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Measurement of particulate matter emissions from in-use locomotives

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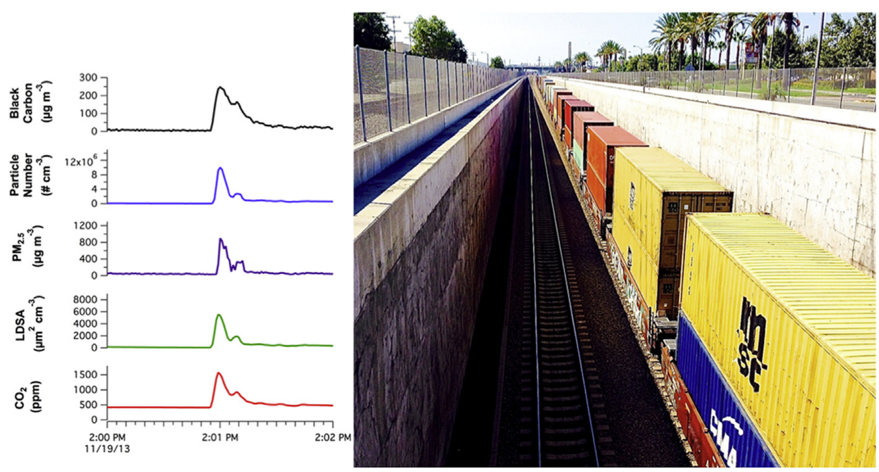
HIGHLIGHTS

- Measured particulate emissions for a large sample (N = 88) of freight locomotives.
- Determined emission factors for black carbon, particle number and mass.
- Proposed a metric for assessing health-relevant emission factors.
- Compared emission factors for locomotives to diesel trucks.
- Current locomotive emissions comparable to truck emissions from a decade ago.

GRAPHICAL ABSTRACT



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ABSTRACT

Particulate matter emissions from a large sample (N = 88) of in-use line-haul freight locomotives were measured in the Alameda Corridor, located near the ports of Los Angeles and Long Beach. Emission factors for black carbon (BC), particle number (PN), fine particulate mass ($PM_{2.5}$), and lung-deposited particle surface area (LDSA) were computed based on 1 Hz measurements of the rise and fall of particulate matter and CO_2 concentrations as the locomotives passed the sampling location. We include LDSA emission factors as relevant for near-source human exposures. Mean emission factors ± standard deviations were 0.9 ± 0.5 g kg^{-1} fuel consumed for BC, $(2.1 \pm 1.5) \times 10^{16}$ # kg^{-1} for PN, 1.6 ± 1.3 g kg^{-1} for $PM_{2.5}$, and $(2.2 \pm 1.7) \times 10^{13}$ μm^2 kg^{-1} for LDSA. Emission factors for individual trains were slightly skewed, with the dirtiest 10% of trains responsible for 20%, 24%, 28%, and 27% of total BC, PN, $PM_{2.5}$, and LDSA emissions, respectively. The relative importance of high-emitters is therefore lower for these locomotives relative to previously reported diesel truck emissions. BC versus PN emissions from individual locomotives were found to be anti-correlated, suggesting that the highest emitters of particle numbers are the lowest emitters of black carbon. Using results presented here along with previous measurements, we compared for freight trains versus diesel trucks the amount of BC emissions associated with pulling an intermodal freight container over a given distance. This assumption-dependent comparison showed that in most cases locomotives emit less BC per container hauled than diesel trucks. However, continual decreases in diesel truck BC means that unless emissions from locomotives are decreased in the near future, emissions associated with hauling a container could become lower for diesel trucks than locomotives.

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1. Introduction

Particulate matter (PM) is known to adversely affect human health by penetrating deeply into the alveolar regions of lungs where it can diffuse into the circulatory system and accumulate in vital organs such as the liver, brain, or heart (Pope et al., 2004; Kennedy, 2007; Campbell et al., 2005). PM also alters regional and global climate through its influence on the radiative balance of Earth, and through additional influences on clouds that indirectly impact climate (Ramanathan et al., 2001; Hansen et al., 2005; Lohmann and Feichter, 2005; Ban-Weiss et al., 2012, 2014; IPCC, 2013). Emissions of PM from motor vehicles have been relatively well characterized, while emissions from many non-road sources including locomotives are uncertain due to a lack of real-world measurements of in-use engines (Dallmann and Harley, 2010; Cahill et al., 2011). As on-road emissions have decreased over past decades (Ban-Weiss et al., 2008; Dallmann et al., 2012), the fraction of PM emitted by non-road sources in California has increased and is out of proportion with its numerical population (Sawant et al., 2007). Locomotives contribute to human exposure of diesel pollutants near ports, railyards, and rail lines. Reducing uncertainty in current estimates of locomotive emissions is needed for enhancing the accuracy of emission inventories with corresponding improvements in health risk, air pollution, and climate assessments.

