.3.1 Prime Mover Engine

The PME operates at eight discrete throttle notch positions, in addition to idle and dynamic braking. A different combination of engine speed, MAP, and horsepower output is associated with each notch position. The percentage of time spent in each notch position over an entire trip is referred to as a duty cycle. Each locomotive has an activity data recorder. Notch position is inferred from engine solenoid operation data archived by the activity data recorder.

Time-based emission factors were estimated based on engine mass air flow, air-to-fuel ratio (AFR), and pollutant exhaust concentrations. AFR was inferred from the measured exhaust composition. Mass air flow was estimated based on key engine parameters using the “speed density” method which is based on the ideal gas law [31, 32]. The key engine parameters include strokes per cycle, compression ratio, displacement, RPM, MAP, IAT, and volumetric efficiency. Intake air molar flow rate is:

$$M_a = \frac{\left(P_M - \frac{P_B}{ER}\right) \times EV \times \left(\frac{ES}{30 \times EC}\right) \times VE}{R \times (T_{int} + 273.15)}, \tag{1}$$

where EC is the engine strokes per cycle (2), ER is the engine compression ratio (typically 15–16), ES is the engine speed (RPM), EV is the engine displacement (L), M_a is the intake air molar flow rate (mole/sec), P_B is the barometric pressure (101 kPa), P_M is the engine manifold absolute pressure (kPa), T_{int} is the intake air temperature (°C), and VE is the engine volumetric efficiency (ratio).

Volumetric efficiency (VE) is the ratio of the actual volume of air that flows through the engine cylinder versus the physical cylinder volume. VE takes into account factors that affect real air flow and is affected by engine design and operational factors, such as notch. VE was found to be well correlated with the product of measured RPM and MAP observed during prior dynamometer measurements of similar EMD 12-710 PMEs [23].

Mass per time emission factors were estimated based upon the mole fraction of each pollutant on a dry basis, dry exhaust molar flow rate, and the molecular weight of the exhaust gas. Exhaust molar flow rate on a dry basis was estimated based on M_a and AFR.

Fuel flow rate was estimated from the mass air flow and AFR. A digital display in the locomotive cab displays the volume of fuel remaining in the locomotive fuel tank, and is updated every 38 L of fuel consumed. In a previous study, a researcher recorded the volume of fuel from the display at the start and finish of multiple RY PME measurements, and compared it to the estimated amount of fuel consumed from the PEMS-measured exhaust emissions. On average, the difference between the estimated and displayed fuel use was 3 %, with a 95-% confidence interval of ±3 %.

For PM, the PEMS reports mg/m^3 concentration on a dry basis. Dry exhaust flow per liter of fuel consumed was estimated based on AFR. The volume of exhaust produced per liter of fuel was multiplied by the mass per volume concentration of PM to estimate the g/L PM emission rate. The latter was multiplied by fuel flow rate to estimate the mass per time PM emission rate.

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

For each segment on each trip, the time spent in each notch position was multiplied by the average time-based PME emission factors for each notch and summed over all notches to derive the total PME emissions released over a segment:

$$E_{xij} = \sum_{n=\text{idle}}^{8} \left(t_{nij}\right)\left(ER_{xn}\right), \tag{2}$$

where E_{xij} is the mass of pollutant x between station i and station j (g), ER_{xn} is the emission rate of pollutant x at notch position n (g/s), and t_{nij} is the time in notch position n between station i and station j (s).

Total PME emissions released over a route are the summation of the total emissions released over all of the segments between the origin and destination stations:

$$E_{xOD} = \frac{\sum_{O}^{D} E_{xij}}{d_{OD}}, \tag{3}$$

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

Mass per passenger emission factors over a segment were derived by dividing the total emissions released over the segment by the average ridership over the segment:

$$EP_{xij} = \frac{E_{xij}}{p_{ij}}, \tag{4}$$

where E_{xij} is the mass of pollutant x between station i and station j (g), EP_{xij} is the mass of pollutant x between station i and station j per passenger (g/pax), and p_{ij} is the ridership between station i and station j (pax).

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

$$ED_{xOD} = \frac{\sum_{O}^{D} EP_{xij}}{d_{OD}}, \tag{5}$$

where d_{OD} is the distance between origin station O and destination station D (km), ED_{xOD} is the mass of pollutant x between origin station O and destination station D summed over all constituent station-to-station pairs i and j per passenger-kilometer (g/pax-km), and EP_{xij} is the mass of pollutant x between station i and station j per passenger (g/pax).

Based on the CO_2 emission factors for the locomotive chassis, including both the PME and HEP engine, energy intensity was estimated using a published diesel net heating value of 35,873 kJ/L and a conversion factor of 2690 g of direct CO_2 emissions per L of diesel [1].

Table 1 Distance, scheduled travel time, and Fiscal Year 2013 average ridership by segment for the Piedmont route from Raleigh to Charlotte, NC

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

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

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

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

2.3.2 Head-End Power (HEP) Engine

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

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

Often, fuel-specific engine output (FSEO) is reported or used in regulatory work to describe fuel consumption. EPA reports a typical FSEO of 4.1 kWhr/L [39]. Therefore, HEP fuel flow is estimated to be 38 g/s at full load, based on this FSEO and assuming a fuel density of 0.8412 mg/L.

