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# Measurement of black carbon emissions from in-use diesel-electric passenger locomotives in California

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## HIGHLIGHTS

- Passenger locomotive emission factors of black carbon (BC) were measured.
- The average emission factor was 0.87 ± 0.66 g BC emitted per kg diesel consumed.
- Estimated $PM_{10}$ emissions were in line with EPA's exhaust emission standards.
- Per commuter mile, locomotives emit 20% of the $CO_2$ but ten times more BC than emitted by cars.
- BC emissions dramatically increase the carbon footprint of locomotive travel.

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## ABSTRACT

Black carbon (BC) emission factors were measured for a California commuter rail line fleet of diesel-electric passenger locomotives (Caltrain). The emission factors are based on BC and carbon dioxide ($CO_2$) concentrations in the exhaust plumes of passing locomotives, which were measured from pedestrian overpasses using portable analyzers. Each of the 29 locomotives in the fleet was sampled on 4–20 separate occasions at different locations to characterize different driving modes. The average emission factor expressed as g BC emitted per kg diesel consumed was $0.87 \pm 0.66$ g kg$^{-1}$ (±1 standard deviation, n = 362 samples). BC emission factors tended to be higher for accelerating locomotives traveling at higher speeds with engines in higher notch settings. Higher fuel-based BC emission factors (g kg$^{-1}$) were measured for locomotives equipped with separate "head-end" power generators (SEP-HEPs), which power the passenger cars, while higher time-based emission factors (g h$^{-1}$) were measured for locomotives without SEP-HEPs, whose engines are continuously operated at high speeds to provide both head-end and propulsion power. $PM_{10}$ emission factors, estimated assuming a BC/$PM_{10}$ emission ratio of 0.6 and a typical power output-to-fuel consumption ratio, were generally in line with the Environmental Protection Agency's locomotive exhaust emission standards. Per passenger mile, diesel-electric locomotives in this study emit only 20% of the $CO_2$ emitted by typical gasoline-powered light-duty vehicles (i.e., cars). However, the reduction in carbon footprint (expressed in terms of $CO_2$ equivalents) due to $CO_2$ emissions avoidance from a passenger commuting by train rather than car is appreciably offset by the locomotive's higher BC emissions.



## 1. Introduction

### 1.1. Background

Diesel particulate matter (PM) poses significant concerns for public health and the environment. For example, diesel PM emissions dominate the total cancer-weighted risk associated with all toxic air contaminant emissions in some urban areas (SCAQMD, 1999; BAAQMD, 2014). Diesel PM is mostly smaller than 2.5 μm in diameter ($PM_{2.5}$), which causes acute respiratory and cardiovascular problems (Kennedy, 2007). Approximately half of the emitted $PM_{2.5}$ from diesel engines is black carbon (BC), which reduces visibility and contributes to global warming and climate change via its absorption of sunlight (Stocker et al., 2013).

The dominant source of diesel PM and BC in many urban areas in the United States is on-road heavy-duty trucks (EPA, 2012;

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BAAQMD, 2014). BC emissions from on-road trucks have been measured in numerous studies and are declining over time (Zhu et al., 2002; Fruin et al., 2004; Ban-Weiss et al., 2009; Dallmann et al., 2011). Emissions from other sources, including off-road diesel engines such as construction engines, ocean-going vessels, and locomotives have not been studied as much as emissions from on-road trucks and are therefore not as well characterized. Although locomotives currently contribute a small fraction of total BC emissions in many urban areas, they pose a significant health risk to populations near rail lines (BAAQMD, 2014) and the relative contribution of locomotives to BC emissions is likely increasing over time due to the declining emissions from heavy-duty trucks.

This article describes an investigation of BC emissions from a fleet of in-use diesel-electric passenger locomotives operating along a California commuter rail line between San Francisco and Gilroy. The locomotive models sampled are in common use in commuter rail systems throughout the United States (e.g., NJ Transit (New Jersey–New York City), Metra (Chicago), MBTA (Boston), MARC and Virginia Railway Express (Washington, D.C.), and Metrolink (Los Angeles)), so the BC emission factors presented here are broadly relevant. The study demonstrates the “plume capture” sampling method as a useful technique for characterizing in-use locomotive emissions.

### 1.2. The Caltrain locomotive fleet

The Caltrain fleet consists of 29 diesel-electric locomotives, categorized in Table 1 into four groups based on the engine make/model and age. Locomotives in groups 1 through 3 are outfitted with the same 16-cylinder Electro-Motive Diesel engine (EMD 16-645E3C). Locomotives in group 4 have a different 16-cylinder engine of the same manufacturer (EMD 16-645F3B) that provides 400 more horsepower. All of the Caltrain locomotives are equipped with 2-stroke engines.

Locomotive power output is controlled by the engineer using a stepped or “notched” throttle. The notch setting is incremented from idle to position 8 to increase the rotational speed and fuel rate of the diesel engine. When the throttle is in the idle position, power is not supplied to the traction motors that propel the locomotive. Notch 1 is the lowest powered setting where current is delivered to the traction motors, while notch 8 is the position where maximum power is available.

