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Short communication

Exposure to ultrafine particles and black carbon in diesel-powered commuter trains

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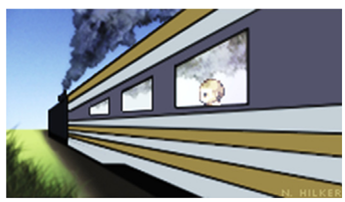
HIGHLIGHTS

- Ultrafine particles (UFP) and black carbon (BC) were measured in passenger trains.
- Train passengers can be exposed to elevated levels of diesel exhaust.
- UFP and BC in pull-trains were notably higher than those for other commuter modes.
- Mitigating actions for exposure in diesel-powered passenger trains are recommended.

GRAPHICAL ABSTRACT



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ABSTRACT

Ultrafine particle (UFP), black carbon (BC) and lung deposited surface area (LDSA) concentrations measured during 43 trips on diesel-powered commuter trains revealed elevated exposures under some conditions. When the passenger coaches were pulled by a locomotive, the geometric mean concentrations of UFP, LDSA, and BC were 18, 10, and 6 times higher than the exposure levels when the locomotive pushed the coaches, respectively. In addition, UFP, LDSA, and BC concentrations in pull-trains were 5, 3, and 4 times higher than concentrations measured while walking on city sidewalks, respectively. Exposure to these pollutants was most elevated in the coach located closest to the locomotive: geometric means were 126,000 # cm^{-3} for UFP, 249 μm^2 cm^{-3} for LDSA, and 17,800 ng m^{-3} of BC; these concentrations are much higher than those previously reported for other modes of public transportation. Markedly high levels of diesel exhaust are present in passenger trains powered by diesel locomotives operated in pull-mode. Thus, it is recommended that immediate steps be taken to evaluate, and where needed, mitigate exposure in diesel-powered passenger trains, both commuter and inter-city.

1. Introduction

Diesel exhaust was recently recognized as carcinogenic to humans and has been associated with a wide range of other health outcomes (IARC, 1989; Benbrahim-Tallaa et al., 2012; Straif et al., 2013). This complex mixture of particle and gas phase compounds contains components that can facilitate detection and assessment of associated exposures. The particle phase for example, contains elevated concentrations of ultrafine particles (UFP, < 100 nm) and black carbon (BC), both of which can be measured in high time resolution with handheld instruments. Furthermore, both these components are toxic in their own right. Some toxicological studies have suggested that UFP may be more harmful than larger particles (>100 nm) due to increased surface area for adsorption and condensation, higher deposition rates in lung alveoli, and greater ability to translocate through organs

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(Oberdörster et al., 2002, 2005; Geiser et al., 2008). The surface area of UFP has also been proposed as an appropriate exposure metric for predicting pulmonary inflammation (Brown et al., 2001; Oberdörster et al., 2005). Furthermore, fresh UFP from traffic emissions can induce DNA damages via systemic oxidative stress (Bräuner et al., 2007; Møller et al., 2008). In epidemiological studies, BC exposure has been associated with detrimental effects to respiratory, cardiovascular, and nervous systems (Suglia et al., 2008; Baja et al., 2010; Patel et al., 2010; Janssen et al., 2011; Heal et al., 2012). Commuting may constitute short but elevated exposures on a regular basis, and likely contributes substantially to overall daily exposure. Recent epidemiological evidence suggests that even short-term exposures to UFP may have measurable impacts on cardiorespiratory morbidity (Weichenthal, 2013; Hemmingsen et al., 2015). In addition to the impact of exposure time, routine exposures (e.g., daily commuting) could be a factor with considerable ability to predict health effects (Pope III, 2007). Individuals are exposed to variable levels of different air pollutants depending on their mode of transit. Acute exposures to UFP and BC while commuting by different modes (i.e., car, bus, rail, bicycle, and waking) have been increasingly investigated in recent years (Knibbs et al., 2011; Karanasiou et al., 2014). The surface area of UFP can be used to derive the alveolar lung-deposited surface area (LDSA), a possible health-relevant metric that has gained attention in recent years (Buonanno et al., 2013; Spinazzè et al., 2015; Geiss et al., 2016; Hudda and Fruin, 2016). The LDSA of UFP is defined as the particle surface area weighted by the deposition efficiency of particles in the alveoli based on a model proposed by the International Commission for Radiological Protection (ICRP, 1994).