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

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

2.4 Light-Duty Gasoline Vehicle (LDGV) Emissions

The EPA's Motor Vehicle Emissions Simulator (MOVES) was used to estimate mass per passenger-kilometer emission factors for LDGVs. The user specifies vehicle types, geographical areas, pollutants, vehicle operating characteristics (e.g., vehicle speed), and road types (e.g., rural/urban, restricted/unrestricted access) [40].

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

To obtain speed and road grade profiles between terminus rail stations, a passenger vehicle was instrumented with an on-board diagnostic (OBD) electronic control unit (ECU) data recorder and a handheld global positioning system (GPS) receiver with barometric altimeter, and driven between Raleigh and Charlotte rail stations. The driver observed speed limits during arterial driving and maintained the speed of the vehicles traveling in the middle lane of a six-lane highway and the left lane of a four-lane highway. Latitude, longitude, and elevation were used to estimate road grade using a methodological approach reported elsewhere [36]. The speed profile from the ECU data recorder and the estimated road grade profile were used as inputs into MOVES.

The instrumented passenger vehicle was driven on three segments, as summarized in Table 2. These routes were determined by readily available online tools and evaluated on judgment as to routes that were likely to be selected by knowledgeable drivers. Vehicle travel and associated emissions were estimated for five station pairs. Travel between the Raleigh and Charlotte station pair is estimated using Segment Road-A. For the other four station pairs, a combination of two additional road segments is needed. For example, parts of Segments Road-A and Road-C are used to obtain speed and road grade profiles for travel between the Durham and Charlotte station pair. Segment Road-C is used for travel from the Durham train station to

Table 2 Road segments used in the Motor Vehicle Emissions Simulator (MOVES) software to estimate light-duty gasoline vehicle emissions

Segment	Station pair	Travel distance (km)	Travel time (s)
Road-A	Raleigh and Charlotte	264.4	8713
Road-B	Cary and Durham	31.7	1377
Road-C	Durham and Greensboro	83.2	3152

Segments are not directional specific. For example, segment Road-A consists of travel from Raleigh to Charlotte and from Charlotte to Raleigh the interstate, where it overlaps with Segment Road-A. Segment Road-A is used from the interstate to Charlotte train station. Likewise, data were spliced to represent vehicle travel between Greensboro and Charlotte, Cary and Charlotte, and Raleigh and Greensboro.

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

3 Results

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

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

3.1 Duty Cycles

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

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

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

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

3.2 Passenger Load Factor

Each Piedmont train is comprised of one locomotive, one baggage/lounge car, and two passenger cars, with additional passenger cars added if warranted by ridership

Table 3 Piedmont rail station pairs with highest ridership for Fiscal Year 2013

Station pair	Average one-way ridership (passengers)	Segments	One-way distance (km)
Raleigh, NC ↔ Charlotte, NC	18.6	A through H	278.3
Greensboro, NC ↔ Charlotte, NC	12.9	E through H	148.2
Cary, NC ↔ Charlotte, NC	12.5	B through H	264.9
Durham, NC ↔ Charlotte, NC	11.5	C through H	235.9
Raleigh, NC ↔ Greensboro, NC	9.1	A through D	130.0

Station pairs are not directional specific

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

Table 4 Comparison of mean measured duty cycles during one-way Piedmont trips based on various differences in travel duration

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

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

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

figures. The capacity of each passenger car varies between 56 and 66 seats, not 84 seats as characterized in the NCRRP report. The average load factor for the Piedmont in Fiscal Year 2013, based on Amtrak ridership data, was approximately 77 %, or 35 percentage points higher than the average load factor used in NCRRP calculations [41]. The results in subsequent sections uses actual Piedmont ridership, rather than a previously published average load factor.

3.3 Locomotive Emission Factors

For each locomotive, notch average emission factors were estimated for idle, dynamic brake, and the eight notch positions of the PME. The measured notch average values of RPM, IAT, and MAP used to estimate emission factors were repeatable, with inter-run variability of typically <5 %. On average, as the load on the PME increases, the notch average emission factors of all pollutants increase. Figure 2 shows fleet average time-based emission rates at each notch position. The lowest emission factors are typically observed at idle and the highest emission factors are at Notch 8. There is not a monotonic trend in the HC emission factors with increasing engine load because most HC concentrations were at or below the PEMS detection limit.

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

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

The NCDOT locomotive fleet average energy intensity estimated is reasonable based on comparisons to published values. The fleet average energy intensity of 1696 kJ/pkm is 22 % higher than the published Amtrak intercity rail energy intensity of 1,389 kJ/pkm [1]. An energy intensity of 1067 kJ/pkm was cited by the U.S. Department of Transportation's Bureau of Transportation Statistics (BTS) for the Amtrak fleet in 2011 [42]. However, not all Amtrak locomotives are diesel-electric powered, like the NCDOT fleet, and the energy intensity accounts for both diesel-electric and electric locomotives. The electric locomotives, which are used on Amtrak's Northeast Corridor, have lower energy intensities than diesel-electric powered locomotives [21]. The breakdown of Amtrak revenue passenger-kilometers between electric and diesel locomotives was not published. However, the Northeast Corridor has Amtrak's second largest ridership [43].