Caltrain locomotives differ in their method of generating the head-end power (HEP) that provides electricity to the passenger cars, and the difference relates to the rotational speed and fuel rate of the diesel engine providing power to the traction motors (i.e., the main propulsion engine or the prime mover). Locomotives in groups 2–4 each have an auxiliary diesel unit that is independent from the prime mover. This auxiliary unit is referred to as a separate HEP generator (SEP-HEP). Locomotives in group 1 do not have SEP-HEPs; rather the prime mover provides both propulsion and head-end power. This is referred to as gear-drive HEP. On locomotives with gear-drive HEP, the prime mover's notch setting is throttled to deliver more or less power to the traction motors (as noted above), but the engine constantly operates at high speed, equivalent to or greater than operation in notch 7, to maintain the required alternating current line frequency regardless of locomotive driving mode.

Locomotive engines are subject to Environmental Protection Agency (EPA) exhaust emission standards for $PM_{10}$, as shown in Table 1. In each instance, the first value is the original standard that applied to the locomotives when manufactured and the second value is the more stringent emission standard for existing locomotives when they are remanufactured (EPA, 2009). The extent to which Caltrain locomotives have been upgraded to meet the revised standards is indicated in the table.

## 2. Methods

### 2.1. Sampling method

Locomotive engine emissions were primarily measured in-use during normal operation at four different rail line locations (Fig. A1 in the Appendix). Locomotives were accelerating, cruising, and decelerating at various speeds based on the type of service and distance to the nearest passenger station, as indicated in Table 2. Emissions from one locomotive in group 2 were also measured when it was connected to a load test box at the Caltrain maintenance facility. The load box simulates in-use engine operation while the locomotive is stationary. During this test, the notch was throttled every minute from idle to 8 and back to idle.

A portable sampling package was used for emissions measurements. A non-dispersive infrared $CO_2$ analyzer (LI-COR; Lincoln, NE; model LI-820), two microAeths that measure BC (AethLabs; San Francisco, CA; model AE-51), an external battery pack, and a laptop computer organized in a 28 cm by 23 cm box comprised the portable package (Fig. 1). The battery pack and laptop served as the power supply and data logger for the $CO_2$ analyzer. The microAeths were connected in series and served as the pump and in line particle filter for the $CO_2$ analyzer. The sampling inlet connected to the microAeths was conductive silicone tubing with a 5 mm inner diameter.

Locomotive exhaust was measured using a “plume capture” method (Ban-Weiss et al., 2009; Dallmann et al., 2011). With the sampling package positioned on a pedestrian overpass, the sampling line was hung over the edge above the engine exhaust of

**Table 1**
Attributes of the Caltrain locomotive fleet at the time of this study.

| Locomotive group | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Engine | EMD 16-645E3C | EMD 16-645E3C | EMD 16-645E3C | EMD 16-645F3B |
| Model year (number in fleet) | 1985 (5) | 1985 (13)<br>1987 (2) | 1998 (3) | 2003 (6) |
| Model | F40PH-2 | F40PH-2-CAT | F40PH-2C | MP36PH-3C |
| Horsepower | 3200 | 3200 | 3200 | 3600 |
| HEP generation[a] | Gear drive | SEP-HEP | SEP-HEP | SEP-HEP |
| $PM_{10}$ standard original/revised[b] (g bhp-$h^{-1}$) | 0.60/0.22 | 0.60/0.22 | 0.60/0.22 | 0.45/0.22 |
| Remanufactured to meet revised $PM_{10}$ standard | No | Yes | Yes | Yes (2 of 6)<br>No (4 of 6) |

[a] HEP = Head-end power. See explanation in Section 1.2.
[b] The EPA's original and revised exhaust $PM_{10}$ emission standards for locomotives (EPA, 2009), which are expressed in terms of emission tiers. Locomotives in groups 1–3 correspond to locomotive emissions tiers 0/0+ and locomotives in group 4 correspond to tier 1/1+. Locomotives that have been remanufactured to meet revised standards are in the “+” tier.

**Table 2**
Driving mode, distance to the nearest station, average speed, estimated notch, and measured black carbon emission factors for Caltrain locomotives at the four sampling locations in this study.

| Driving mode (type of service) | Sampling location | Distance from nearest station (km) | Average speed (km $h^{-1}$)[a] | Estimated notch[b] | BC (g $kg^{-1}$)[c] |
|---|---|---|---|---|---|
| Accelerating out of station | Millbrae | 0 | 8 | 1 | 0.35 ± 0.17 |
| Accelerating (local service) | Mountain View | 0.33 | 51 | 3–5 | 1.02 ± 0.82 |
| | Sunnyvale | 0.61 | 76 | | |
| | Santa Clara | 0.65 | 80 | | |
| Accelerating (express service) | Mountain View | 0.33 | 120 | 6–8 | 1.30 ± 0.74 |
| Cruising | All | | Variable | Idle-2 | 0.70 ± 0.47 |
| Decelerating | All | | Variable | Idle | 0.92 ± 0.56 |

[a] The speed of each train was measured using a hand-held radar gun.
[b] The notch assignment is approximate and based on discussion with Caltrain staff, distance from nearest station, measured speed, and type of service (local or express). At the Millbrae site, locomotives were observed pulling directly into (idle notch) and out of (notch 1) the station and in cruise. At the other three sites, locomotives were accelerating away from or decelerating into a more distant station, or in cruise. Caltrain "local" service stops at most or all stations and rarely exceeds notch 5. The express service doesn't stop at many stations and thus frequently exceeds notch 5 while attaining maximum speed. Cruising trains are assumed to be in a lower notch (idle, 1, or 2) because it is typical for the operator to decrease the notch after maximum speed is attained to limit fuel consumption. Trains decelerating into the station are assumed to be in idle.
[c] Average ± 1 standard deviation.

