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Carbonaceous composition of $PM_{2.5}$ emitted from on-road China III diesel trucks in Beijing, China

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HIGHLIGHTS

- 17 in-use diesel trucks were tested in Beijing using a PEMS.
- Emission characteristics of carbonaceous $PM_{2.5}$ for tested vehicles were analyzed.
- $PM_{2.5}$, OC, and EC EFs of DTs were calculated based on distance and CO_2 emissions.
- The EC/OC, OC/$PM_{2.5}$, and EC/$PM_{2.5}$ mass ratios were strongly dependent on driving conditions.

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ABSTRACT

Fine particulate matter ($PM_{2.5}$) has attracted increasing attention due to its impacts on air quality and human health. As an important source of $PM_{2.5}$, diesel vehicles are often the focus of research. In this study, we characterized the carbonaceous composition of $PM_{2.5}$ that is emitted from on-road China III diesel trucks (DTs). Organic carbon (OC), elemental carbon (EC), and $PM_{2.5}$ emission characteristics were determined for 17 China III DTs, including 6 light-duty diesel trucks (LDDTs), 5 medium-duty diesel trucks (MDDTs), and 6 heavy-duty diesel trucks (HDDTs), based on real-world measurements in Beijing, China, using a portable emissions measurement system (PEMS). The average distance-based $PM_{2.5}$ emission factors (EFs) (g km^{-1}) generally increased and the average CO_2-based $PM_{2.5}$ EFs (g (kg of CO_2)$^{-1}$) generally decreased with increased vehicle size from LDDTs to MDDTs to HDDTs. The effects of driving conditions on the EFs for carbonaceous $PM_{2.5}$ were analyzed. The results show that distance-based and CO_2-based EFs strongly depend on driving conditions. Generally, greater amounts of $PM_{2.5}$ and OC are emitted from non-highway driving cycles, and greater amounts of EC are emitted from highway driving cycles for vehicles of the same size. For LDDTs, MDDTs, and HDDTs, no significant differences were observed between vehicles with different EC/OC ratios; therefore, the EC/OC ratio is not useful for distinguishing between the emissions generated by differently sized vehicles. The EC/OC, OC/$PM_{2.5}$, and EC/$PM_{2.5}$ mass ratios are strongly dependent on driving conditions for vehicles of the same size. The results of this study provide EFs for the carbonaceous composition of $PM_{2.5}$ that are more appropriate for China; these results will be helpful for improving policies that are designed to control the carbonaceous composition of $PM_{2.5}$ emitted from on-road DTs in China.

1. Introduction

Beijing, the capital of China, frequently experiences severe haze-fog pollution of widespread public and scientific concern (Quan et al., 2011; Gao et al., 2015). The main cause of this haze is a rapid or persistent increase in fine particle ($PM_{2.5}$, i.e., particles with an aerodynamic diameter of 2.5 μm or less) concentrations in the air, which is accompanied by relatively stable synoptic conditions (Liu et al., 2014; Sun et al., 2006). Many studies have shown that vehicle exhaust is a major source of $PM_{2.5}$ in ambient air pollution in Beijing (Song et al., 2006; Wang et al., 2008; Cheng et al., 2013; Yu et al., 2013). On-road vehicles are the largest local emission source and are responsible for contributing 22.2% of the

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$PM_{2.5}$ concentration (including primary and secondary $PM_{2.5}$ but excluding vehicle-induced road dust) in Beijing (Beijing EPB, 2012). $PM_{2.5}$ contributed by diesel vehicles has been shown to account for a significant proportion of all $PM_{2.5}$ contributed by vehicles on roads in Beijing (Huo et al., 2011; Wu et al., 2011; Wang et al., 2010).

An analysis of the diesel exhaust PM composition showed that elemental carbon (EC) and organic carbon (OC) contribute more than 80% of the total PM in diesel engine exhaust by weight (Watson et al., 1994; Lu et al., 2012). The carbonaceous composition of $PM_{2.5}$ emitted from diesel trucks (DTs) is of central interest for climate change, source apportionment, and aerosol modelling (Maricq, 2007). The optical properties of diesel PM can reduce visibility due to the absorption of direct light by EC and light scattering (Eldering and Cass, 1996; Eidels-Dubovoi, 2002). The elemental fraction stems from fuel droplet pyrolysis (Abdul-Khalek et al., 1998). Diesel engines are believed to be the main source of EC in urban environments and in the global atmosphere (Schauer et al., 1996; USEPA, 2002). Consequently, EC serves as a surrogate for monitoring exposures to and concentrations of diesel particulate matter (Birch and Cary, 1996; NIOSH, 1996; Groves and Cain, 2000). The organic fraction originates from unburned fuel, lubricating oil and combustion byproducts (Abdul-Khalek et al., 1998; CFR 86). In addition, it has been shown that OC contains many carcinogenic and mutagenic compounds (Kleeman et al., 2000; Chien et al., 2009). However, many studies have shown that the emission rates of EC and OC from diesel engines vary with engine load, mode of vehicle operation, vehicle type, vehicle age, fuel quality, and ambient conditions (Li et al., 2014; Liu et al., 2009; Sharma et al., 2005; Shah et al., 2004; Cocker et al., 2004; Johnson et al., 2011; Robert et al., 2007; Lu et al., 2012). Thus, using EC as a marker for diesel exhaust or as a surrogate for total diesel PM is only valid when the other factors are well defined (Fraser et al., 2002; Schauer, 2003). Therefore, further research on the emissions of OC and EC from diesel is important for deeply understanding and assessing diesel pollutant emissions.