The energy intensity for a Piedmont train estimated by the MMPASSIM and reported in the NCRRP report is 1063 kJ/pkm, similar to the energy intensity from BTS and

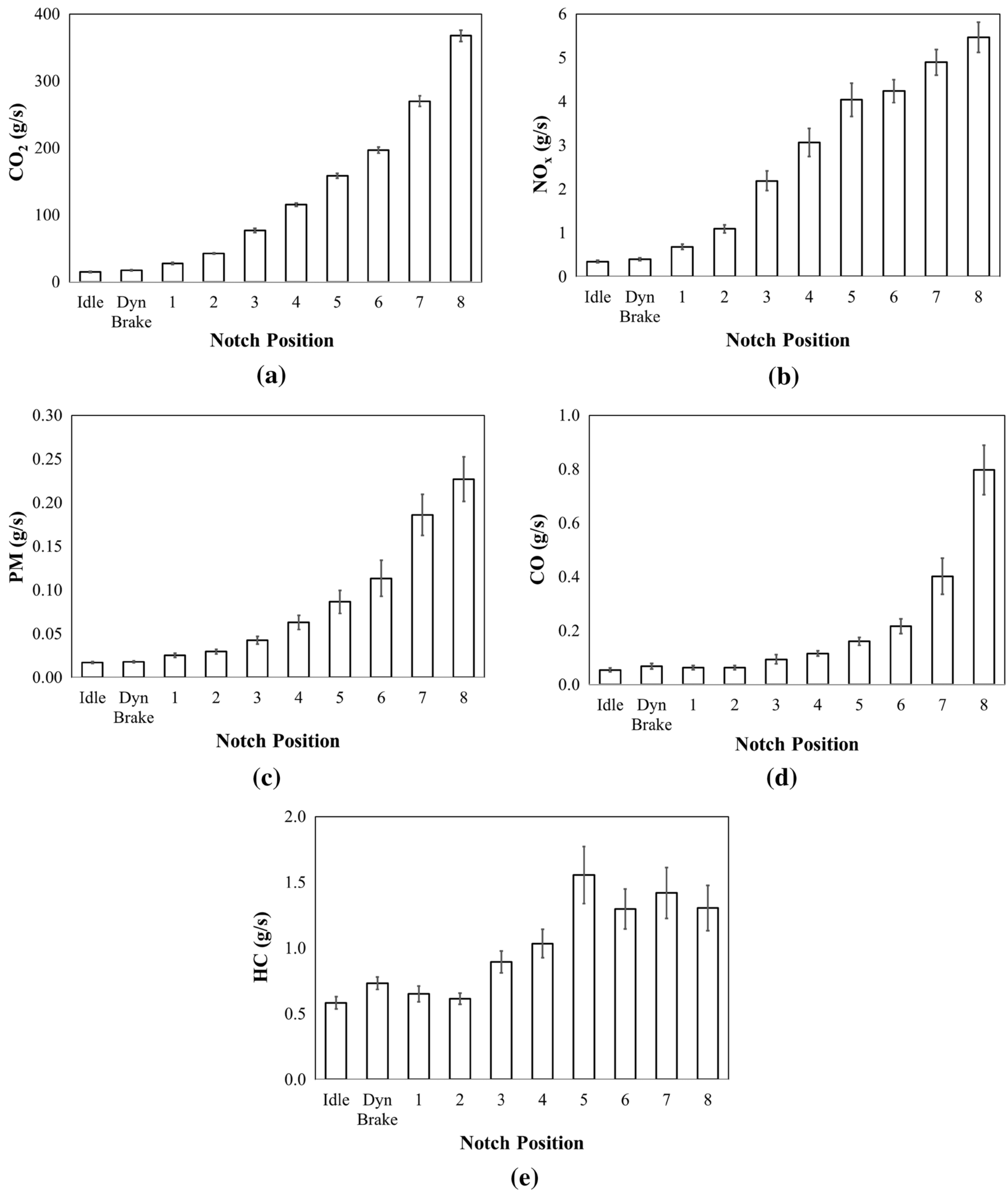

Fig. 2 Fleet average emission factors of the prime mover engine at each notch position from thirty-six over-the-rail measurements using six locomotives. *Error bars* represent 95 % confidence intervals of the mean emission factor. **a** Carbon dioxide, **b** Nitrogen oxides, **c** Particulate matter, **d** Carbon monoxide, **e** Hydrocarbons

37 % lower than the energy intensity estimated based on measured CO_2 emission factors. The NCRRP report states that train weight, length, rolling resistance, and seating capacity are needed to calculate energy intensity in MMPASSIM [21]. The number of passenger cars and seating capacity of each car was incorrectly assumed in the NCRRP report for the Piedmont. This will affect the overall weight and length of the train consist and, therefore, the energy intensity estimation. The NCDOT fleet average CO_2 emission factor was approximately 88 % higher than the 904 kJ/pkm emission factor published for Metrolink locomotives with larger remanufactured engines that meet more stringent emission standards than the NCDOT locomotives [19]. Metrolink commuter service also had average

Table 5 Locomotive per passenger-kilometer (pkm) emission factors for on-time one-way Piedmont trips between Raleigh and Charlotte, NC

