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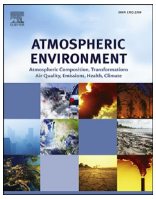

Emission factors of fine particles, carbonaceous aerosols and traces gases from road vehicles: Recent tests in an urban tunnel in the Pearl River Delta, China

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HIGHLIGHTS

- Emission factors of air pollutants for road vehicles measured in an urban tunnel.
- Decadal changes of $PM_{2.5}$, OC and EC emission factors measured in the same tunnel.
- EFs of SO_2, NO_x, CO, CO_2 and NMHCs for road vehicles from tunnel tests.
- Diurnal variation of emission factors revealed changes with fleet compositions.

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ABSTRACT

Motor vehicles contribute primarily and secondarily to air quality problems due to fine particle ($PM_{2.5}$) and ozone (O_3) pollution in China's megacities. Characterizing vehicle emission with the rapid change of vehicle numbers and fleet compositions is vital for both bottom-up emission survey and top–down source apportioning. To obtain emission factors (EFs) of $PM_{2.5}$, carbonaceous aerosols and trace gases for road vehicles, in urban Guangzhou we conducted a field campaign in 2014 in the Zhujiang Tunnel, a heavily burdened tunnel with about 40,000 motor vehicles passing through each of its two separated bores per day. $PM_{2.5}$ and volatile organic compounds (VOCs) were sampled for offline analysis while trace gases including SO_2, NO_x and CO were measured online and in situ. An eddy covariance system with an integrated 3-D sonic anemometer was also adopted to measure CO_2 and winds inside the tunnel. We recorded an average fleet composition of 61% light-duty gasoline vehicles (LDVs) + 12% heavy-duty diesel vehicles (HDVs) + 27% liquefied petroleum gas vehicles (LPGVs), and EFs of 82.7 ± 28.3, 19.3 ± 4.7 and 13.3 ± 3.3 mg veh^{-1} km^{-1}, respectively, for $PM_{2.5}$, organic carbon (OC) and elemental carbon (EC). These EFs were respectively 23.4%, 18.3% and 72.3% lower when compared to that measured in the same tunnel in 2004. EFs of $PM_{2.5}$, OC and EC were higher at night time (148 ± 126, 29 ± 24 and 21 ± 18 mg veh^{-1} km^{-1}, respectively) due to significantly elevated fractions of HDVs in the traffic fleets. An average ratio of OC to EC 1.45 from this tunnel study was much higher than that of ~0.5 in previous tunnel studies. The EFs of SO_2, NO_x, CO, CO_2 and NMHCs for road traffic were also obtained from our tunnel tests, and they were 20.7 ± 2.9, (1.29 ± 0.2)E+03, (3.10 ± 0.68)E+03, (3.90 ± 0.49)E+05, and 448 ± 39 mg veh^{-1} km^{-1}, respectively.

1. Introduction

Air pollution due to fine particles ($PM_{2.5}$) and ozone (O_3) has become tough problems of wide concern in China's megacities

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(Chan and Yao, 2008; Zhang et al., 2012a; Guo et al., 2014) due to impaired visibility (Che et al., 2007; Wu et al., 2007; Cao et al., 2012), adverse health endpoints (Xu et al., 2008; Tie et al., 2009; Huang et al., 2012; Chen et al., 2013b; Shang et al., 2013) and damage to ecological services (Krupa et al., 2001; Wang et al., 2007). Particularly in the urban areas, vehicle exhausts are convinced a major source of air pollutants leading to China's air quality headaches including $PM_{2.5}$ and O_3. Apart from emission of primary particulate matters (PM) (Kleindienst et al., 2002; Huang et al., 2014), motor vehicles can also emit a variety of trace gases such as VOCs and NO_x (Schauer et al., 1999; Kirchstetter et al., 1999; Hao et al., 2000; Imhof et al., 2006), which are important precursors to both secondary aerosols (Ng et al., 2007) and ozone (Derwent et al., 1996). As an example, in China's Pearl River Delta (PRD) region, a substantial fraction of aromatic hydrocarbons were sourced from vehicle exhausts (Liu et al., 2008b; Cheng et al., 2010a; Zhang et al., 2012b), and they were major anthropogenic precursors of both secondary organic aerosols (SOA) (Ding et al., 2012; Wang et al., 2013) and ambient ozone (Cheng et al., 2010b; Zhang et al., 2013b). Therefore vehicle emission control is an enduring task to combat air pollution in China in light of its rapidly increasing vehicle numbers.

The contribution of vehicle emission to $PM_{2.5}$ in China, however, is a debatable issue. Even in Beijing, the capital city of China, observation-based $PM_{2.5}$ source apportioning revealed quite large gaps for the percentages shared by vehicle exhausts (Song et al., 2007; Zhang et al., 2013a; Huang et al., 2014). On the other hand, bottom-up emission inventories still have pretty large uncertainties for vehicle emission. Zheng et al. (2009) demonstrated that vehicle emissions accounted for 67%, 36%, 39%, 36%, and 22% of CO, NO_x VOCs, $PM_{2.5}$ and PM_{10}, respectively, in the Pearl River Delta (PRD) region with 2006 as the base year, and they claimed uncertainties from -60% to $+70\%$ for both particle and gaseous pollutants from vehicle emissions in the emission inventory. A major reason for the uncertainties related to the top–down or bottom-up survey of vehicle emission is the lack of extensive characterization of vehicle emission, particularly the source profiles and emission factors, in China. As a matter of fact, the possession of civil vehicles numbers in China increased rapidly from about 27 million in 2004 to over 127 million in 2013 with an annual increasing rate of ~40% (National Bureau of Statistics of China (NBSC), 2014). This would inevitably induce great changes in China's on-road vehicles including the engines, oil consumption, energy efficiency and emission standards, and thereby result in fast changing emission factors and chemical compositions of air pollutants from vehicles. Under this situation, updating emission factors and source profiles for motor vehicles is in pressing need to keep pace with the fast changing motor vehicles, either in numbers or in compositions.

