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Influences of accumulated mileage and technological changes on emissions of regulated pollutants from gasoline passenger vehicles

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ABSTRACT

In this study, the influences of accumulated mileage (deterioration) and technological changes (emission standards) on emission factors (EFs) of regulated pollutants (CO, HC, and NOx) from gasoline passenger vehicles were investigated based on Inspection and Maintenance (I/M) data using the chassis dynamometer method. The accumulated mileage of passenger vehicles was significantly linearly correlated with vehicle age. For most cases, the average EFs of CO, HC and NOx were significantly linearly correlated with accumulated mileage, indicating that emission deterioration had a significant impact on pollutant EFs. Implemented emission standards markedly influenced the EFs of regulated pollutants, and EFs markedly decreased with progressing emission standards. The present study also compared EFs of regulated pollutants between this study and the International vehicle emission (IVE) model, and marked differences in EFs were seen with variations in emission standards, vehicle types and accumulated mileage; NOx EFs in this study were higher than in the IVE model. The results provide new insight into estimating regulated pollutant emissions using the IVE model.

Introduction

During recent decades, the rapid growth of industrialization and urbanization has led to faster increases in numbers of motor vehicles (in particular passenger vehicles) in the mega-cities of China; therefore, vehicle emissions constitute one of the main sources of atmospheric pollution (Guo et al., 2006; Zhou et al., 2010; Che et al., 2011; Zheng et al., 2012; Wu et al., 2017). In recent years, more frequent haze events in China have been caused by the large amount of pollutants emitted by vehicles (Huang et al., 2012; Wang et al., 2014). For example, VOC emissions in Shanghai from motor vehicles accounted for 25% of total emissions (Cai et al., 2010), and emissions of NOx in Hangzhou from motor vehicles accounted for more than 70% of total emissions (Zhang et al., 2008).

The estimation of vehicular emissions depends mainly on the values of emission factors (EFs), which are used for the development of a comprehensive emission inventory of vehicles (Mishra and Goyal, 2014). Emission factors of vehicles are dependent upon many factors such as vehicle type, fuel

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quality, vehicle age, mileage, technology level, and inspection and maintenance (I/M) (Liu et al., 2008; Liu et al., 2009, 2013; Q. Zhang et al., 2013; S. Zhang et al., 2013).

Combustion-powered vehicles tend to deteriorate with usage and accumulated mileage, and emission control equipment will be degraded or malfunction; and as a result, emission levels can elevate significantly (Lau et al., 2012; Borken-Kleefeld and Chen, 2015). The pollution degree of vehicles is mostly affected by vehicle age, and motor vehicles deteriorate with age (Zachariadis et al., 2001). Some studies reported that the deterioration of motor vehicles shows increasing trends with increases in the accumulated mileage; for example, pollutant EFs increase with accumulated mileage (Singer and Harley, 2000; Chiang et al., 2008); and 60% of the pollutants resulted from 20% of vehicles that had the highest accumulated mileages in Hangzhou city, China (Guo et al., 2006). NOx emissions from all cars and light commercial vehicles in European emission inventories were found to increase by 5%–10%, accounting for deterioration (Chen and Borken-Kleefeld, 2016).

China has adopted the European standards for new vehicles since 2001, and vehicle emission standards have played a key role in reducing vehicle emission levels in China. For example, the Beijing government has efficiently implemented emission standards and fuel quality standards, resulting in reductions in vehicle emissions (Wang et al., 2011; Zhang et al., 2014). For the Pearl River Delta region in south China, upgrading China's national IV emission standard has been the most effective individual measure to reduce average NOx and PM_{10} concentrations (Che et al., 2011). In Guangzhou during 2005–2009, vehicle emissions were estimated to have been reduced through technological improvement by 12% for CO and 21% for Total hydrocarbons THC relative to levels in 2005 (Q. Zhang et al., 2013; S. Zhang et al., 2013).

The inspection and maintenance (I/M) program is one of important elements among overall measures to mitigate vehicle emissions (Wenzel, 2001; Schifter et al., 2003; Houtte and Niemeier, 2008). Many nations use vehicle I/M programs to identify high-emitting vehicles and ensure that they operate to meet emission standards (Wenzel, 2001; Schifter et al., 2003; Eisinger, 2005; Chang and Yeh, 2006; Li and Crawford-Brown, 2011). I/M programs based on periodic short tests can identify those problem cars, and require a re-test after necessary maintenance to assure their repair. Engine characteristics, vehicle age, fuel quality, mileage, and maintenance are found to be strong determinants of emissions and test failure rates (Wenzel, 2001; Eisinger, 2005). Therefore, the I/M programs contribute substantially to the reduction of pollutants caused by vehicles; Zhang et al. (2014) reported that the enhanced I/M program for light duty vehicles was estimated to reduce 11% of CO, 9% of THC and 2% of NOx relative to total vehicle emissions. Meanwhile, in-use vehicle I/M programs also generate a tremendous volume of data that provides a valuable means for evaluating the emission characteristic of vehicles (Bin, 2003; Beydoun and Guldmann, 2006; Chang and Yeh, 2006; Chiang et al., 2008). The I/M data can also be used to perform an extensive analysis of emission deterioration (Chiang et al., 2008; Chen and Borken-Kleefeld, 2016). For developing countries, it is not easy to develop EFs; furthermore, the I/M programs can be used to develop the EFs of vehicles (Schifter et al., 2003). Nowadays, China's developed cities have improved test methods and upgraded the measuring equipment for the I/M program; currently, the I/M programs have become a low-cost, highly effective, and easy test in the developed cities. The I/M stations can automatically measure vehicles on real-time basis, which gives the I/M data the accuracy necessary to evaluate the characteristics of vehicle emissions and calculate EFs for establishing an emission inventory.