Past work on emissions and health impacts from locomotives is summarized here. Popp et al. (1999) measured NO emissions from locomotives, but the remote sensing methods employed in their approach were not capable of measuring relevant metrics for PM such as fine particle mass ($PM_{2.5}$) and particle number (PN) concentrations. A series of studies (Fritz, 1993, 1995; Fritz et al., 1994, 1995; Hedrick and Fritz, 2008) measured locomotive emissions in detail, but the number of locomotives investigated was generally small and therefore may not be representative of the in-use fleet. Yanowitz (2003) found that notch changes in line-haul and switcher locomotives account for approximately 40% of locomotive PM emissions. Johnson et al. (2013) measured emission factors of particle number, $PM_{2.5}$, SO_2, and NO_x from a large sample (N = 56) of trains from an Australian shipping port. Another study (Galvis et al., 2013) estimated railyard BC and $PM_{2.5}$ emission factors using a downwind/upwind difference approach in Atlanta, Georgia. Their emission factors were representative of both line-haul and switcher locomotives, and included possible other local sources of emissions. Hricko et al. (2014) completed one of the few studies on health risks associated with 18 railyards in California and found that the higher cancer risk zones surrounding railyards were represented primarily by low-income and minority populations.

Freight locomotives are powered by large two- or four-stroke diesel engines. Emissions regulations set by the Environmental Protection Agency for new and remanufactured locomotives have become modestly more stringent over the last four decades (EPA, 2009). Tier 0 and Tier 1 standards, which apply to locomotives manufactured from 1973–92 and 1993–2004, respectively, require particulate matter emissions to be below 0.22 g per brake horsepower-hour (g/bhp-hr) for line-haul locomotives. More stringent PM regulations of 0.10 g/bhp-hr were imposed for “Tier 2” (2005–11) and “Tier 3” (2012–14) line-haul locomotives. These standards were met using modifications to engine design and operation. “Tier 4” locomotives (2015 and newer) will be required to reduce particulate matter emissions substantially (0.03 g/bhp-hr), requiring the use of exhaust after-treatment devices including diesel particle filters (EPA, 2008). While regulatory control has been effective at reducing emissions from on-road sources (e.g. Ban-Weiss et al., 2008; Dallmann et al., 2012), locomotive emissions of PM have remained relatively constant (Dallmann and Harley, 2010).

In this study, we performed measurements of particulate matter emissions from a large sample (N = 88) of in-use freight locomotives traveling through the Alameda corridor. The Alameda Corridor is a 32 km freight rail expressway within urban Los Angeles that connects the two largest ports in the United States, the Ports of Los Angeles and Long Beach, to the national rail system (ACTA, 2014). Emission factors were derived for individual trains using concurrent 1 Hz measurements of CO_2 and particulate matter including BC, PN, $PM_{2.5}$, and particle lung-deposited surface area (LDSA). We present distributions of emissions from individual trains along with relationships between different PM metrics (i.e. BC vs. PN) for the measured fleet. Since trains and trucks are the two main modes of transporting freight containers on land, we compare emission results derived here to those for diesel trucks, including a comparison of BC emitted per freight container hauled for trains versus heavy-duty diesel trucks. Emission factors for locomotives presented here establish a baseline prior to reductions that are anticipated as a result of Federal regulation in 2015 (EPA, 2009).

2. Materials and methods

2.1. Location

Particulate emissions were measured from freight locomotives traveling through the Alameda Corridor to and from the Ports of Los Angeles and Long Beach. Roughly 40% of trains traveling through the Alameda Corridor have destinations outside of California, and the remaining 60% travel to locations within California (ACTA, 2015). Thus, the freight locomotives measured here are reasonably representative of line-haul freight locomotives in California and the United States. Portions of the corridor are trenched with a depth of about 10 m (ACTA, 2014), allowing measurement sample line inlets to be placed directly over the railroad tracks at approximately 1 m above locomotive exhaust stack heights. The sampling location was about 16 km north of the Port of Los Angeles and Long Beach at the intersection of E. Greenleaf Blvd. and S. Alameda Street.

2.2. Sampling

Sampling was completed on eight days during the period between November 2013 to January 2014. Measurements were conducted during either 08:00–12:00 h or 13:00–17:00 h. Emission factors were derived from the measured rise and fall of pollutant concentrations as the locomotive passed the measurement site (Fig. 1) and are reported per kg fuel consumed. This technique has been used for deriving emission factors from motor vehicles (e.g. Hansen and Rosen, 1990; Ban-Weiss et al., 2009; Hak et al., 2009; Dallmann et al., 2011, 2012). See Section 3.7 for an analysis of dilution ratio (DR) of the sampled exhaust.

2.3. Meteorology

Based on historical weather data in Compton, California, the mean high temperature at the beginning of November 2013 was 22 °C (72 °F), and at the end of January 2014 was 19.5 °C (67 °F) (Weather Underground, 2015). Although measurements were performed in the winter season, the temperatures in Los Angeles remained remarkably moderate. We note that the particle number concentrations measured here may be dependent on ambient temperature since semi-volatile species are more likely to be found in the particle phase in colder conditions (Turpin et al., 1994).

2.4. Instruments

All instruments (see Supplementary Information, Table S1) were portable and battery-powered with internal pumps, allowing for