Locomotive	Emission factor (g/pkm)[a]				
	CO_2	NO_x^b	PM[c]	CO	HC[d]
Prime mover engine					
NC 1810	120 (*0.17*)	1.55 (*0.02*)	0.07 (*0.18*)	0.38 (*0.19*)	1.01 (*0.09*)
NC 1859	109 (*0.17*)	1.37 (*0.14*)	0.10 (*0.16*)	0.20 (*0.17*)	1.20 (*0.10*)
NC 1869	129 (*0.16*)	1.74 (*0.13*)	0.12 (*0.15*)	0.35 (*0.20*)	0.24 (*0.17*)
NC 1893	99.0 (*0.16*)	1.62 (*0.14*)	0.05 (*0.15*)	0.13 (*0.18*)	0.30 (*0.10*)
F59PH average	114 (*0.16*)	1.57 (*0.11*)	0.09 (*0.16*)	0.27 (*0.19*)	0.69 (*0.12*)
NC 1755	99.1 (*0.16*)	1.62 (*0.14*)	0.05 (*0.15*)	0.13 (*0.19*)	0.30 (*0.11*)
NC 1797	108 (*0.16*)	2.85 (*0.13*)	0.04 (*0.17*)	0.18 (*0.15*)	0.87 (*0.09*)
F59PHI average	104 (*0.16*)	2.24 (*0.14*)	0.05 (*0.16*)	0.16 (*0.17*)	0.59 (*0.10*)
Fleet average	111 (*0.16*)	1.79 (*0.12*)	0.07 (*0.16*)	0.23 (*0.18*)	0.65 (*0.11*)
Head-end power (HEP) engine					
NC 1810	7 (*0.11*)	0.07 (*0.11*)	<0.01 (*0.11*)	0.03 (*0.11*)	0.02 (*0.11*)
NC 1859	7 (*0.11*)	0.07 (*0.11*)	<0.01 (*0.11*)	0.03 (*0.11*)	0.01 (*0.11*)
NC 1869	7 (*0.11*)	0.05 (*0.11*)	<0.01 (*0.11*)	0.04 (*0.11*)	0.01 (*0.11*)
Average	7 (*0.10*)	0.06 (*0.17*)	<0.01 (*0.14*)	0.03 (*0.14*)	0.01 (*0.23*)

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

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

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

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

ridership of 275 passengers per train, approximately 2.2 times greater ridership than the average Piedmont service.

3.3.1 On-Time Scenario

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

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

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

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

A sensitivity analysis was conducted to determine the difference in PME emissions if Piedmont passenger rail service was operated by a Tier 4 locomotive, rather than the locomotives in the NCDOT fleet. The Tier 4 NO_x emission standard is 90 % lower than the OTR-measured fleet average NO_x emission rate of 7.46 g/kW-h. The Tier 4 PM and HC emission standards are 96–99 % lower, respectively, than the fleet average PM and HC emission rates of 0.30 and 7.20 g/kW-h, respectively, for the locomotives in the NCDOT fleet. There was no difference between the fleet average CO emission rate and the Tier 4 standard.

3.3.2 Sensitivity of Locomotive Emission Factors to Delays

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

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

3.3.3 Sensitivity of Locomotive Emission Factors to Station Pair

Average emission factors vary depending on the O/D pair, as shown in Table 7. For example, the fleet average CO_2 emission factors vary from 96.9 to 135 g/pkm when comparing the lowest rate, for the Durham and Charlotte station pair, to the highest rate, for the Raleigh and Greensboro station pair. The per passenger-kilometer emission rates for the Durham and Charlotte station pair are 28–31 % higher among each of the pollutants when compared to the

Table 6 Locomotive per passenger-kilometer (pkm) emission factors for Piedmont service between Raleigh and Charlotte, NC for on-time and delayed trips

Locomotives	Emission factor (g/pkm)[a]				
	CO_2	NO_x^b	PM[c]	CO	HC[d]
On-time (45 trips, average trip duration: 11,480 s)					
F59PH	121 (*0.13*)	1.63 (*0.14*)	0.09 (*0.15*)	0.30 (*0.17*)	0.70 (*0.17*)
F59PHI	110 (*0.13*)	2.30 (*0.16*)	0.05 (*0.15*)	0.19 (*0.16*)	0.60 (*0.16*)
Fleet	118 (*0.13*)	1.86 (*0.15*)	0.08 (*0.15*)	0.26 (*0.16*)	0.67 (*0.17*)
10- to 20-min late (13 trips, average trip duration: 12,261 s)					
F59PH	125 (*0.11*)	1.67 (*0.15*)	0.09 (*0.14*)	0.31 (*0.14*)	0.74 (*0.19*)
F59PHI	113 (*0.12*)	2.34 (*0.15*)	0.05 (*0.14*)	0.20 (*0.14*)	0.63 (*0.18*)
Fleet	121 (*0.11*)	1.89 (*0.15*)	0.08 (*0.14*)	0.27 (*0.14*)	0.70 (*0.19*)
20- to 30-min late (8 trips, average trip duration: 12,852 s)					
F59PH	122 (*0.09*)	1.63 (*0.13*)	0.09 (*0.11*)	0.31 (*0.12*)	0.75 (*0.18*)
F59PHI	111 (*0.09*)	2.30 (*0.13*)	0.05 (*0.11*)	0.20 (*0.12*)	0.65 (*0.18*)
Fleet	118 (*0.09*)[e]	1.85 (*0.13*)[e]	0.08 (*0.11*)	0.27 (*0.12*)	0.71 (*0.18*)
More than 30-min late (2 trips, average trip duration: 14,449 s)					
F59PH	130 (*0.06*)	1.87 (*0.12*)	0.10 (*0.10*)	0.31 (*0.12*)	1.07 (*0.23*)
F59PHI	118 (*0.06*)	2.73 (*0.14*)	0.06 (*0.16*)	0.22 (*0.15*)	0.96 (*0.25*)
Fleet	126 (*0.06*)	2.15 (*0.13*)	0.09 (*0.12*)	0.28 (*0.13*)	1.04 (*0.24*)