China has widely used some computer models to estimate mobile source emissions for inventories, such as the international vehicle emission (IVE) model (Wang et al., 2008; Che et al., 2011; Yao et al., 2014). The IVE model is specifically designed for developing nations to address mobile source emissions, and the advantage of the IVE model is its sensitivity to existing vehicle technologies and driving behavior in developing countries (Guo et al., 2007a; Wang et al., 2008; Huo et al., 2011; Nagpure and Gurjar, 2012; Shrestha et al., 2013). The IVE model is an important tool to calculate average emission rates for different vehicle categories and facility types. However, the EFs or basic emission rates of emissions in the IVE model are U.S- and European-based, which may cause deviations in estimated emissions for developing countries (Tung et al., 2011; Kim Oanh et al., 2012). Moreover, the base EFs in the IVE model were based on data taken by a laboratory dynamometer method, with limited emission tests.

The IVE model is allowed to use local correction factors to estimate local vehicle emissions; correction EFs are important to develop improved EFs based on the IVE model (Tung et al., 2011; Kim Oanh et al., 2012; Shrestha et al., 2013). It is necessary to update the emissions in specific areas to reflect regional vehicle emissions. To our knowledge, the IVE model has not still been upgraded and is based on rather old data. In recent years, some nations have adopted modified versions of EFs based on U.S or European values.

Vehicle emissions vary with vehicle types, adopted emission standards, and emission deterioration; therefore, it is necessary to determine the factors considering parameters such as cylinder capacity, vehicle age, mileage, and emission standards.

Hangzhou, located in east China, is an important developed city with major tourist industry in China, and Hangzhou has high emission density from vehicles. The goal of Hangzhou is to become an influential international city; for example, in September 4, 2016, Hangzhou succeeded in holding the G20 summit. In coming years, Hangzhou will hold several international events, such as the 2020 Asian Games. To date, Hangzhou government has taken many measures to mitigate vehicle emissions, *i.e.*, implementing tightened emission standards, improving fuel quality, upgrading the I/M program, stringent license control, and scrappage of older vehicles.

Vehicles are mainly concentrated in cities with denser populations; urban gasoline passenger vehicles account for a high proportion of total motor vehicles in China. In 2010, the ratio of gasoline passenger vehicles to total motor vehicles in Hangzhou was 64.49% (NBSC, 2011). Therefore, it is necessary to characterize the emissions of gasoline passenger vehicles to improve the air quality of the urban environment due to low- and medium-passenger vehicles for private use and high-passenger vehicles for business use. The objectives of this study are to investigate emission changes with vehicle age or accumulated mileage and technological level using a large data sample from the I/M program, and to compare the EFs from this study with those of the IVE model. Further, the results are compared with the IVE model for simulation of measured values. The basic EFs in the IVE model were modified by this work.

1. Methodology

1.1. Data sources

In this study, all data for the period 2010–2011 were provided by the I/M program of Hangzhou, China. Since 2008, Hangzhou city has adopted the upgraded Simple Driving Mode Conditions (SDMC) for its annual I/M program, following China's national standard (GB 18285–2005). Because China has adopted Euro emission standards, SDMC for the I/M programs in China are similar to the European urban driving cycle (UDC), representing urban operation conditions. The UDC involves driving 1013 m at an average speed of 18.7 km/hr during 195 sec, and this routine is repeated four times in sequence, totaling 4052 m in 780 sec in urban driving conditions. However, China's SDMC is slightly different from UDC, having only one cycle with 1013 m driven during 195 sec, compared with the four cycles in the European UDC.

For the current SDMC driving cycle, the measurement system included a chassis dynamometer (Model ACCG-3, Magtrol, Inc.), a gas flow analyzer (Model ML-100, McCrometer, Inc.), and a five-gas analyzer (Model MQW-50A, Mingtrun, Inc.) that can automatically analyze the concentrations of HC, CO and NOx from the vehicles. During the test, a gasoline vehicle was driven on the chassis dynamometer, and the vehicle was operated through an entire cycle (SDMC), including idle, acceleration, constant speed, and deceleration. The five-gas analyzer and flow analyzer were used to measure the pollutant concentrations and flow rates, which were then converted to EFs (g/km) based on mileage.

Meanwhile, vehicle age, vehicle type, accumulated mileage, and the model year (in relation to emission standards) were collected for each vehicle.

1.2. Quality Assurance

A chassis dynamometer was used (Model ACCG-3, speed indication error: ±0.2 km/hr, torque and power indication error: ±1.0%) to simulate the driving cycles of acceleration and uniform speed for vehicles on the road. The dynamometer has two wheels, whose diameters are 295 mm. The deviation for the center distance of the wheels is −6.5–12.7 mm.

The sampling probe's length is 650 mm, and it should be inserted into the vehicle exhaust pipe at depth greater than 250 mm. The length of any exhaust pipe less than 250 mm should be extended, the change of air pressure in the exhaust pipe must be less than 0.25 kPa.

A five-gas analyzer (Model MQW-50A, detection accuracy of CO: ±3%, HC: ±3%, O_2: ±5%, NOx: ±4%, CO_2: ±3%) was used to automatically analyze the concentrations of HC, CO, CO_2, NOx, and O_2 from vehicle exhaust. The concentrations of CO, HC, and CO_2 were tested by the Non-Dispersive Infra-Red (NDIR) method, and the concentration of NOx was tested by electrochemical methods.

The gas flow analyzer (Model ML-100, detection accuracy of O_2: ±5%, flow rate: ±4%) was used to control the exhaust gas flow in the pipe during testing.

1.3. Data processing

According to the IVE model, gasoline passenger vehicles in this study were classified into three types based on engine capacity and vehicle weight, *i.e.*, light gasoline passenger vehicle (LGPV) with <1.5 L (engine capacity) and <2268 kg (weight), medium gasoline passenger vehicle (MGPV) with 1.5–3 L and 2268–2994 kg, and heavy gasoline passenger vehicle (HGPV) with >3 L and 2994–4082 kg. European emission standards for motor vehicles have been implemented in China since 2001, and China's serial emission standards such as grades I, II, III, IV, and V are equal to Euro 1, 2, 3, and 4 emission standards, respectively. Therefore, this study used Euro 1, 2, 3, and 4 to represent China's grades I, II, III, and IV.