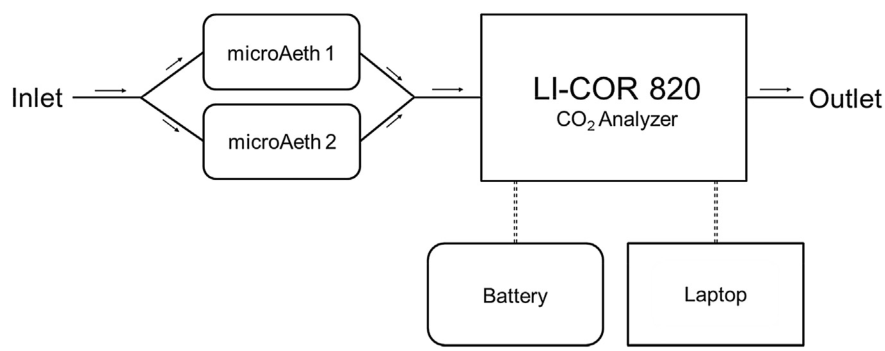


**Fig. 1.** A schematic of the portable sampling equipment used to measure BC emission factors in this study.

passing locomotives. BC and $CO_2$ concentrations were measured at 1 Hz, fast enough to measure peaks associated with the exhaust plumes of passing locomotives (Fig. 2). The length of the inlet tubing was varied from 1 to 5 m, depending on the sampling location, in order to sample close to the locomotive exhaust.

BC emission factors were calculated using Equation (1). The time interval $t_1 \leq t \leq t_2$ corresponds to a window during which a single plume capture occurred. From each point during the interval, the baseline concentrations of BC and $CO_2$ preceding the locomotive passing (i.e., $BC(t_1)$ and $CO_2(t_1)$) were subtracted. The ratio of integrated peak areas for BC and $CO_2$ gives the relative amounts of BC and $CO_2$ emitted by the locomotive. Multiplying this ratio by the carbon weight fraction in diesel ($w_c = 0.87$) yields the BC emission factor in units of grams emitted per kg diesel fuel consumed.

$$EF_{BC} = w_c \frac{\int_{t_1}^{t_2} [BC(t) - BC(t_1)]dt}{\int_{t_1}^{t_2} [CO_2(t) - CO_2(t_1)]dt} \qquad (1)$$

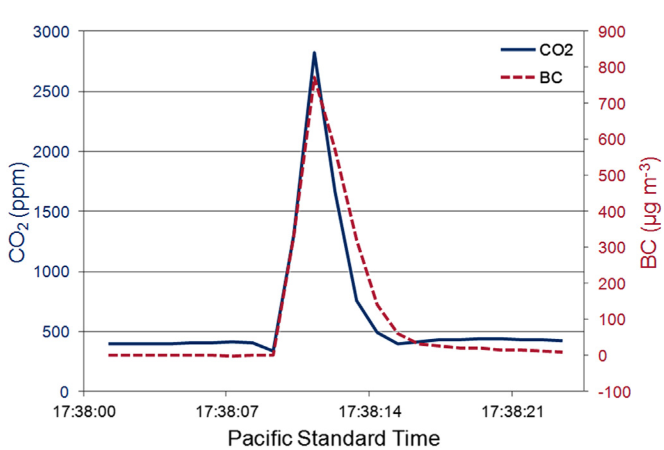


**Fig. 2.** An example of a successful plume capture: BC and $CO_2$ concentration peaks measured when a locomotive passed the sampling site.

### 2.2. *Quality assurance*

Several potential sources of measurement error were evaluated and minimized, as detailed in the Appendix and summarized here. Particle loss in the inlet tubing was found experimentally and theoretically to be negligible (Fig. A2). The underestimation of BC concentrations that occurs when aethalometers sample low-albedo PM was corrected using a modified form of the empirical relationship that Kirchstetter and Novakov (2007) developed for the rack-mountable version of the aethalometer. In this study, a correction for the microAeth was determined experimentally (Fig. A3). BC concentrations measured along the rail line and from the locomotive connected to the load test box were increased by as much as 35% and 65%, respectively.

Measured $CO_2$ concentrations required adjustment to minimize the influence of two competing sampling artifacts: the overestimation of peak $CO_2$ concentrations due to an overshoot of the LI-820 analyzer (Fig. A4) and the underestimation of $CO_2$ concentrations due to sorption of $CO_2$ to conductive silicone tubing (Timko et al., 2009). Sorption of $CO_2$ to silicone tubing was the dominant sampling artifact for the conditions encountered when sampling along the rail line, and $CO_2$ concentrations were adjusted upward from 5 to 11% depending on the magnitude of measured concentrations (Fig. A6). When sampling emissions from the locomotive connected to the load test box, much higher $CO_2$ concentrations were measured and the LI-820 overshoot dominated the sorption artifact (Fig. A7). Accordingly, $CO_2$ concentrations were adjusted downward by as much as 30%.