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

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

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

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

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

Table 7 Locomotive and light-duty gasoline vehicle (LDGV) per passenger-kilometer (pkm) emission factors for on-time Piedmont service between five origin and destination station pairs

Transport method	Emission factor (g/pkm)[a]				
	CO_2	NO_x^b	PM[c]	CO	HC[d]
Raleigh (RGH) ↔ Charlotte (CLT)					
F59PH locomotive	121 (*0.13*)	1.63 (*0.14*)	0.09 (*0.15*)	0.30 (*0.17*)	0.70 (*0.17*)
F59PHI locomotive	110 (*0.13*)	2.30 (*0.16*)	0.05 (*0.15*)	0.19 (*0.16*)	0.60 (*0.16*)
Locomotive fleet	118 (*0.13*)	1.86 (*0.15*)	0.08 (*0.15*)	0.26 (*0.16*)	0.67 (*0.17*)
LDGV	265	0.59	0.008	5.39	0.14
Greensboro (GRO) ↔ Charlotte (CLT)					
F59PH locomotive	103 (*0.13*)	1.39 (*0.14*)	0.08 (*0.15*)	0.25 (*0.16*)	0.58 (*0.17*)
F59PHI locomotive	93.9 (*0.13*)	1.96 (*0.15*)	0.04 (*0.15*)	0.16 (*0.15*)	0.49 (*0.16*)
Locomotive fleet	100 (*0.13*)	1.58 (*0.14*)	0.06 (*0.15*)	0.22 (*0.16*)	0.55 (*0.17*)
LDGV	262	0.58	0.008	5.08	0.14
Cary (CYN) ↔ Charlotte (CLT)					
F59PH locomotive	105 (*0.12*)	1.42 (*0.13*)	0.08 (*0.14*)	0.26 (*0.16*)	0.60 (*0.16*)
F59PHI locomotive	96.0 (*0.12*)	2.00 (*0.15*)	0.04 (*0.14*)	0.16 (*0.15*)	0.51 (*0.15*)
Locomotive fleet	102 (*0.12*)	1.62 (*0.14*)	0.07 (*0.14*)	0.23 (*0.15*)	0.57 (*0.16*)
LDGV	262	0.58	0.008	5.13	0.14
Durham (DNC) ↔ Charlotte (CLT)					
F59PH locomotive	100 (*0.13*)	1.35 (*0.13*)	0.07 (*0.14*)	0.30 (*0.17*)	0.70 (*0.17*)
F59PHI locomotive	90.9 (*0.13*)	1.90 (*0.15*)	0.04 (*0.14*)	0.15 (*0.15*)	0.48 (*0.16*)
Locomotive fleet	96.9 (*0.13*)	1.53 (*0.14*)	0.06 (*0.14*)	0.22 (*0.16*)	0.54 (*0.16*)
LDGV	262	0.58	0.008	5.13	0.14
Raleigh (RGH) ↔ Greensboro (GRO)					
F59PH locomotive	139 (*0.14*)	1.88 (*0.15*)	0.10 (*0.16*)	0.35 (*0.17*)	0.82 (*0.17*)
F59PHI locomotive	127 (*0.14*)	2.64 (*0.16*)	0.06 (*0.15*)	0.22 (*0.16*)	0.71 (*0.17*)
Locomotive fleet	135 (*0.14*)	2.13 (*0.15*)	0.09 (*0.15*)	0.30 (*0.17*)	0.78 (*0.17*)
LDGV	264	0.58	0.008	5.17	0.14

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

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

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

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

Raleigh and Greensboro station pair. There are a larger number of station stops per kilometer between Raleigh and Greensboro than for other portions of the Piedmont route. In addition, the rail segments between Raleigh, Cary, and Durham have the lowest ridership. Therefore, station pairs that include these segments have higher per passenger-kilometer emission rates than the station pairs that exclude these segments.

3.4 Light-Duty Gasoline Vehicles (LDGVs)

Fleet average emission factors based on MOVES for travel by PC and PT are shown in Table 8. The LDGV emission factors for CO_2, NO_x, and CO are within approximately 10 % of national average emission factors estimated using EPA total emissions and U.S. Department of Transportation highway statistics [1]. The HC and PM emission factors based on MOVES are lower by approximately 80 %. The EPA total emissions used to estimate the national average HC and PM emission factors included motorcycles, which emit higher levels of HC and PM compared to LDGVs [44]. Thus, the emission factor estimates for these pollutants are appropriately comparable to other reported values and appear to be valid.

The LDGV fleet average energy intensity based on MOVES is estimated at 3674 kJ/pkm. The MMPASSIM-estimated energy intensity for a LDGV traveling between Raleigh and Charlotte was 3528 kJ/pkm, or 4 % lower.