This study obtained a total of 86,142 datasets for EFs of regulated pollutants from gasoline passenger vehicles for the period 2010–2011 in Hangzhou, and the total valid data used in this study were 82,905 datasets, excluding some data with recording errors and outliers (the 5% most extreme values were designed as outliers following the box-plot method). The sample size was large enough to eliminate inter-vehicle variation; therefore, the mean values of EFs were used to take into account averaging effects.

To explore the correlation between vehicle age and accumulated mileage, the entire data set was classed according to vehicle age; then the average accumulated mileages for the same vehicle ages were calculated.

In order to study the impacts of accumulated mileage and implemented emission standards on EFs, the data on EFs of CO, HC and NOx for both the same emission standard and the same vehicle type were classed based on accumulated mileage (10 × 1000 km increment scale); then the data falling within the same scale were averaged to obtain mean EFs. Further, correlations between average EFs of CO, HC and NOx and accumulated mileages were analyzed (Pearson correlation coefficients) and simple linear curves were fitted between the EFs and accumulated mileages.

To compare the EFs in this study with those in the IVE model, EFs of CO, HC and NOx were grouped with respect to vehicle types (LGPV, MGPV and HGPV), accumulated mileages (<79,000 km, 80,000–161,000 km and > 161,000 km) and emission standards (Euro 1–4) according to the IVE model, and the mean EFs falling within the same groups were calculated, respectively.

1.4. Operational Street Pollution Model (OSPM)

The OSPM is a parameterized model for flow and dispersion conditions in the street canyons (Berkowicz et al., 2003). It has been widely used to simulate the pollutant concentrations in air near the street across the world (Assael et al., 2008; Berkowicz et al., 2008; Wang et al., 2010). We used OSPM to verify whether the modifications in the IVE model were reasonable.

2. Results and discussion

2.1. Relationship between vehicle ages and accumulated mileages

The mileage of vehicles is an important parameter because it is involved in traffic emission assessment. Fig. 1 represents that the relationship between vehicle age and accumulated mileage, showing significantly strong correlation between vehicle age and accumulated mileage. The result indicated that the accumulated mileage of gasoline passenger vehicles increased with vehicle age. This is consistent with other studies; and EFs are highly dependent on vehicle age (Zachariadis et al., 2001; Liu et al., 2007; Yang et al., 2007; Chen and Borken-Kleefeld, 2016).

2.2. Relationship between accumulated mileage and EFs

As shown in Fig. 2, the relationship between average CO EFs and accumulated mileage exhibited significantly positive correlations under different emission standards. Meanwhile, emission standards had marked influences on CO EFs, which decreased with tighter emission standards. The linear curves differed between vehicle types. For Euro 1 and Euro 2 vehicles, the CO EFs of HGPVs were much higher than those of LGPVs and MGPVs (Fig. 2a and b), while for Euro 3 and Euro 4 vehicles, there was no available data for HGPVs (Fig. 2c and d), which was because the number of Euro 3 and Euro 4 HGPVs was lower because of the congestion and lack of parking in urban areas. There were similar change trends for CO EFs with accumulated mileage between LGPVs and MGPVs. Moreover, because the implementation time of Euro 4 was relatively short compared with other emission standards, the accumulated mileages of Euro 4 vehicles were short; therefore, Euro 4 vehicles did not exhibit deterioration with accumulated mileage.

The relationships between average HC EFs and accumulated mileage are shown in Fig. 3; note that there was no available data for HGPVs for Euro 3 and Euro 4. As shown in Fig. 3, the curve slopes and intercepts differed among vehicle types and emission standards, and except for Euro 4 MGPVs (as shown in Fig. 3d), the average HC EFs of different vehicle types covering Euro 1–4 had significantly positive correlation with accumulated mileage. The average HC EFs of HGPVs were markedly higher than those of LGPVs and MGPVs (Fig. 3a and b), and for Euro 3 and Euro 4, the HC EFs of LGPVs and MGPVs exhibited similar change trends with accumulated mileage (Fig. 3c and d), which was explained by the fact that LGPVs and MGPVs were mainly used for personal transportation and had low mileage and good maintenance. Emission standards markedly influenced the HC EFs, which markedly decreased with progressing emission standards. As presented in Fig. 3d, there may be lower numbers of vehicles implementing Euro 4 emission standards, and the lower curves of Euro 4 vehicles may be due to implementation of the stricter emission standards. Because Euro 4 vehicles had very low mileage, in reality, they did not present deterioration effects (Fig. 3d).

Fig. 4 presents the relationship between average NOx EFs and accumulated mileage, and marked differences in slopes and intercepts of linear curves were observed among vehicles and emission standards. Except for Euro 1 HGPVs, the average NOx EFs of different vehicle types covering Euro 1–4 significantly positively correlated with accumulated mileage, the average NOx EFs of different vehicle types covering different standards presented increasing trends with accumulated mileage, and the average NOx EFs markedly decreased with advanced emission standards (as shown in Fig. 4). The NOx EFs of HGPVs were higher than those of LGPVs and MGPVs under Euro 1 and Euro 2 (Fig. 3a and b), while the NOx EFs of LGPVs and MGPVs implementing Euro 3 and Euro 4 had similar change trends with accumulated mileage. Because Euro 4 vehicles were driven for relatively short times, there were limited data for Euro 4 compared with other standards. The accumulated mileages of Euro 4 LGPVs and MGPVs were less than 161,000 km, which did not represent emission deterioration (Fig. 4d).

Deterioration of an engine and catalyst can cause high levels of emission, because the engine and catalyst degrade with use and vehicle age (Faiz et al., 2006). In-use cars show a clear deterioration in emission behavior as the cars become older, mainly because of the aging of their catalytic converters and the degradation of their emission control systems (Zachariadis et al., 2001). The slope values of curves can be used to evaluate the deterioration in vehicle pollutant EFs (Yang et al., 2007). In this study, these curves gave fits with R^2 squared values ranging from 0.067 to 0.880, and almost all curves had statistical significance (as shown in Figs. 2–4). Further, regression slopes and intercepts better depict the deterioration of Euro 1, Euro 2 and Euro 3 vehicles; suggesting that emission deterioration is better modeled with linear functions of mileage. In contrast, Euro 4 vehicles had relatively low mileage levels, which did not reflect emission deterioration. Air-pollutant emissions would increase after long-term driving (Yang et al., 2007). Singh and Sloan (2006) reported that the emission rate of a vehicle is a linear function of the vehicle mileage or age, and the deterioration rate increased with accumulated vehicle mileage.