Several studies have focused on the particle size distributions and carbonaceous compositions of $PM_{2.5}$ emitted from diesel engines using chassis dynamometer tests, tunnel tests, roadside measurements, or direct engine dynamometer measurements (Kim Oanh et al., 2010; Biswas et al., 2008; May et al., 2014; Chellam et al., 2005; Ntziachristos et al., 2007; Sharma et al., 2005; Park et al., 2003). For example, Kim Oanh et al. (2010) characterized $PM_{2.5}$, EC and OC emissions from 93 vehicles using a chassis dynamometer under the ETC/EUDC cycle in Bangkok. In addition, Ntziachristos et al. (2007) measured EC and OC concentrations next to the freeway carrying the highest ratio (up to 25%) of heavy-duty diesel vehicles in Los Angeles. Robert et al. (2007) analyzed total carbon and EC collected from 4 diesel vehicles equipped with different engine and emission control technologies; the vehicles were tested using a chassis dynamometer under the California Air Resource Board (CARB) heavy heavy-duty diesel trucks (HHDDT-5) mode driving cycle in California. Li et al. (2014) studied the effects of fuel injection pressure (FIP), start injection (SOI) and the application of exhaust gas recirculation (EGR) on particle size distributions and OC and EC emissions generated by a common rail diesel engine in China. However, tests using chassis dynamometers cannot fully reveal all emission trends during a dynamic driving cycle (Holmen and Ayala, 2002; Saitoh et al., 2003), tunnel and roadside tests cannot fully capture the range of driving cycles of diesel trucks (DTs) (Geller et al., 2005; Zanini et al., 2006; He et al., 2006), and direct engine dynamometer measurements do not fully represent emissions from complete DTs (Park et al., 2003; Sharma et al., 2005). In recent years, on-board tests using the mobile emission laboratory method (MEL) and portable emission measurement systems (PEMS) have become important for vehicle emission research worldwide, because these methods can measure emission characteristics directly from the tailpipe in the real world (Giechaskiel et al., 2014; Durbin et al., 2007; Johnson et al., 2011; Kittelson et al., 2006; Shah et al., 2004; Cocker et al., 2004). Shah et al. (2004) reported the EC, OC and PM emission rates of 11 HHDDTs operating under real-world conditions by following the speed trace from the CARB HHDDT cycle using a MEL in Coachella. In China, PEMS are gradually used to measure the EFs of DTs on roads, resulting in the generation of a larger number of reports of $PM_{2.5}$ EFs (Chen et al., 2007; Liu et al., 2009; Huo et al., 2012; Wang et al., 2012; He et al., 2014). However, EFs that represent the carbonaceous composition of $PM_{2.5}$ from on-road diesel vehicles remain limited in China.

This study aims to characterize the carbonaceous compositions of $PM_{2.5}$ that is emitted from on-road DTs in Beijing. A PEMS was used to record data and collect $PM_{2.5}$ samples from DTs under on-road driving conditions. The results of this study can provide EFs related to the carbonaceous composition of $PM_{2.5}$, which will be helpful for model simulation and source apportionment. In addition, the characterization of these emissions from DTs under real-world conditions is important for understanding where continuing efforts on improving air quality should be focused.

2. Experimental section

2.1. Sampling system and method

In this study, all samples were collected from a PEMS that was developed based on our previous on-board emission system (Yao et al., 2007; Huo et al., 2012; Zhang et al., 2013; Yao et al., 2014), as shown in Fig. 1. This system comprises four main parts: a Semtech EFM-2 tube, a Semtech-DS mobile emission analyzer, a Semtech-MPS (Micro Proportional Sample System, MPS) and a $PM_{2.5}$ sampling system. The flow of diesel exhaust was measured after dividing the Semtech-EFM-2 (Sensors Inc., Ann Arbor, MI, USA) tube into two sample channels. One of the sample flows was sent directly to the Semtech-DS (Sensors Inc., Ann Arbor, MI, USA) for CO and CO_2 analysis using non-dispersive infrared absorption (NDIR), NO_X analysis using non-dispersive ultraviolet absorption (NDUV), and THC analysis using a flame ionization detector (FID). Temperature/pressure sensors and GPS devices were included to monitor vehicle speed, altitude, latitude, longitude, and air temperature and pressure. The second sample flow was routed through the Semtech-MPS (Sensors Inc., Ann Arbor, MI, USA), which mixes clean air with the sample at a controlled rate. The average dilution factor was approximately 14.6 to 1 (a range of 7.5–22.5 to 1 was maintained), and clean air was provided using an oil-less air compressor (JCW-600H-9, UDUN, China) through a high efficiency particulate air (HEPA) capsule filter (12144, PALL, USA) to guarantee that the air supply was particulate free.

The exhaust flow in the second sample channel, which was connected with the Semtech-MPS, was heated to 110 °C to avoid water and organic condensation. The Semtech-MPS was connected with the Semtech-EFM-2 tube to measure the exhaust mass flow rate. In addition, the Semtech-MPS was used to transmit the measured data (dilution rate, exhaust flow rate, etc.) to the Semtech-DS for recording. The main data was monitored in real time using a laptop connected to the Semtech-DS.

The diluted sample flow was then pumped into the $PM_{2.5}$ sample system. The inlet of the $PM_{2.5}$ sample system was equipped with a $PM_{2.5}$ cyclone (URG 2000-30EHW, URG Corp, USA) to collect particles with an aerodynamic diameter of 2.5 μm or less. The sample flow through the $PM_{2.5}$ cyclone was divided into two parallel channels. Channel 1 consisted of bare-quartz (bare-Q) and backup quartz filters, whereas channel 2 consisted of a front