Table 8 Light-duty gasoline vehicle per passenger-kilometer (pkm) energy intensity and emission factors for travel between Raleigh and Charlotte, NC under various delay scenarios

Delay scenario	Trip average speed (kph)	Energy intensity (kJ/pkm)	Emission factor (g/pkm)[a, b]				
			CO_2	NO_x	PM	CO	HC
On-time		**3681**	**265**	**0.59**	**0.008**	**5.39**	**0.14**
Passenger car	109	*2969*	*213*	*0.31*	*0.005*	*3.05*	*0.07*
Passenger truck		*4464*	*321*	*0.89*	*0.011*	*7.96*	*0.21*
15 min		**3742**	**269**	**0.60**	**0.008**	**5.40**	**0.14**
Passenger car	100	*3025*	*217*	*0.32*	*0.005*	*3.06*	*0.07*
Passenger truck		*4531*	*326*	*0.90*	*0.011*	*7.97*	*0.22*
30 min		**3801**	**273**	**0.63**	**0.008**	**5.40**	**0.15**
Passenger car	90.6	*3077*	*221*	*0.34*	*0.005*	*3.06*	*0.07*
Passenger truck		*4596*	*330*	*0.94*	*0.011*	*7.99*	*0.23*
45 min		**3859**	**277**	**0.63**	**0.008**	**5.43**	**0.15**
Passenger car	83.3	*3130*	*225*	*0.34*	*0.005*	*3.06*	*0.07*
Passenger truck		*4660*	*335*	*0.94*	*0.011*	*8.02*	*0.24*
60 min		**3916**	**281**	**0.65**	**0.008**	**5.43**	**0.16**
Passenger car	77.2	*3181*	*229*	*0.35*	*0.005*	*3.06*	*0.08*
Passenger truck		*4725*	*340*	*0.97*	*0.011*	*8.04*	*0.24*

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

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

MMPASSIM estimates LDGV energy intensity based on chosen route characteristics and the vehicle characteristics of purchased and driven vehicles of recent years [21]. MOVES uses an age distribution to account for differences in energy use and emissions of LDGV of different model years that may be more representative of the vehicle fleet than just recent model years. However, the LDGV energy intensity from MOVES and the NCRRP report are quite similar given the differences in estimation methodologies.

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

The LDGV fleet average emission rates for all pollutants increased as the duration of the delay increased. This is in agreement with previous literature [26–28]. Based on real-world measurements of older Tier 1 certified vehicles, Unal et al. found that the magnitude of increase in total emission for the same distance is comparable to the percentage increase in travel time [27]. Here, for 15 min of delay, which increased travel time by 10 %, the trip average emission rates for HC increased by 3 %, NO_x and CO_2 increased by 2 %, and CO and PM increased by less than 0.2 %. For 45 min of delay, the trip average HC emission rates increased by 12 %, NO_x increased by 11 %, CO_2 increased by 6 %, and CO and PM increased by less than 1 %. Although the increase in trip average emission rates was modest, the emission rates for the delay segments were higher than for the rest of the trip for HC, CO_2, CO, NO_x, and PM by 172, 83, 36, 11, and 4 %, respectively. Each 15-min delay on the highway equates to an additional 1.2 g of HC, 2.8 g of CO, 3.6 g of NO_x, 1.2 kg of CO_2, and 0.5 mg of PM.

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

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

The energy intensities for PCs and PTs estimated by MOVES were similar to published values. The on-time PC energy intensity from MOVES of 2962 kJ/pkm is 7 % lower than the 3195 kJ/vehicle-km in the literature, assuming one person per vehicle [1]. The on-time PT energy intensity of 4458 kJ/pkm from MOVES is 5 %