The growth trends of pollutant EFs for HGPVs were the fastest among the vehicle types, which indicated that the deterioration effects of HGPVs on the pollutant emissions

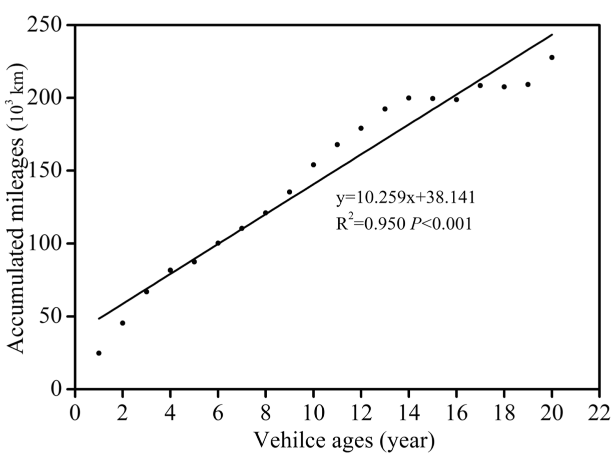

Fig. 1 – Relationships between vehicle age and accumulated mileage.

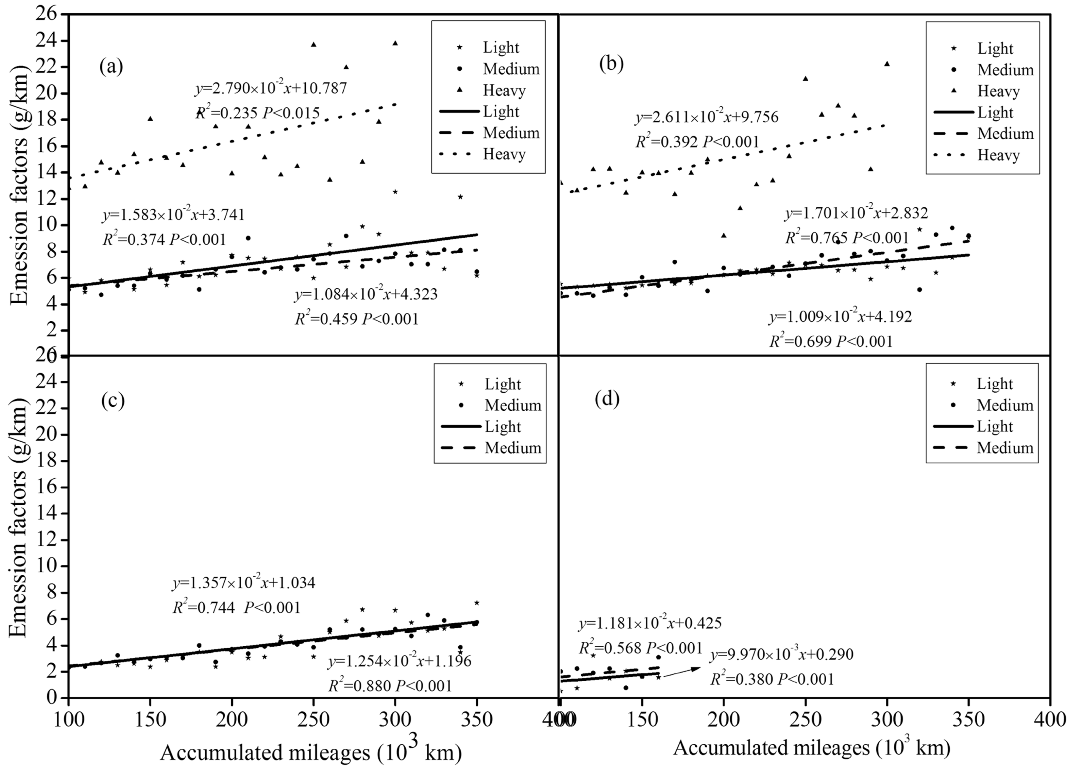

Fig. 2 – Relationships between CO EFs for three gasoline passenger vehicles and accumulated mileages, (a) Euro 1, (b) Euro 2, (c) Euro 3, and (d) Euro 4. EFs: emission factors.

