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On-board measurements of gaseous pollutant emission characteristics under real driving conditions from light-duty diesel vehicles in Chinese cities

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ABSTRACT

A total of 15 light-duty diesel vehicles (LDDVs) were tested with the goal of understanding the emission factors of real-world vehicles by conducting on-board emission measurements. The emission characteristics of hydrocarbons (HC) and nitrogen oxides (NO_x) at different speeds, chemical species profiles and ozone formation potential (OFP) of volatile organic compounds (VOCs) emitted from diesel vehicles with different emission standards were analyzed. The results demonstrated that emission reductions of HC and NO_x had been achieved as the control technology became more rigorous from Stage I to Stage IV. It was also found that the HC and NO_x emissions and percentage of O_2 dropped with the increase of speed, while the percentage of CO_2 increased. The abundance of alkanes was significantly higher in diesel vehicle emissions, approximately accounting for 41.1%–45.2%, followed by aromatics and alkenes. The most abundant species were propene, ethane, *n*-decane, *n*-undecane, and *n*-dodecane. The maximum incremental reactivity (MIR) method was adopted to evaluate the contributions of individual VOCs to OFP. The results indicated that the largest contributors to O_3 production were alkenes and aromatics, which accounted for 87.7%–91.5%. Propene, ethene, 1,2,4-trimethylbenzene, 1-butene, and 1,2,3-trimethylbenzene were the top five VOC species based on their OFP, and accounted for 54.0%-64.8% of the total OFP. The threshold dilution factor was applied to analyze the possibility of VOC stench pollution. The majority of stench components emitted from vehicle exhaust were aromatics, especially *p*-diethylbenzene, propylbenzene, *m*-ethyltoluene, and *p*-ethyltoluene.

Introduction

The changes of the gaseous pollutant contents in the atmospheric environment have been associated with the growth of China's vehicle population (Chan and Yao, 2008). The motor vehicle population was 208 million in 2011 in China, with automobiles, light-duty trucks, and motorcycles accounting for 44.7%, 5.9%, and 49.4%, respectively. The automobile category was divided into gasoline vehicles and diesel vehicles, and the contribution ratios to nitrogen oxides

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(NO_x) and hydrocarbons (HC) were 90% and 70% of the total motor vehicle population, respectively (MEP, 2011). Vehicle emissions have gradually been recognized as a significant source of ambient volatile organic compounds (VOCs) (Huang et al., 2011), which play an important role in atmospheric chemistry and urban air quality. An investigation showed that vehicle emissions accounted for more than 50% of the ambient VOCs in some cities (Liu et al., 2008a). In order to control the vehicle exhaust pollution and improve the urban air quality, national governments have implemented numerous control measures, including promoting clean transportation fuel, improving exhaust after-treatment technology as well as enacting strict emission standards (Yao et al., 2007). Among them, implementing vehicle exhaust emission standards has become one of the main measures of urban motor vehicle pollution control at home and abroad. Various vehicle emission standards were implemented in different stages in China. However, the desired ambient air quality has not been achieved due to the rapid increase of vehicles and kilometers driven (Huo et al., 2012a). Gaseous pollutants have still remained at a higher level of pollution in urban atmospheres.

Pollutants discharged from vehicles are complicated, and mainly come from incomplete combustion of fuels. The exhaust measurements show that the main composition consists of carbon monoxide (CO), HC, NO_x, sulfur oxides (SO_x), and particulate matter (PM) (Fu, 2009). The HC and NO_x are major pollutants in vehicle emissions. As mobile pollution sources, vehicles often accumulate in flourishing areas and the pollutants have toxic effects on atmospheric chemistry (Tsigaridis and Kanakidou, 2007) and adverse health effects (Zhang et al., 2008). First of all, VOCs are important HC of vehicle exhaust pollution, which include a variety of carcinogenic substances (Louie et al., 2013). They can stimulate the visual and olfactory organs and result in anemia and even acute poisoning. Additionally, VOCs can convert into secondary organic aerosols (SOA) through photochemical oxidation, which also has significant influence on human health (Pachauri et al., 2013). Last but not least, VOCs can react with NO_x generated in the process of combustion and form the secondary pollutant ozone (O_3) under strong light (Suthawaree et al., 2012).