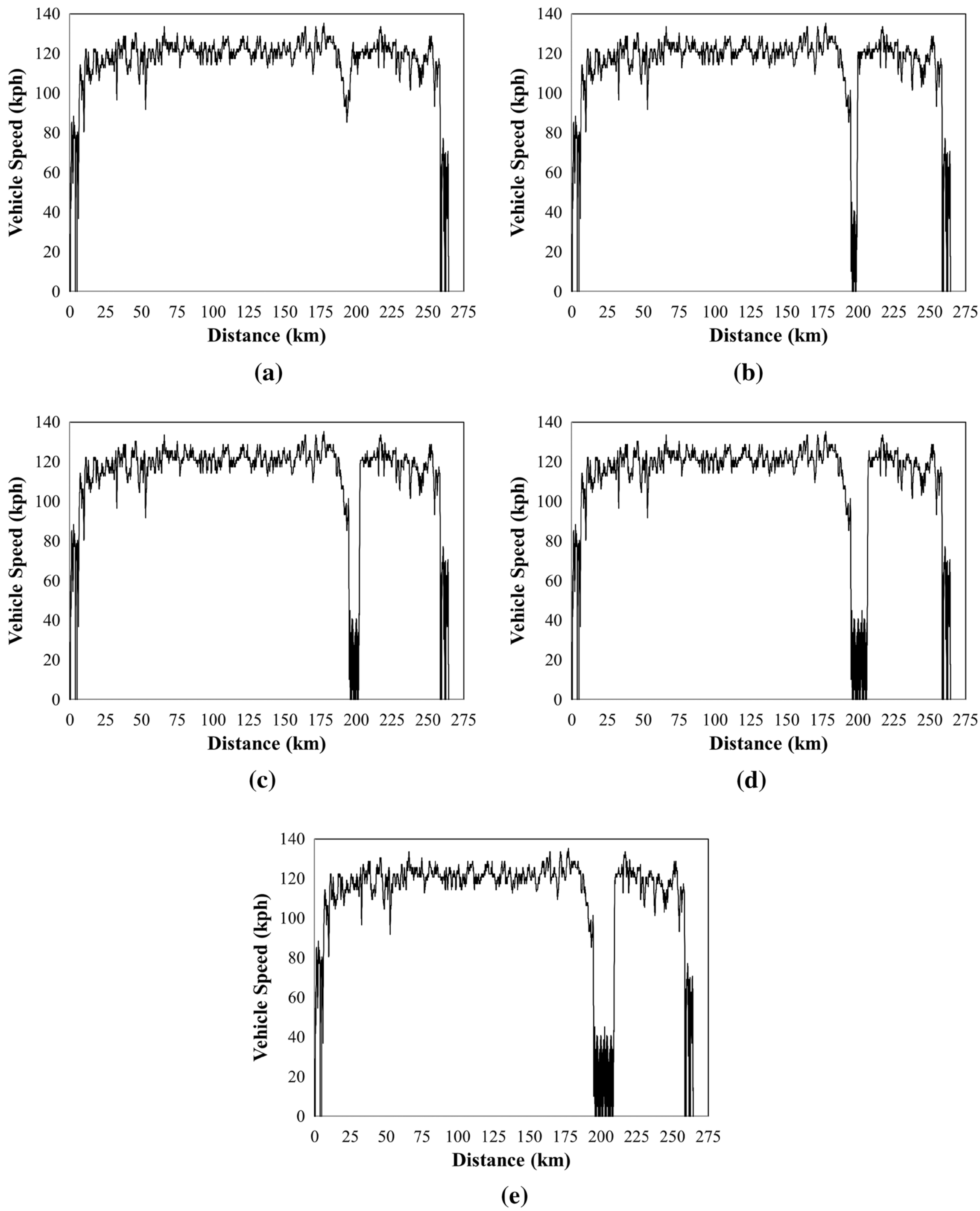

Fig. 3 Highway vehicle drive schedules used in the Motor Vehicle Emissions Simulator (MOVES) software for on-time and delayed one-way trips between Raleigh and Charlotte, NC. **a** On-time, **b** 15 min delay, **c** 30 min delay, **d** 45 min delay, **e** 60 min delay

greater than the 4227 kJ/vehicle-km published energy intensity [1]. The BTS estimates the PC and PT energy intensities to be 2547 and 3588 kJ/pkm, respectively, assuming an average of 1.39 and 1.34 people in the vehicle, respectively [42]. The on-time PC and PT energy intensities from MOVES are 16 and 7 % lower, respectively, than the BTS values, adjusted for single occupancy. Assuming the LDGV fleet is 52 % PC and 48 % PT, the fleet average energy intensity from BTS is 4073 kJ/pkm, which is 11 % higher than the MOVES estimate. Thus, the energy intensity estimates reported here are similar to other estimates and appear to be valid.

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

3.5 Comparison of Locomotive to LDGV Emission Factors

For the Raleigh to Charlotte trip, the train has clear advantages with respect to emissions of CO_2 and CO compared to an LDGV. The locomotive fleet CO_2 emission rate of 118 g/pkm is 55 % lower than LDGVs. The CO emission rate for the locomotive fleet is 95 % lower compared to LDGVs. Gasoline vehicles tend to produce high levels of engine-out CO emissions. Even though gasoline vehicles have very effective control of CO emissions using three-way catalytic converters, their exhaust emissions are higher than those of the diesel engines used in the locomotives [32].

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

To assess the validity of the Piedmont to LDGV emission factor comparisons, the results were compared to Barth et al., who compared Metrolink commuter rail service in California to commuting by personal vehicle. They report that the train had lower CO per passenger emissions, but higher NO_x and PM per passenger emissions [19]. This was also seen with the Piedmont for NO_x, PM, and CO. The Metrolink study reported lower rail HC emissions per passenger than for a highway vehicle. However, Metrolink carries 2.2 times more riders per train than the Piedmont.

The base case analysis excluded locomotive idling time at the first and last station stops. The locomotive emits, on average, 885, 35, 21, 3, and 1 g of CO_2, HC, NO_x, CO, and PM, respectively, for every minute of idling. Therefore, if the locomotive idles 10 min prior to departing the origin rail station and 10 min after arriving at the destination rail station, then the emission rates for a passenger traveling between Raleigh and Charlotte would increase by 3, 4, 4, 5, and 21 % for CO_2, CO, NO_x, PM, and HC, respectively. Adding this station idling time would not change the findings that the locomotive emits less CO_2 and CO and more NO_x, PM, and HC per passenger-kilometer than a single-occupant LDGV for on-time travel.

Figure 4 depicts the effect of travel delay on emission factors for both the locomotive and an LDGV with one occupant. For locomotive fleet travel delays in excess of 30 min, the advantage of rail to on-time highway travel with respect to CO_2 is reduced from 44 % lower to 37 %. Train delays exacerbate differences for NO_x, PM, and HC. The comparison of CO emission rates is not sensitive to delays for either the locomotive or the LDGV. If there are two occupants in the LDGV, the train still has lower CO_2 and CO emission rates and higher NO_x, PM, and HC emission rates.