## 3. Results

BC emission factors were computed for 362 locomotive exhaust plumes. The mean BC emission factor (±1 standard deviation) is $0.87 \pm 0.66$ g kg$^{-1}$, which is similar to BC emission factors measured by Galvis et al. (2013) for diesel switcher locomotives at a railyard in the Atlanta metropolitan area (0.7–1.0 g kg$^{-1}$) and Johnson et al. (2013) for line-haul locomotives at the Port of Brisbane (~0.7 g kg$^{-1}$). It is also comparable with BC emission factors measured for heavy-duty diesel trucks without diesel particle filters ($1.07 \pm 0.18$ g kg$^{-1}$) (Dallmann et al., 2011). BC emission factors measured using the two microAeths were in good agreement, differing by ~3% on average (Fig. A8).

The emission factor distribution is positively skewed, including 17 emission factors greater than 2.0 g kg$^{-1}$ and a maximum emission factor of 6.3 g kg$^{-1}$ (Fig. 3). The skewness means that a minority of exhaust plumes contained a majority of BC emissions: the largest 25% of the emission factors measured (those greater than 1.2 g kg$^{-1}$) represented 50% of the BC emissions. Emission factors were found to vary for individual locomotives, across locomotive types, and across driving modes, as discussed below.

Each locomotive in the Caltrain fleet was measured 4–20 times and under different driving conditions. Fig. 4 shows the range of replicate emission factors against the average emission factor for each locomotive, separately for each driving condition. The range was largest for locomotives with higher average emission factors. The variability in replicate emission factors illustrates that the average of numerous “plume captures” including different driving modes provides a more robust measure of the overall emissions performance of a locomotive than a single measurement.

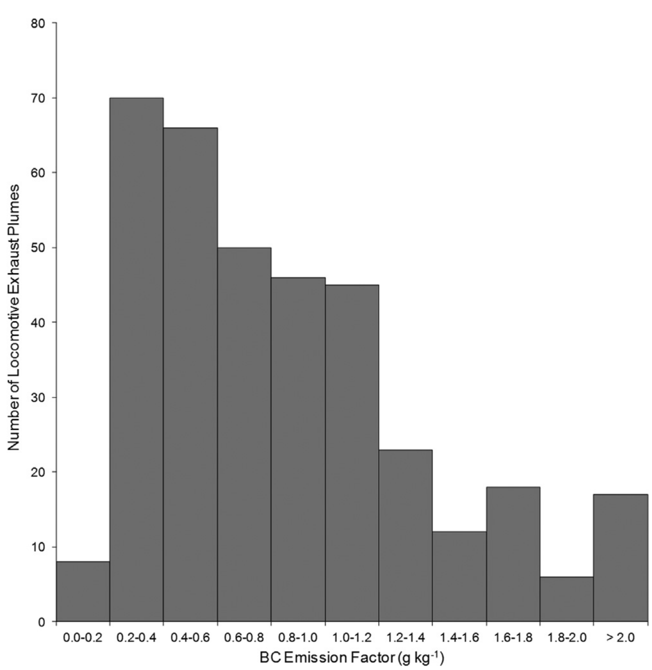


**Fig. 3.** Distribution of BC emission factors for 362 locomotive exhaust plume measurements.

The distributions of fuel-based emission factors for each driving mode listed in Table 2 are shown for each locomotive group in Fig. 5a. Though not entirely consistent for all locomotive groups, BC emission factors tended to be higher for accelerating locomotives traveling at higher speeds with engines in higher notch settings. As reported in Table 2, averaged across engine groups, locomotives pulling just out of the station (notch 1) traveled at lower speeds and had a lower average BC emission factor than engines in cruise (notch $\leq 2$). Likewise, the emission factor for cruising engines was lower than for engines accelerating further out of the station in local (notches 3–5) and express service (notches 6–8). Not following this trend, the average emission factor measured for decelerating locomotives (notch 0, idle) was comparable to that for local service locomotives.

The locomotive operated on the load test box in this study, which belonged to the 1985–1987 F40, SEP-HEP-equipped category (group 2 in Table 2), exhibited a similar trend of increasing emission factor with increasing notch setting (Fig. 6). In this case, the lowest BC emission factor was measured when the locomotive on the load test box was decelerating in the idle notch (0.10 g kg$^{-1}$). Fig. 6 also shows results from two earlier studies, where the trend of increasing emission factor with increasing notch setting was in one case much less pronounced (EPA, 1998) and in the other case the emission factor was largely independent of notch setting (Fritz and Cataldi, 1991).

The 1985 model year engines in the Caltrain fleet without SEP-HEPs (group 1) had the lowest g kg$^{-1}$ emission factors in several driving modes (Fig. 5a). Since they do not have SEP-HEPs, they are operated at constant speed and fuel rate. According to Caltrain engineers, this avoids soot production that can occur when engines are throttled. With newer locomotives equipped with SEP-HEPs, incomplete combustion of fuel delivered to the main engine's cylinders ahead of the step change in rotational speed when the notch is increased can increase soot production.

In Fig. 5b, BC emission factors for each engine group are reported with time rather than mass of fuel burned in the denominator (i.e., gBC h$^{-1}$). The conversion from fuel-based to time-based emission factors is based on the fuel consumption rates corresponding to the observed locomotive driving modes. Fuel consumption rates increase with notch, as reported in Table A2. Although locomotives without SEP-HEPs have the lowest fuel-based emission factors, they have the highest time-based emission factors because their engines are constantly run at high speeds to power the passenger cars. The main engine in locomotives with SEP-HEPs (i.e., the prime mover) decreases rotational speed and fuel consumption rate when it is throttled into a lower notch. Consequently, time-based emission factors for the prime movers are an order of magnitude lower for less intensive driving modes.