In this case, determining the emission characteristics of vehicles in real-world conditions, especially for policy makers, is an intractable issue in controlling the vehicle emissions more effectively. During the past several years, the majority of sampling methods have mainly included remote sensing techniques (Carslaw and Rhys-Tyler, 2013), traffic tunnel measurements (Ho et al., 2009), dynamometer tests (Tsai et al., 2006), and roadside sampling (Phuleria et al., 2007). For instance, Ho et al. (2013) collected samples at roadside locations, and the most abundant VOC was ethane, which accounted for 9.5%–29.0% of the total quantified VOCs. However, these methods show great differences from real driving conditions on account of limitations of technology and equipment. Investigations on driving patterns (Tong et al., 2000) have reported that the actual driving pattern emissions were generally higher than those derived from dynamometer tests if the effect of the operating conditions of the vehicles is neglected. It is also clear that research on the emission characteristics of various vehicle models is relatively scarce and limited. In addition, the problems caused by diesel vehicle emissions have gradually become more prominent with better control of gasoline vehicle emissions (Fu, 2009). Therefore, in order to reveal the vehicle emission characteristics of China's diesel vehicles under real traffic conditions, a total of 15 light-duty diesel vehicles (LDDVs) were employed to collect HC, nitrogen oxides (NO_x), and VOC samplings using a developed dilution sampling system for vehicle exhaust under real driving conditions during 2013 and 2014 in the cities of Tangshan and Hengshui in Hebei province of China. The objectives of this study mainly include: (1) investigating the HC and NO_x emission characteristics and the influence of vehicle speed on HC and NO_x emissions; (2) analyzing the chemical profiles of VOCs emitted from LDDVs in real conditions; and (3) evaluating the ozone formation potential (OFP) and stench index of VOCs emitted from LDDVs.

1. Experimental methods

1.1. Sampling system for vehicle exhaust

The majority of sampling methods discussed above have not considered real driving conditions and the transformation of gaseous pollutants to secondary fine particles when the exhaust is cooled and diluted with the ambient atmosphere. This might overestimate the VOC emission due to the high temperature of vehicle exhaust. The flue gas temperature should be at 42°C or lower according to the dilution sampling standard proposed by the International Organization for Standardization (ISO 25597:2013). However, the temperatures of vehicle exhaust measured in this study were all above 42°C. Therefore, an on-board emission measurement system containing an exhaust gas dilution system was employed to collect samplings from diesel vehicles under real driving conditions (Fig. 1).

This system mainly includes the following parts: (1) A flow meter was used to measure instantaneous exhaust flow rate and temperature from test vehicles. (2) A heated inlet line was used to ensure that the temperature of exhaust gas did not drop from the flow meter to the mixing chamber. (3) A five-gas analyzer (Gasboard-5030, Wuhan Cubic Optoelectronics Co., Ltd., China) was utilized to measure the real-time emissions of gaseous pollutants, such as percent by volume of oxygen (O_2), carbon dioxide (CO_2), and the concentration of HC and NO_x every 3 sec. To ensure the accuracy of the data, the five-gas analyzer was checked for tightness and zeroed in the atmosphere before use. (4) A global position system (GPS) device (Columbus V-990, CDH Electronic Technology Co., Ltd., China) was applied to monitor the instantaneous speed and location of test vehicles. (5) A zero gas generator was used to provide pure air mixed with exhaust in the mixing chamber to simulate the rapid cooling and dilution processes after hot exhaust exited the tail pipe. Finally, the temperature of the air mixture was dropped to below 42°C. (6) A computer was used to control the software, and data including the dilution ratios, the flow of diluent air, and other parameters could be recorded and exported after the sampling. The sampling equipment was always placed inside the vehicles in the process of testing (Huo et al., 2012c). Due to the different