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

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

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

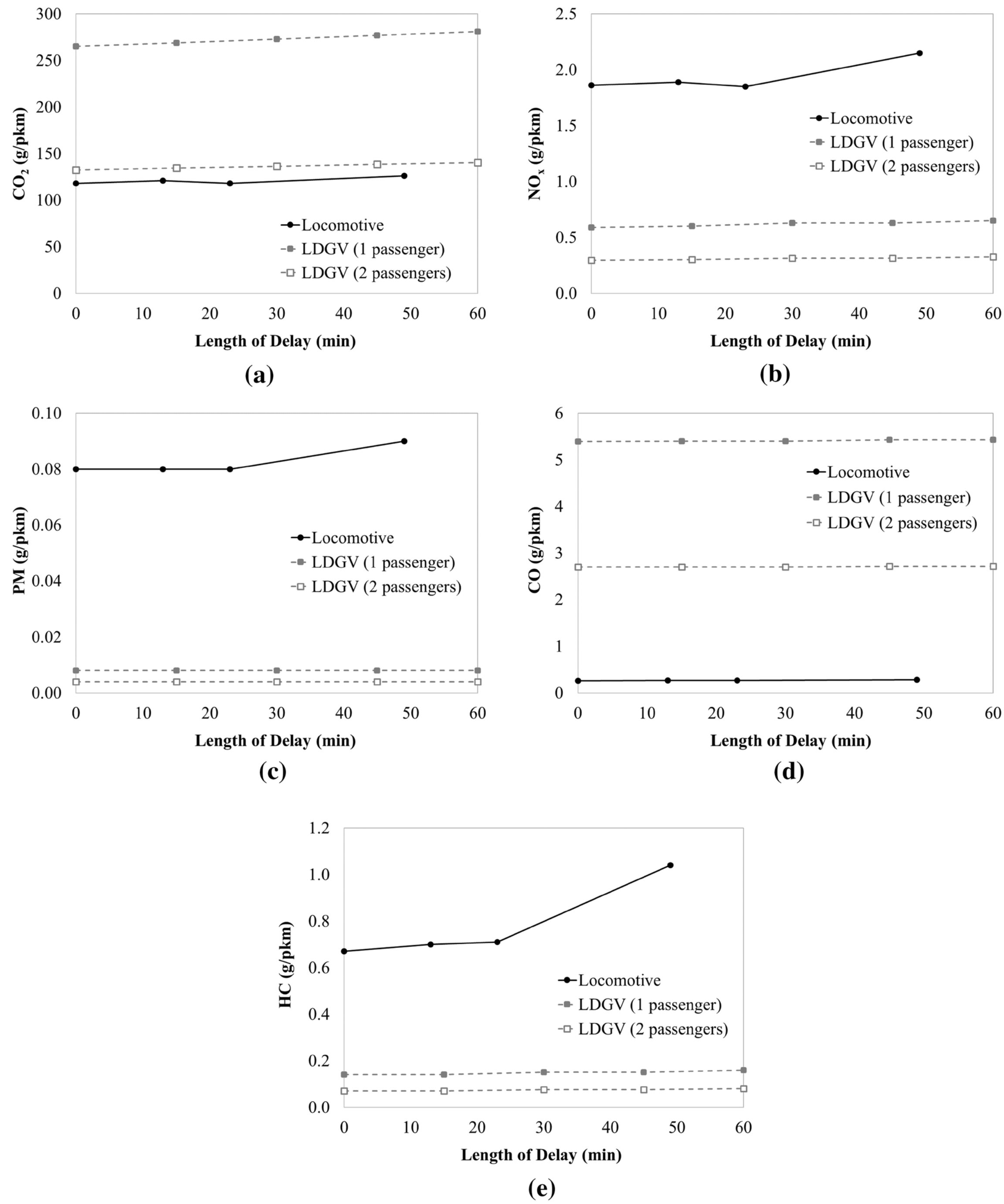

Fig. 4 Fleet average locomotive and light-duty gasoline vehicle (LDGV) emission factors for on-time and delayed one-way trips between Raleigh and Charlotte, NC. **a** Carbon dioxide, **b** Nitrogen oxides, **c** Particulate matter, **d** Carbon monoxide, **e** Hydrocarbons

4 Conclusion

In this first-of-its-kind study, emissions from passenger rail were measured using PEMS and actual ridership data. The emission rates are based on real-world measurements of the actual emissions of a train, and not based on an estimate or a model. Train emissions are highly sensitive to engine load. The distribution of engine load varies between adjacent stations and varies depending on travel time delays. Emission rates also vary from one locomotive to another even if they have similar chassis and engines. Per passenger-kilometer emission estimates vary substantially from one station-to-station segment versus another depending on actual ridership. Thus, this real-world study provides new data regarding multiple factors that cause variability in actual emission rates.

For on-time travel, passenger rail emits less CO_2 and CO per passenger-kilometer compared to a LDGV with one or two occupants. However, the NO_x, HC, and PM emission rates were higher for passenger rail. Ridership on the Piedmont would have to increase, the existing locomotives would have to be retrofitted with emission controls, or newer locomotives would have to be brought into service for the train NO_x, HC, and PM emissions to be comparable to highway vehicles. The advantages of the train for CO_2 and CO emission rates are robust to different assumptions regarding the amount of idling at the initial and final stations of the route.

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

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

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

LDGV emission factors are modestly affected by travel delays, with the largest increases estimated for the CO_2 emission rates. Additional instrumented LDGV trips should be completed to capture actual highway delays between Raleigh and Charlotte.

The empirical-based method to comparing rail and passenger car emissions on a per passenger-kilometer basis can be extended to additional locomotives and highway vehicles. Data such as these are critically needed to evaluate models, such as MMPASSIM and others, that are being developed for policy-relevant applications. Furthermore, measurements, such as those reported here, can be used to improve the calibration and estimation approaches in such models. The identification of key sources of variability in real-world per passenger-kilometer emission rates from this type of work can help local, state, or national governments make transportation policy decisions that reduce energy intensity and emissions. Furthermore, rail operators could estimate emission factors for their fleet, and use the information to prioritize the retrofitting or replacement of locomotives, or to determine where rail improvement projects should occur to decrease travel delays.

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