## 4. Discussion

### 4.1. Duty cycle-weighted average BC emission factor

A duty cycle-weighted average emission factor for the Caltrain passenger locomotive fleet ($EF_{avg}$) is calculated by multiplying the average fuel-based emission factor for each notch ($EF_i$) by the fraction of fuel consumed in each notch ($f_i$), and summing over all notches (Table A3). Because local and express service duty cycles are different, a duty cycle-weighted average emission factor is computed for each service and the fleet average emission factor is equal to the weighted sum of the two:

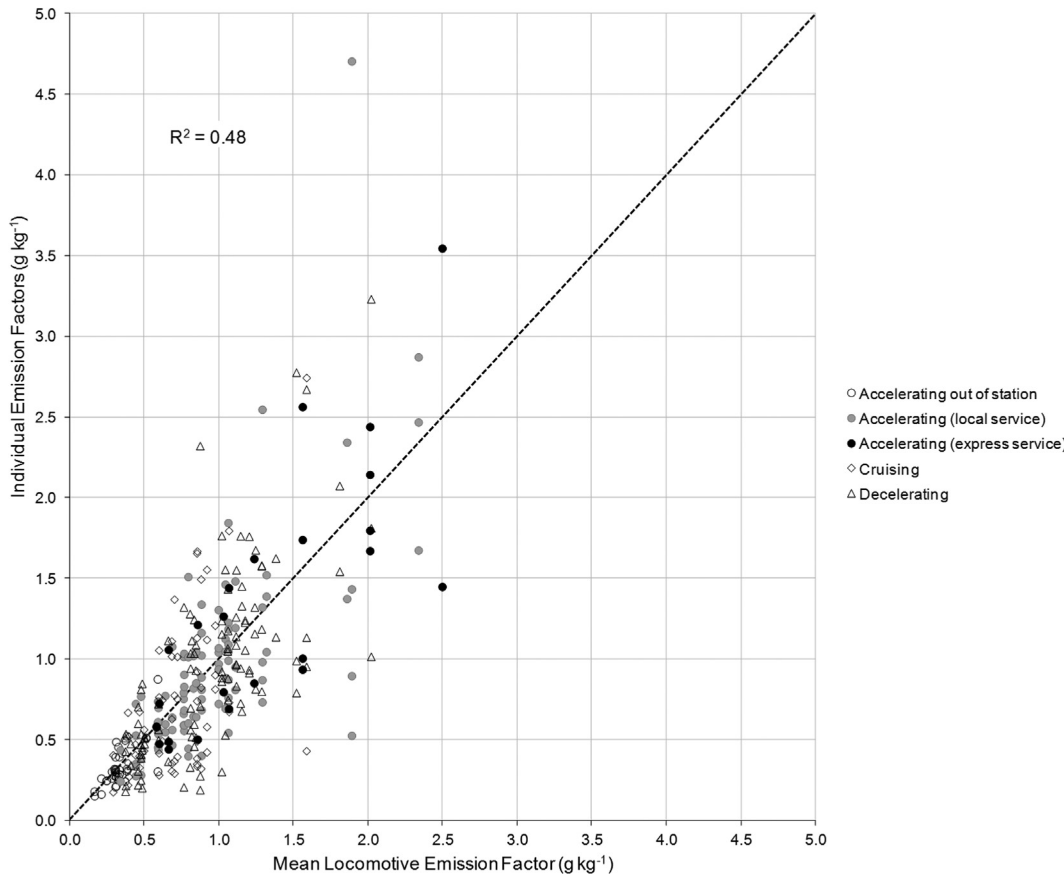


**Fig. 4.** Replicate emission factors plotted against the mean emission factor for each locomotive, with separate series plotted for each driving mode. The solid line has a slope of 1 and the dashed lines indicate 95% confidence intervals based on the distribution of individual emission factors about the mean emission factor.

$$EF_{avg} = w_1 \sum_{i,l} EF_i f_i + w_{ex} \sum_{i,ex} EF_i f_i \quad (2)$$

The fractions of fuel consumed in local ($w_l$) and express ($w_{ex}$) services are 0.78 and 0.22, respectively. The resulting emission factors for the local and express services are 0.93 g $kg^{-1}$ and 1.10 g $kg^{-1}$, respectively. The fleet average emission factor is 0.97 g $kg^{-1}$ and is used below. Data sources and calculations are provided in Section A.3 of the Appendix.

### 4.2. Comparison with EPA exhaust $PM_{10}$ emissions

$PM_{10}$ emission factors can be estimated from the BC emission factors measured in this study. BC is approximately 50% of the $PM_{10}$ emitted by diesel-electric locomotive engines (Galvis et al., 2013). The average ratio of power output to fuel consumption throughout a locomotive's duty cycle is 6.62 bhp-h $kg^{-1}$ (EPA, 2009). This conversion factor is based off the same duty cycle as assumed for Caltrain's local service. Based on these values, the duty cycle-weighted fleet average BC emission factor corresponds to a 0.29 g bhp-$h^{-1}$ $PM_{10}$ emission factor. This is slightly above the EPA's projection for the calendar year 2014 passenger fleet average $PM_{10}$ emission factor (0.26 g bhp-$h^{-1}$) (EPA, 2009).