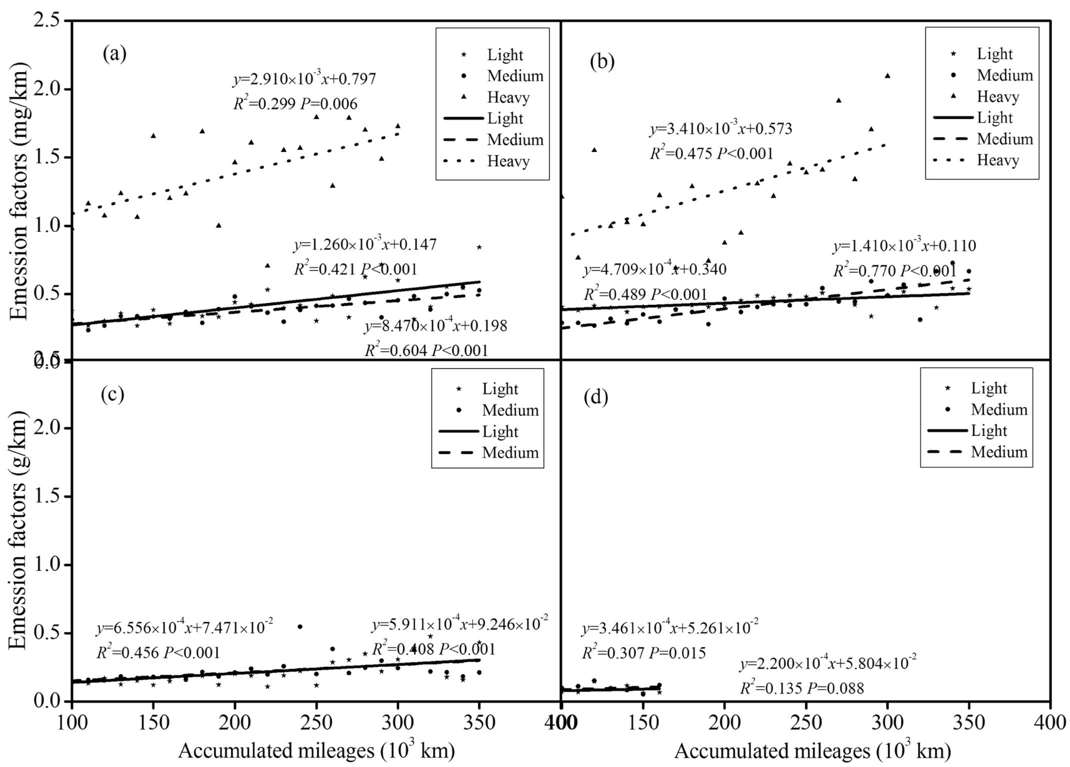

Fig. 3 – Relationships between HC EFs for three gasoline passenger vehicles and accumulated mileages: (a) Euro 1, (b) Euro 2, (c) Euro 3, and (d) Euro 4. EFs: emission factors.

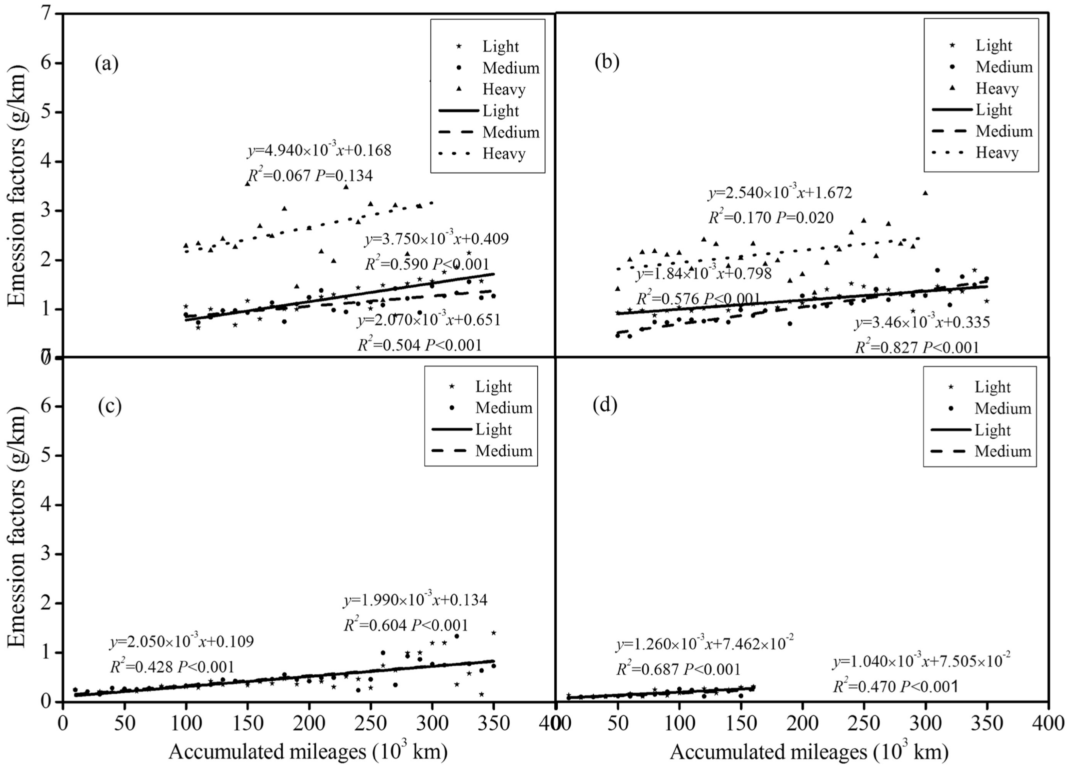

Fig. 4 – Relationships between NOx EFs for three gasoline passenger vehicles and accumulated mileages: (a) Euro 1, (b) Euro 2, (c) Euro 3, and (d) Euro 4. EFs: emission factors.

were significantly higher than those of LGPVs and MGPVs. HGPVs tended to have the highest emissions among vehicle types, because HGPVs belong to the government public corporation and tourism sector and have high utilization rates and ages. As for Euro 4 vehicles, a few driving years may not be enough to observe an aging effect on emission. It was seen that LGPVs and MGPVs of Euro 1 and Euro 2 had similar curves, which is explained by the fact that LGPVs and MGPVs are classed as private cars for personal use with better maintenance and low mileages.

Marked differences in the slopes and intercepts of linear curves among emission standards are shown in Figs. 2–4, and the lower curves were due to the application of newer vehicle technologies. The results indicated that emission deterioration was strongly associated with emission standards, and Euro 1 and Euro 2 vehicles exhibited higher emissions than Euro 3 and Euro 4. Low-emission-standard vehicles with have caused significant deterioration with long-term use and result in increased emissions. In this study, aged Euro 1 vehicles may be a great concern because they have shown higher deterioration with increasing mileage, especially HGPVs. The contributions of Euro 4 vehicles to total emissions of regulated pollutants were the lowest, because new vehicles have likely benefited from technological improvement, while the contributions of Euro 1, Euro 2 vehicles were relatively high, showing that older vehicles have higher emissions than younger vehicles. Consequently, it is necessary to introduce stringent emission standards for a wide range of vehicle categories to reduce road transport emissions.