Emission factors (EFs) for motor vehicles can be measured by a variety of methods including chassis and engine dynamometer testing under controlled conditions in laboratories (Artelt et al., 1999; Nine et al., 1999), remote sensing method (Bishop and Stedman, 1996), on-road (chase) measurements (Shorter et al., 2005) and tunnel studies (Jamriska et al., 2004; Hueglin et al., 2006). Among them tunnel study has its advantages in obtaining absolute levels of emissions by capturing a cross-section of the on-road vehicle fleet and representing real-world operation conditions (Franco et al., 2013). In China, on-board measurements of emission factors for pollutants from vehicles has been extensively performed by using a portable emissions measurement system (PEMS), mostly in Beijing (Liu et al., 2009; Huo et al., 2011; Wang et al., 2011; Shen et al., 2014; Yao et al., 2015), Shanghai (Chen et al., 2007), Chongqing (Wang et al., 2012a) and Macao (Hu et al., 2012; Wang et al., 2014). Remote sensing measurements of EFs were previously conducted in Hangzhou in 2004 and 2005 (Guo et al., 2007), and Li et al. (2013) reported $PM_{2.5}$ emissions from light-duty vehicles measured on a chassis dynamometer. However, only a few tunnel studies about the emission factors for road vehicles were carried out in mainland China, all in the Pearl River Delta region except one measuring PM_{10}-bound polycyclic aromatic hydrocarbons in the Fu Gui-shan Tunnel in Nanjing (Chen et al., 2013a). He et al. (2006) chemically characterized $PM_{2.5}$ based on the 4 sets of particle samples collected from the Wutong Tunnel in the PRD's Shenzhen city, and Cheng et al. (2006; 2010c) and Ho et al. (2006, 2009) measured EFs of $PM_{2.5}$, VOCs and carbonyl compounds in the Shing Mun Tunnel in Hong Kong. Based on studies in the Zhujiang Tunnel in urban Guangzhou, the same one for this study, Wang et al. (2001) calculated EFs of PM_{10} and some gaseous pollutants from a campaign in 1999; Huang et al. (2006) and He et al. (2008) reported size distribution of EC and $PM_{2.5}$ emissions from a campaign in 2004. As chemical compositions and EFs of pollutants from vehicles would change quite a lot accompanying with the rapid change of vehicle numbers, fleet compositions, fuel quality and control strategies, these EFs need to be updated to reflect current vehicle emissions and to include more pollutant species. However, a very recent study in the Zhujiang Tunnel in 2013 only secured EFs of ammonia (Liu et al., 2014), $PM_{2.5}$ and major $PM_{2.5}$ components (Dai et al., 2015). Moreover, only two particulate samples were collected per day, this would mask peak or valley values as large diurnal variations of EFs were observed in many tunnel and on-board tests (Ammoura et al., 2014; Shen et al., 2014).

This study aimed to update EFs of $PM_{2.5}$ and carbonaceous aerosols (OC and EC) and to extend our measurements for obtaining EFs of gaseous pollutants including VOCs, NO_x, CO and SO_2 for road vehicles in the Pearl River Delta region based on our campaign in the Zhujiang Tunnel in June 2014. These results are not only the latest emission factors of gaseous and particulate pollutants for road vehicles in the PRD region, but also valid data to assess the effectiveness of vehicle emission controls in the recent decade when comparing them with that previously measured in the same tunnel.

2. Methods

2.1. Description of the Zhujiang Tunnel

The Zhujiang Tunnel (23.11°N, 113.23°E), located in the Liwan District in urban Guangzhou, is the first underwater tunnel crossing the Pearl River in the Pearl River Delta. It has two bores with two lanes for each direction; its total length is 1238.5 m with a 721 m flat underwater section (Fig. 1). We conducted our tests in this flat underwater section. The outlet sampling site is about 50 m to the end of this flat underwater section. Further information can be

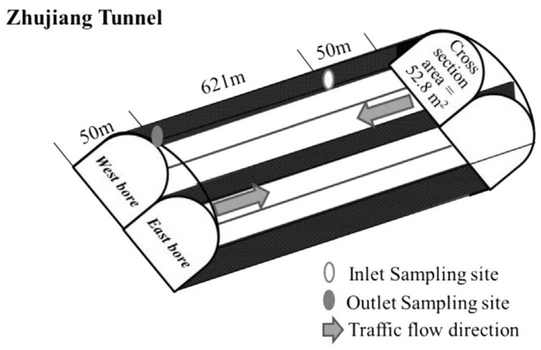

Fig. 1. Schematic diagram of the straight line segment of the Zhujiang Tunnel.