The mean duty cycle-weighted $PM_{10}$ emission factor for group 1 locomotives in this study (0.17 g bhp-$h^{-1}$) is already lower than the EPA's revised standard (0.22 g bhp-$h^{-1}$) even though these locomotives have not yet been upgraded explicitly to meet this more stringent standard (Table 1). The mean duty cycle-weighted $PM_{10}$ emission factor for locomotive groups 2 and 3 is 0.31 g bhp-$h^{-1}$. This considerably lower than EPA's original standard (0.60 g bhp-$h^{-1}$) but somewhat higher than the revised and more stringent standard that applies to these remanufactured locomotives (0.22 g bhp-$h^{-1}$). The estimated $PM_{10}$ emission rate for group 4 locomotives (0.31 g bhp-$h^{-1}$) is closer to the revised standard (0.22 g bhp-$h^{-1}$) than the original standard (0.45 g bhp-$h^{-1}$) even though four of the six locomotives in this group have yet to be remanufactured to meet the revised standard. Altogether, these results suggest that the in-use emissions are generally in line with EPA's exhaust emission standards.

### 4.3. Carbon footprint

When choosing between car and locomotive, commuters may consider carbon footprint in addition to other factors. Carbon footprint calculations often consider only $CO_2$ emissions. Since BC has a high global warming potential (GWP) and significantly contributes to global warming (Stocker et al., 2013), we considered both $CO_2$ and BC (Table 3).

Per passenger mile, a Caltrain locomotive emits about 3200 times more $CO_2$ than BC by mass. However, the locomotive's emissions of BC and $CO_2$ are about equal when BC is expressed in terms of $CO_2$ equivalents using its 20 year GWP. Thus, on a 20 year time scale, BC and $CO_2$ emissions from the locomotives in this study contribute about equally to global warming. Over a 100 year time horizon, the BC emissions from the locomotives constitute one-fifth of the GWP because a significant portion of the $CO_2$ emissions will remain in the atmosphere long after the BC emissions have been removed.