2.3. Comparison of EFs between this study and the IVE model

Basic EFs or basic rate of emissions of the IVE model are based on laboratory chassis dynamometer data from the U.S and European countries (Wang et al., 2008; Nagpure and Gurjar, 2012; Shrestha et al., 2013). The IVE model allows the application of these locally specific emissions through the use of emission correction factors (Tung et al., 2011). The data used to generate the EFs in the IVE model are now rather old, and may no longer be representative of modern vehicles; therefore, it is necessary to update the emissions in each area to reflect these regional differences. Some developing countries have improved the basic EFs in the IVE model to reflect local emissions based on local features (Guo et al., 2007b; Huo et al., 2011; Tung et al., 2011; Kim Oanh et al., 2012).

The IVE model uses basic EFs for three segments to reflect the emission deterioration; namely, the accumulated mileage in the IVE model was divided into three segments: <79,000 km, 80,000–161,000 km, and > 161,000 km. In this study, the mean EFs of CO, HC and NOx with respect to vehicle types and emission standards were calculated for each segment to compare the EFs of this study with the basic EFs in the IVE model.

Comparisons of EFs of CO, HC and NOx between this study and the IVE model are summarized in Table 1. The average CO EFs of this study differed from the IVE model, and their differences were related to emission standards, vehicle types and accumulated mileage (shown in Table 1). For Euro 4 vehicles, regardless of the vehicle type and mileage class, the

Table 1 – Comparison of EFs between this study and the IVE model.

Standards	Vehicle types	Accumulated mileages ($\times 10^3$ km)	Emission factors (g/km)					
			CO		HC		NOx	
			This study	IVE	This study	IVE	This study	IVE
Euro 1	Light	<79	4.936	4.193	0.243	0.200	0.713	0.156
		80–161	5.796	6.343	0.306	0.600	0.896	0.201
		>161	7.755	19.445	0.468	1.100	1.358	0.283
	Medium	<79	5.115	2.976	0.259	0.300	0.796	0.314
		80–161	5.741	14.042	0.306	0.900	0.915	0.361
		>161	7.07	30.641	0.414	1.800	1.177	0.431
	Heavy	<79	12.447	3.637	0.987	0.300	1.928	0.383
		80–161	14.198	17.162	1.159	1.100	2.252	0.441
		>161	18.011	34.803	1.55	2.300	2.985	0.527
Euro 2	Light	<79	4.753	2.935	0.365	0.109	0.908	0.156
		80–161	5.39	4.44	0.397	0.292	1.022	0.201
		>161	6.765	13.612	0.46	0.507	1.264	0.283
	Medium	<79	4.003	2.083	0.213	0.121	0.59	0.314
		80–161	4.91	9.829	0.281	0.405	0.759	0.361
		>161	7.12	21.449	0.466	0.831	1.205	0.431
Euro 3	Heavy	<79	11.013	2.546	0.752	0.148	1.784	0.383
		80–161	12.762	12.014	0.958	0.495	1.966	0.441
		>161	16.665	24.362	1.491	1.016	2.342	0.527
	Light	<79	1.888	1.761	0.108	0.076	0.239	0.094
		80–161	2.554	2.664	0.144	0.204	0.335	0.12
		>161	4.451	8.167	0.243	0.355	0.624	0.17
	Medium	<79	1.991	1.25	0.128	0.085	0.296	0.188
		80–161	2.831	5.898	0.164	0.284	0.429	0.216
		>161	5.424	12.869	0.258	0.582	0.857	0.259
Euro 4	Light	<79	0.759	1.409	0.068	0.061	0.129	0.075
		80–161	1.464	2.131	0.084	0.164	0.225	0.096
		>161	5.094	6.534	0.123	0.284	0.64	0.136
	Medium	<79	0.992	1	0.069	0.068	0.124	0.151
		80–161	1.808	4.718	0.093	0.227	0.198	0.173
		>161	5.627	10.295	0.163	0.466	0.468	0.207

IVE: International vehicle emission; EFs: emission factors.

mean CO EFs in this study were lower than those of the IVE model, which may be explained by fewer Euro 4 vehicles being implemented. For Euro 1, 2 and 3 vehicles with <79,000 km, regardless of vehicle type, the CO EFs in this study were higher than the basic CO EFs in the IVE model. For the range of 80,000–161,000 km, CO EFs in this study showed complex behavior compared with the basic EFs in the IVE model, which was dependent upon emission standards and vehicle types. For accumulated mileages >161,000 km, regardless of vehicle type and emission standards, the basic CO EFs in the IVE model were markedly higher than those in this study, showing that deterioration with accumulated mileage in the U.S and Europe was more serious than in Hangzhou city, China.

As shown in Table 1, the present study compared the HC EFs between this study and the IVE model; the differences in EFs were associated with emission standards, vehicle types and mileage classes. For accumulated mileage <79,000 km, the average HC EFs in this study were generally greater than the basic EFs in the IVE model; in contrast, for accumulated mileage >161,000, except for Euro 2 HGPVs, HC EFs in this study were lower than in the IVE model, showing that the deterioration in China was lower than in the U.S and European nations.

As summarized in Table 1, for NOx EFs, except for Euro 4 MGPVs of <79,000 km, regardless of emission standards, vehicle type and accumulated mileage class, NOx EFs of this study were higher than those in the IVE model; therefore, the result showed that emissions of NOx in Hangzhou, China were higher than in the U.S and Europe. This result further indicates that the control level of the emission of NOx was poor for the gasoline passenger vehicles in China. Therefore, China needs to further improve fuel quality and control the emission of NOx from motor vehicles.

Moreover, it is possible to refine the basic EFs using scaling factors for the deterioration in emissions with age or mileage. Incorporating the emission data collected in this study will further improve the ability of the IVE model to correctly estimate current emissions and provide better tools for the prediction of future scenarios at regional levels.