Past research supports that commuting to and from work often accounts for a large portion of individuals' daily exposure to BC and UFP and that the level of exposure is dependent on transit mode (Knibbs et al., 2011; Karanasiou et al., 2014). In terms of rail systems, most studies have focused on the exposure in electrified train systems such as subways and light rail (Seaton et al., 2005; Aarnio et al., 2005; Cheng et al., 2009; Knibbs and de Dear, 2010; Dons et al., 2012; Li et al., 2015). Many North Americans take commuter trains from the suburbs to the downtown core of large cities. According to the 2011 National Household Survey in Canada, 11% of public transit users commuted by commuter train or streetcar (Statistics Canada, 2011). In the greater Toronto area alone, approximately 180,000 passengers travel by commuter train on an average weekday (Go Annual Report, 2012). Furthermore, similar diesel locomotives are used for public transportation in Canadian and U.S. cities such as Vancouver, Chicago, San Francisco, Washington D.C., Boston, Los Angeles, and Seattle. All commuter trains in 18 out of 26 transit agencies in Canada and the U.S. are hauled by diesel locomotives, while 6 transit agencies use both diesel locomotives and electric locomotives (or electric multiple units). The status of the electrification of commuter trains in Canada and the U.S. has been summarized in the Supporting Information. However, there is little quantitative information that exists regarding in-transit exposure of passengers commuting by diesel-powered trains; to the authors' knowledge, only one previous study has reported on this potentially important source of UFP and BC exposure (Hill and Gooch, 2010).

The purpose of this paper is to evaluate exposure to UFP, LDSA, and BC in trains pulled/pushed by a diesel locomotive during routine morning and evening commuting trips. The exposure levels in different positions of passenger trains were also examined in this study. The in-train exposure levels were compared to pollutant levels measured while walking on urban sidewalks.

2. Experimental methods

2.1. Study location and design

The concentrations of UFP and BC were measured inside commuter trains linking suburban Richmond Hill and Union Station in downtown Toronto, the most densely populated city in Canada with an estimated population of 6 million people for the metropolitan area (Statistics Canada, 2011). Trains on the Richmond Hill line consist of 10 bi-level passenger coaches (26 m long × 3 m wide × 5 m high) pulled or pushed by a diesel locomotive capable of 4 000 hp. The locomotive is powered by ultra-low sulfur diesel fuel with a maximum sulfur content of 15 mg/kg. Each coach has two heating, ventilation and air conditioning (HVAC) units: one at each end of the coach. Outdoor air is introduced into recycled air upstream of filters. The mixed air passes through these filters and into the HVAC unit before being blown into the coach, which has sealed windows. The outdoor air fan works to maintain positive pressure within the coach when the doors are closed, and automatically shuts off when the doors are opened at stations. There is no change in the operation of the recycled and outdoor air systems between summer and winter.

The measurements were conducted in the upper level of the passenger coaches. Inbound trips to Toronto between 7 a.m. and 10 a.m. and outbound trips between 5 p.m. and 8 p.m. were undertaken on weekdays from July 6 to August 21, 2015. A total of 43 trips were completed during the measurement period. Walking measurements (38 trips) were taken between the University of Toronto and Union Station immediately before or after the in-train measurement. A single route was chosen for the in-transit (~33 km) and walking (~3 km) trip, which typically required ~50 min and ~30 min per one-way, respectively. The walking route consisted of sidewalks on University Avenue for ~20 min from Union Station and nearby 4-lane arterial roads (e.g., McCaul Street) for ~10 min. University Avenue is a busy 8-lane road in downtown Toronto with approximate annual average daily traffic (AADT) of 48,000 vehicles per day. Sampling was completed using portable UFP and BC samplers (described in more detail later) carried in a backpack along with a GPS device. The in-train and walking measurements were made on days without rain; ambient temperature and relative humidity ranged from 16 °C to 29 °C with a mean of 23 °C and 34%–84% with a mean of 57%, respectively.

2.2. Black carbon measurement

Black carbon was measured every 10 s using a microAeth (AE51, AethLabs, USA). The optical attenuation of light from an 880 nm LED source is estimated by comparing light intensities though a reference blank spot and the spot of aerosol on the filter strip of AE51 (Weingartner et al., 2003). All filter absorption photometers are affected by loading effects, which is related to a nonlinear absorption response to filter loading. BC concentrations measured by the AE51 erroneously decrease as the filter loading increases. The filter strip of the AE51 was changed every trip and the attenuation was kept below 80. In addition, all BC data were post-processed to correct the loading effect. The loading effect correction and the performance evaluation of the AE51 are given in the Supporting Information (Fig. S1).

2.3. Ultrafine particle number concentrations and surface area measurement

The real-time number concentrations of ultrafine particles (UFP) were measured using a DiscMini (Testo AG, Germany), which is based on unipolar charging of the aerosol and detection in two