Since a passenger on a locomotive displaces a passenger in a light-

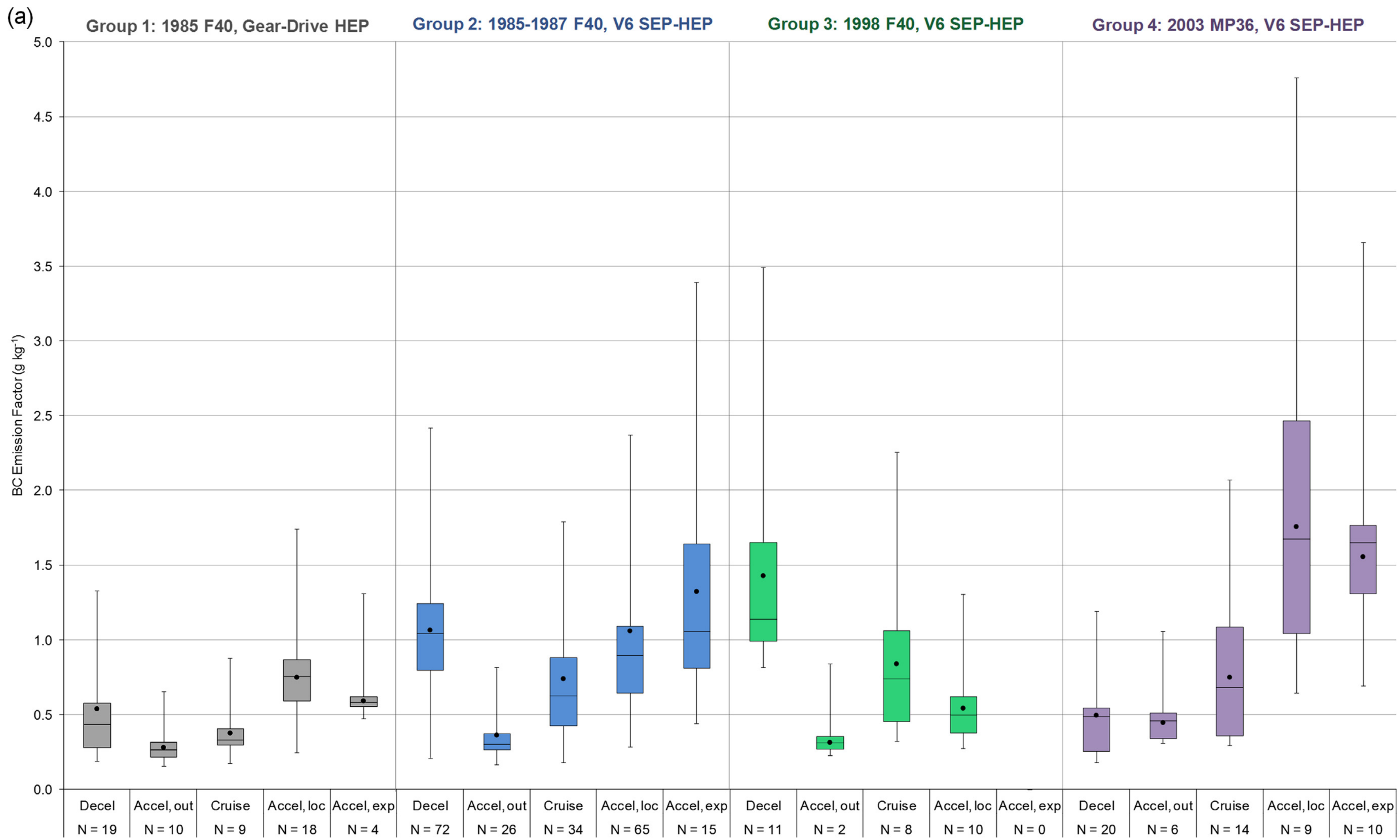


**Fig. 5.** Box and whisker plots illustrating the distribution of emission factors (in units g kg$^{-1}$ in figure (a) and in units gh$^{-1}$ in figure (b)) by driving mode for each locomotive group in the Caltrain fleet. Whiskers indicate 95% confidence intervals.

