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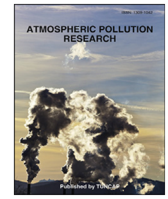

Evaluating real-world emissions of light-duty gasoline vehicles with deactivated three-way catalyst converters

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Xuan Zheng [a], Ye Wu [a, b, *], Shaojun Zhang [c], Liqiang He [a], Jiming Hao [a, b]

[a] *School of Environment, State Key Joint Laboratory of Environment Simulation and Pollution Control, Tsinghua University, Beijing, 100084, PR China*
[b] *State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing, 100084, PR China*
[c] *Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY, 14850, USA*

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A B S T R A C T

Three-way catalyst (TWC) converter is one of the most important after-treatment device for modern light-duty gasoline vehicles (LDGVs), which can efficiently control exhaust emissions of carbon monoxide (CO), total hydrocarbons (THC) and nitrogen oxides (NO_X). Nevertheless, a considerable part of in-use taxis in Beijing would operate with TWC purposely removed, which have been indicated by vehicular on-board diagnostic (OBD) systems. In light of high vehicle-use intensity for taxis, we recruited three China 4 non-TWC taxis and three China 4 normal taxis in a comparative experimental test by using a portable emissions measurement system (PEMS). The results indicated that non-TWC taxis emitted significantly higher emissions of air pollutants than normal taxis with TWC functioning. For example, average emission factors of non-TWC vehicles were comparable to emission levels of China 1 LDGVs measured in previous studies. By contrast, emissions from normal China 4 taxis were all below China 4 emission limits. Furthermore, an operating mode binning method and a micro-trip approach have been employed to link vehicle emissions with driving conditions. For non-TWC taxis, we identified strong correlations of all pollutant categories between emission factors and average speed. However, such correlations for normal taxis were less strong, in particular for CO and THC emissions that were hardly sensitive to speed changes. This phenomenon indicates that the role of traffic conditions in affecting real-world emissions would become weaker when TWC can effectively mitigate emissions. This paper highlights the importance of in-use emission inspection to avoid any "high emitters" that have violated regulation enforcement.

1. Introduction

The issue of air quality caused by mobile source emissions is one of the major focus of current research in the world (Iodice and Senatore, 2013, 2015a; Tong et al., 2015, 2016a, 2016b; Liu et al., 2016). With China's rapid economic development over the past decades, surges of vehicle population are seen in many regions since 2000 (Wu et al., 2016, 2017). Beijing, the capital of China, is also the city with largest vehicle population in this country. Although a series of transportation restrictions have been implemented by the municipal government (Zhang et al., 2014a). Beijing's vehicle population has climbed to 5.3 million by 2015 (BSMB, 2016). As a result, on-road vehicles have become one of the major air pollution contributors in many cities of China (Wang and Hao, 2012). Among all vehicle categories, light-duty gasoline vehicles (LDGVs) are account responsible for over 90% of total vehicle population in Beijing, among which more than 600 thousand are taxi vehicles. LDGVs are estimated to contribute considerably total vehicular emissions, for example, 70% of carbon monoxide (CO), 75% of total hydrocarbon (THC) and 30% of nitrogen oxides (NO_X). CO is one criterial air pollutant that is regulated by the National Ambient Air Quality Standard (NAAQS) in China, while THC and NO_X are important precursors of secondary air pollutants (e.g., secondary aerosol, ozone) (Yuan et al., 2013; Kroll et al., 2006; Ke et al., 2017). Thus, vehicle emissions and associated air pollution

* Corresponding author. School of Environment, State Key Joint Laboratory of Environment Simulation and Pollution Control, Tsinghua University, Beijing, 100084, PR China.
E-mail address: ywu@tsinghua.edu.cn (Y. Wu).
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problems have created serious concerns of both governmental stakeholders and urban dwellers in China. To mitigate vehicle emissions, Beijing has implemented a series of emissions control strategies and polices since the 1990s, notably adopting advanced after-treatment devices (e.g. three-way catalyst, TWC) to comply with increasingly stringent emission standards (Zhou et al., 2010; Zhang et al., 2014a; 2014b; Wu et al., 2017).

In Beijing, special attentions in terms of emission control have been paid to the taxi fleet, because taxi vehicles have significantly higher mileage compared with regular personal vehicles (Zhang et al., 2014a; He et al., 2016). In general, higher vehicle mileage indicates increased risks of emission level deterioration, although taxis have a rapid turnover rate in Beijing (e.g., approximately 6 years). For example, taxis in Beijing mostly run over 100 thousand km per year, which means that their total accumulated mileage levels would exceed emission control durability requirements in emission standards (e.g., 160 thousand km of the China 5 standard) after one or two years. In addition, on-board diagnostic (OBD) system has become a required technology since the China 3 emission standard to indicate whether the emission control system functions properly. Nevertheless, we found that many taxis were operating with the OBD warning light (i.e., "engine check" light) on, which indicated that their emission control devices (i.e., three-way catalyst, TWC) might probably be malfunctional. Such phenomenon has been rarely observed in regular personal vehicles that have equipped with OBD systems. After chatting with taxi drivers, the OBD warning was because these taxi drivers purposely removed the TWC in order to reduce fuel consumption. When the taxis were required to receive annual inspections, the taxi drivers would rent a new and temporary TWC, which would guarantee that these taxis would meet inspection regulations. These taxis (i.e., mentioned as non-TWC taxis hereinafter) would emit tremendous amount of gaseous pollutants in usual service while their TWC devices were malfunctional.