Furthermore, we used the basic EFs in the IVE model and modified EFs as input to the OSPM model to simulate the NO_2 concentrations, and then compared them to the measured values. In this case, the NO_2 concentrations and traffic flow on

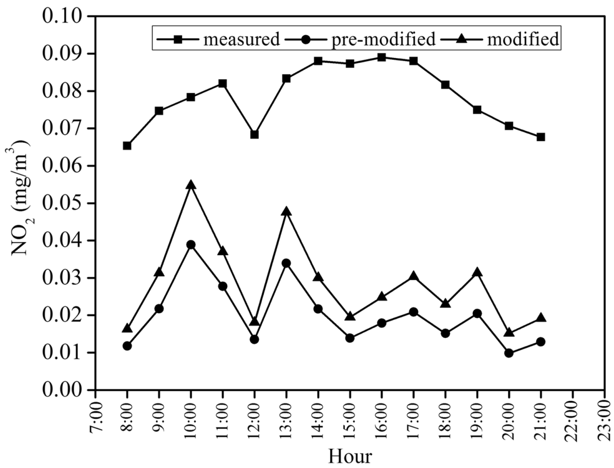

Fig. 5 – Temporal variation of measured and modelled concentrations of NO_2 on May 7, 2011.

Wenyi Road in Hangzhou were measured by the Environmental Monitoring Center Station from 8:00 to 21:00 on May 7th, 2011. The street geometry parameters within 50 m of the monitoring receptor were recorded and the meteorological data used were from the Weather Underground Website. The results in Fig. 5 show that the NO_2 simulation results with the modified EFs are closer to the observations compared to the basic EFs in the IVE model.

3. Conclusions

The present study explored the effects of deterioration (represented by accumulated mileage) and technological improvements (represented by emission standards) on emissions of regulated pollutants (CO, HC and NOx) on the basis of I/M data using the chassis dynamometer method. The results indicated that there were significantly linear relationships between the EFs of CO, HC and NOx and accumulated mileage, and the growth trends of the EFs of CO, HC and NOx markedly increased with increasing mileages. Emission standards markedly influenced the EFs of CO, HC and NOx, with decreasing trends with progressing emission standards, indicating that emission standards played a key role in emission reduction. The effects of deterioration of HGPVs on the pollutant emissions were much higher than for LGPVs and MGPVs.

The present study compared the EFs in this study and in the IVE model, and differences between this study and the IVE model were strongly associated with vehicle types, emission standards and mileage classes. The average EFs of three pollutants for the accumulated mileage with <79,000 km were generally greater than the base EFs in the IVE model; in contrast, when the accumulated mileage was >161,000 km, the average CO and HC EFs in this study were generally less than the basic EFs in the IVE model; NOx EFs in this study were higher than in the IVE model. Given these major changes in EFs, the EFs in the IVE model need to be updated to accurately evaluate regional vehicle emissions.

The basic EFs of the IVE model and modified EFs were used as input to the OSPM model to simulate the NO_2 concentrations; we found that the NO_2 simulation results with the modified EFs are closer to the observations relative to the basic EFs of the IVE model. The result shows that EFs obtained with the method of this paper are more reasonable. The real effects of vehicles on air quality are more serious than those estimated with EFs without considering deterioration.

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REFERENCES

Assael, M.J., Delaki, M., Kakosimos, K.E., 2008. Applying the OSPM model to the calculation of PM_{10} concentration levels in the historical center of the city of Thessaloniki. Atmos. Environ. 42 (1), 65–77.

Berkowicz, R., Olesen, H.R., Jensen, S.S., 2003. User's guide to WinOSPM. Ministry of the Environment National Environmental Research Institute.

Berkowicz, R., Ketzel, M., Jensen, S.S., Hvidberg, M., Raaschou-Nielsen, O., 2008. Evaluation and application of OSPM for traffic pollution assessment for a large number of street locations. Environ. Model. Softw. 23 (3), 296–303.

Beydoun, M., Guldmann, J.-M., 2006. Vehicle characteristics and emissions: logit and regression analyses of I/M data from Massachusetts, Maryland, and Illinois. Transp. Res. D Transp. Environ. 11 (1):59–76. https://doi.org/10.1016/j.trd.2005.09.003.

Bin, O., 2003. A logit analysis of vehicle emissions using inspection and maintenance testing data. Transp. Res. D Transp. Environ. 8 (3):215–227. https://doi.org/10.1016/S1361-9209(03)00004-X.

Borken-Kleefeld, J., Chen, Y., 2015. New emission deterioration rates for gasoline cars — results from long-term measurements. Atmos. Environ. 101:58–64. https://doi.org/10.1016/j.atmosenv.2014.11.013.

Cai, C., Geng, F., Tie, X., Yu, X., An, J., 2010. Characteristics and source apportionment of VOCs measured in Shanghai, China. Atmos. Environ. 44:5005–5014. https://doi.org/10.1016/j.atmosenv.2010.07.059.

Chang, H.-L., Yeh, T.-H., 2006. Regional motorcycle age and emissions inspection performance: a Cox regression analysis. Transp. Res. D Transp. Environ. 11 (5):324–332. https://doi.org/10.1016/j.trd.2006.06.004.

Che, W., Zheng, J., Wang, S., Zhong, L., Lau, A., 2011. Assessment of motor vehicle emission control policies using Model-3/CMAQ model for the Pearl River Delta region, China. Atmos. Environ. 45 (9):1740–1751. https://doi.org/10.1016/j.atmosenv.2010.12.050.

Chen, Y., Borken-Kleefeld, J., 2016. NOx emissions from diesel passenger cars worsen with age. Environ. Sci. Technol. 50 (7): 3327–3332. https://doi.org/10.1021/acs.est.5b04704.

Chiang, H.-L., Tsai, J.-H., Yao, Y.-C., Ho, W.-Y., 2008. Deterioration of gasoline vehicle emissions and effectiveness of tune-up for high-polluted vehicles. J. Traffic Transp. Eng. 13 (1):47–53. https://doi.org/10.1016/j.trd.2007.07.004.

Eisinger, D.S., 2005. Evaluating inspection and maintenance programs: a policy-making framework. J. Air Waste Manag. Assoc. 55 (2):147–162. https://doi.org/10.1080/10473289.2005.10464609.

Faiz, A., Ale, B., Nagarkoti, R., 2006. The role of inspection and maintenance in controlling vehicular emissions in Kathmandu valley, Nepal. Atmos. Environ. 40 (31):5967–5975. https://doi.org/10.1016/j.atmosenv.2005.11.064.