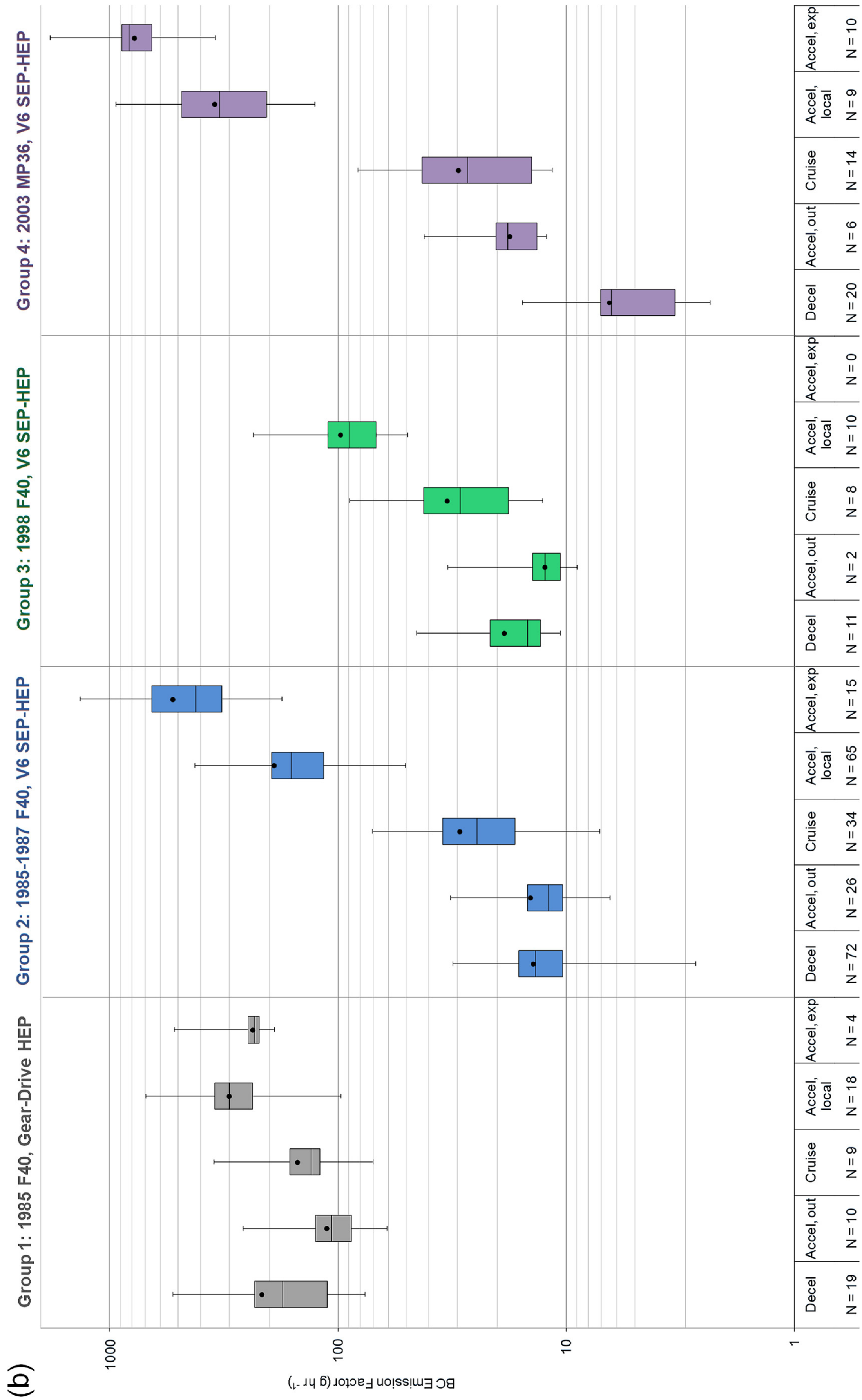


**Fig. 5.** (*continued*).

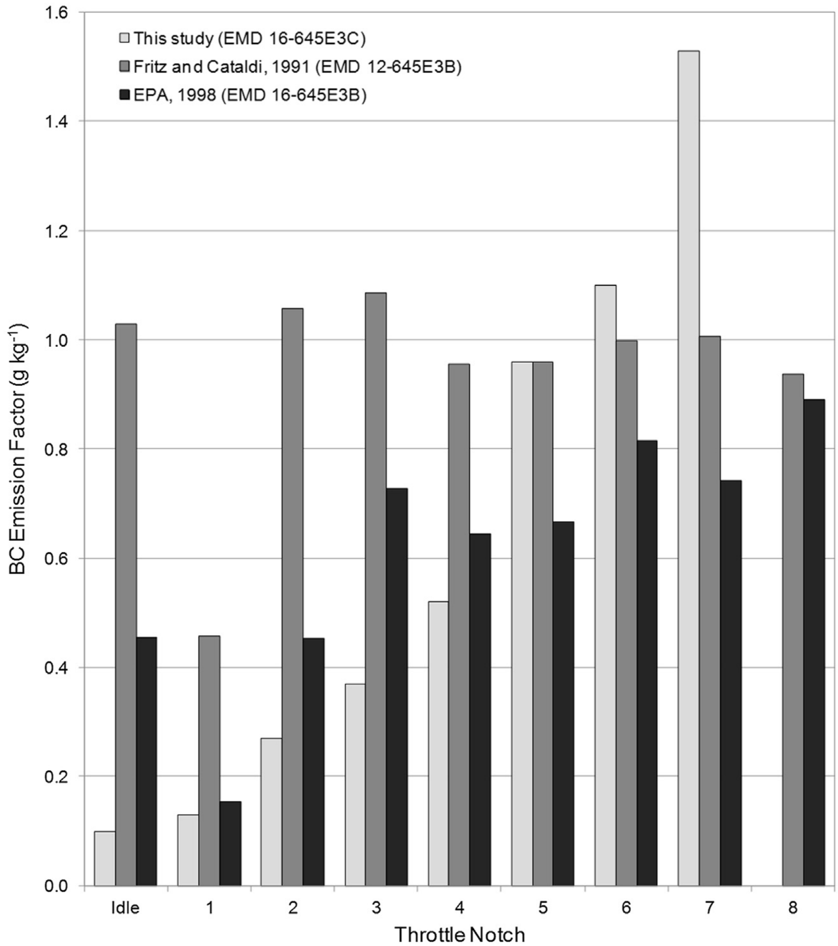


**Fig. 6.** Emission factors for locomotives operating in each notch setting as measured in this study and in two previous studies (Fritz and Cataldi, 1991; EPA, 1998).

**Table 3**
Mass emission rates of carbon dioxide, black carbon, and black carbon expressed as carbon dioxide equivalents for a Caltrain locomotive and a light-duty vehicle (LDV) per passenger per mile of travel.

| Species | Unit | Locomotive[a] | LDV[b] |
|---|---|---|---|
| *Mass emission rates* | | | |
| $CO_2$ | g/passenger-mile | 60 | 336 |
| BC | mg/passenger-mile | 19 | 1.9 |
| *Mass emission rates expressed as $CO_2$ equivalents* | | | |
| BC (20 y)[c] | gCO2e/passenger-mile | 61 | 6 |
| BC (100 y)[c] | gCO2e/passenger-mile | 17 | 2 |
| $CO_2$ + BC (20 y) | gCO2e/passenger-mile | 121 | 342 |
| $CO_2$ + BC (100 y) | gCO2e/passenger-mile | 77 | 338 |

[a] The $CO_2$ calculation for the locomotive is based on 0.25 mi $gal^{-1}$ fuel economy, diesel fuel with 840 g $L^{-1}$ density and 0.87 carbon weight fraction, and 677 passengers per locomotive during peak hours (Caltrain, 2014). The fuel economy is based on annual fuel consumption and miles traveled (FTA, 2009). The BC calculation is based on the 1.0 gBC $kg^{-1}$ duty cycle-weighted emission rate determined in this study.

[b] The $CO_2$ calculation for the light-duty vehicle is based on 23 mi $gal^{-1}$ fuel economy (EPA, 2008), gasoline with 740 g $L^{-1}$ density and 0.85 carbon weight fraction (Kirchstetter et al., 1999), and 1.13 passengers per car during the work commute (USDT, 2009). The BC calculation is based on the 0.018 gBC $kg^{-1}$ light-duty fleet-average emission rate measured in a San Francisco Bay Area roadway tunnel (Dallmann et al., 2013).

[c] The conversion of BC to $CO_2$ equivalents is based on a 20 year global warming potential of 3200 and a 100 year global warming potential of 900 (Bond et al., 2013).

duty vehicle, we compare $CO_2$ and BC emissions from a Caltrain locomotive and a gasoline-powered vehicle. Per passenger mile, the locomotive emits only 18% of the $CO_2$ but ten times more BC than the light-duty vehicle. Thus, the carbon footprint reduction due to $CO_2$ emissions avoidance from a passenger commuting by train rather than light-duty vehicle is reduced by the locomotive's higher BC emissions. Considering both $CO_2$ and BC emissions, and expressing BC in terms of $CO_2$ equivalents over 20 years, the global warming potential per passenger mile is 2.8 times larger for the light-duty vehicle than the train.

Interestingly, Caltrain will undergo electrification in 2019 and most of its locomotives will switch from diesel-electric to fully-electric power. Thus, their BC emissions will be mitigated. Short of electrification, exhaust particle filters required for 2015 and newer locomotive engine model years are intended to reduce by an order of magnitude PM emissions compared to those measured in this study.

## Acknowledgments

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2015.05.001.

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