Gaseous emissions from LDGVs have been evaluated worldwide primarily through dynamometer testing and remote sensing measurements (May et al., 2014a; Zhu et al., 2016; Yang et al., 2015; Corvaian and Urrutia, 2000; Maricq et al., 1999; Zhou et al., 2014). Nevertheless, some limitations still remain among these studies. For example, in dynamometer tests, potential uncertainties may result from the simple test cycle (Franco et al., 2014). For remote sensing measurements, the test duration is usually relatively short and measurement sites are setup at limited locations. With recent advancement in portable emission measurement system (PEMS), real-world emissions of air pollutants are measured by using on-board PEMS from LDGVs in China (Huo et al., 2012; Wu et al., 2015a; Hu et al., 2012). For example, Huo et al. (2012) and Hu et al. (2012) both identified that air pollutant emissions were significantly reduced as their emission standards got tightened. Furthermore, Wu et al. (2015a) compared the impacts from driving conditions between regular gasoline cars and hybrid electric gasoline cars. However, there have rare PEMS studies available concerning real-world emissions of in-use taxis without TWC devices functioning properly.

Six LDGVs, including three non-TWC taxis (i.e., OBD waring light on) and three normal taxis (i.e., OBD warning light off), were recruited in this on-road measurement study. One PEMS system was employed to measure instantaneous emissions of major gaseous pollutants and real-world driving conditions. The testing routes covered different driving conditions in Beijing, including both congested fractions on local roads and high-speed fractions on freeways. This paper characterized instantaneous emissions and potential effects from driving conditions by using operating mode binning (Wu et al., 2012; Zheng et al., 2016) and micro-trip (Zhang et al., 2014c; 2014d) methods. A particular focus was attained to comparing real-world emissions between TWC-malfunctional and normal taxis. The findings of this paper could emphases the importance of in-use inspection and regulation enforcement to controlling vehicle emissions.

2. Methodology

2.1. Experimental section

Six LDGVs, including three non-TWC taxis and TWC taxis, were recruited in Beijing. All these vehicles were manufactured during 2009–2012, and are declared to compare with the China 4 emission standard (the information of China 4 emission standard is listed in Table S1). The China 4 emission standard was implemented in 2008 in Beijing and could account for more than 50% of registered LDGVs by 2013. In addition, the unified emission certification level could help to better explore the role of normal TWC in controlling vehicle emissions. The detail information of each vehicle is listed in Table 1. We carefully checked the status of after-treatment before each test. For three non-TWC samples, their TWC had been manually removed by drivers, and OBD waring lights were on during the tests. By contrast, three TWC taxis received TWC replacement by taxi companies a few weeks ago, and the OBD warning signals were off during the tests (see Table 1).

The on-road tests were conducted in Beijing. The testing routes consisted of two road types: local roads and urban freeways to represent various driving conditions (see Fig. 1). The total tested distance and average speed by road types for each LDGV are presented in Table S2. Average speed on local roads and freeways were 21 ± 1 km h^{-1} and 61 ± 10 km h^{-1}, indicating the significant distinction of traffic conditions between the two road types. The gasoline fuels used for on-road tests were obtained from one gasoline station, and should meet the ultra-low sulfur content limit (i.e., sulfur content less than 10 ppm, namely the China 5 gasoline quality standard). Each tested taxi was operated along the sampling routes to ensure a continuous test duration of approximately 2 h.

In this study, a Sensors Inc.'s SEMTECH EcoStar PEMS was employed, which consisted of an exhaust flow meter, a global position system (GPS) and gas analyzers (see Fig. S1). The SEMTECH EcoStar PEMS is capable of meeting the regulatory requirements in U.S., Europe and China. The high-speed exhaust flow meter could record real-time exhaust volume data and normalize instantaneous results to standard conditions (i.e., 25 °C and 1 atm). The GPS was employed to obtain instantaneous profiles regarding driving conditions (e.g., speed, acceleration). Instantaneous THC, CO, carbon dioxide (CO_2) and NO_X concentrations were measured using non-dispersive infrared (NDIR, for CO and CO_2), flame ionization detector (FID, for THC) and non-dispersive ultra-violet (NDUV, for NO_X) analyzers. Before each test, the SEMTECH EcoStar PEMS was zeroed with nitrogen and was calibrated using standard gases to assure data accuracy.

2.2. Data processing

Based on instantaneous emission profiles for gaseous species, the emission ratios of THC, CO, CO_2 and NO_X for individual LDGVs are calculated based on pollution concentrations and exhaust volume, as Eq. (1) illustrates:

$$ER_{i,t} = P_{i,t} \cdot V_t \quad (1)$$

where $ER_{i,t}$ is the instantaneous emission rate of pollutant i at second t, g s^{-1}; $P_{i,t}$ is the instantaneous concentration of pollutant i at second t, g m^{-3}, which is recorded by the gas analyzer; V_t is the instantaneous vehicle exhaust volume at second t, m^3 s^{-1}, and the