Guo, H., Zhang, Q., Shi, Y., Wang, D., Ding, S., Yan, S., 2006. Characterization of on-road CO, HC and NO emissions for petrol vehicle fleet in China city. J Zhejiang Univ Sci B 7: 532–541. https://doi.org/10.1631/jzus.2006.B0532.

Guo, H., Zhang, Q., Shi, Y., Wang, D., 2007a. On-road remote sensing measurements and fuel-based motor vehicle emission inventory in Hangzhou, China. Atmos. Environ. 41:3095–3107. https://doi.org/10.1016/j.atmosenv.2006.11.045.

Guo, H., Zhang, Q.-Y., Shi, Y., Wang, D.-H., 2007b. Evaluation of the International Vehicle Emission (IVE) model with on-road remote sensing measurements. J. Environ. Sci. 19 (7):818–826. https://doi.org/10.1016/S1001-0742(07)60137-5.

Houtte, J.V., Niemeier, D., 2008. A critical review of the effectiveness of I/M programs for monitoring PM emissions from heavy duty vehicles. Environ. Sci. Technol. 42 (21):7856–7865. https://doi.org/10.1021/es8001794.

Huang, K., Zhuang, G., Lin, Y., Fu, S., Wang, Q., Liu, T., et al., 2012. Typical types and formation mechanisms of haze in an Eastern Asia megacity, Shanghai. Atmos. Chem. Phys. 12: 105–124. https://doi.org/10.5194/acp-12-105-2012.

Huo, H., Zhang, Q., He, K., Yao, Z., Wang, X., Zheng, B., et al., 2011. Modeling vehicle emissions in different types of Chinese cities: importance of vehicle fleet and local features. Environ. Pollut. 159 (10):2954–2960. https://doi.org/10.1016/j.envpol.2011.04.025.

Kim Oanh, N.T., Thuy Phuong, M.T., Permadi, D.A., 2012. Analysis of motorcycle fleet in Hanoi for estimation of air pollution emission and climate mitigation co-benefit of technology implementation. Atmos. Environ. 59:438–448. https://doi.org/10.1016/j.atmosenv.2012.04.057.

Lau, J., Hung, W.T., Cheung, C.S., 2012. Observation of increases in emission from modern vehicles over time in Hong Kong using remote sensing. Environ. Pollut. 163:14–23. https://doi.org/10.1016/j.envpol.2011.12.021.

Li, Y., Crawford-Brown, D.J., 2011. Assessing the co-benefits of greenhouse gas reduction: health benefits of particulate matter related inspection and maintenance programs in Bangkok, Thailand. Sci. Total Environ. 409 (10):1774–1785. https://doi.org/10.1016/j.scitotenv.2011.01.051.

Liu, H., He, K., Wang, Q., Huo, H., Lents, J., Davis, N., et al., 2007. Comparison of vehicle activity and emission inventory between Beijing and Shanghai. J. Air Waste Manag. Assoc. 57: 1172–1177. https://doi.org/10.3155/1047-3289.57.10.1172.

Liu, H., He, K., He, D., Fu, L., Zhou, Y., Walshc, M., et al., 2008. Analysis of the impacts of fuel sulfur on vehicle emissions in China. Fuel 87:3147–3154. https://doi.org/10.1016/j.fuel.2008.03.019.

Liu, H., He, K., Lents, J.M., Wang, Q., Tolvett, S., 2009. Characteristics of diesel truck emission in China based on portable emissions measurement systems. Environ. Sci. Technol. 43:9507–9511. https://doi.org/10.1021/es902044x.

Liu, H., Rönkkö, T., Keskinen, J., 2013. Impact of vehicle development and fuel quality on exhaust nanoparticle emissions of traffic. Environ. Sci. Technol. 47:8091–8092. https://doi.org/10.1021/es401805r.

Mishra, D., Goyal, P., 2014. Estimation of vehicular emissions using dynamic emission factors: a case study of Delhi, India. Atmos. Environ. 98:1–7. https://doi.org/10.1016/j.atmosenv.2014.08.047.

Nagpure, A.S., Gurjar, B.R., 2012. Development and evaluation of vehicular air pollution inventory model. Atmos. Environ. 59: 160–169. https://doi.org/10.1016/j.atmosenv.2012.04.044.

NBSC (National Bureau of Statistics of China), 2011. China Statistical Yearbook. China Statistics Press, Beijing, China, pp. 16–24 (in Chinese).

Schifter, I., Díaz, L., Vera, M., Guzmán, E., Durán, J., Ramos, F., et al., 2003. Evaluation of the vehicle inspection/maintenance program in the metropolitan area of Mexico City. Environ. Sci. Technol. 37 (1):196–200. https://doi.org/10.1021/es020549t.

Shrestha, S.R., Kim Oanh, N.T., Xu, Q., Rupakheti, M., Lawrence, M.G., 2013. Analysis of the vehicle fleet in the Kathmandu Valley for estimation of environment and climate co-benefits of technology intrusions. Atmos. Environ. 81:579–590. https://doi.org/10.1016/j.atmosenv.2013.09.050.

Singer, B.C., Harley, R.A., 2000. A fuel-based inventory of motor vehicle exhaust emissions in the Los Angeles area during summer 1997. Atmos. Environ. 34:1783–1795. https://doi.org/10.1016/S1352-2310(99)00358-1.

Singh, R.B., Sloan, J.J., 2006. A high-resolution NOx emission factor model for North American motor vehicles. Atmos. Environ. 40 (27):5214–5223. https://doi.org/10.1016/j.atmosenv.2006.04.012.

Tung, H.D., Tong, H.Y., Hung, W.T., Anh, N.T., 2011. Development of emission factors and emission inventories for motorcycles and light duty vehicles in the urban region in Vietnam. Sci. Total Environ. 409 (14):2761–2767. https://doi.org/10.1016/j.scitotenv.2011.04.013.

Wang, H., Chen, C., Huang, C., Fu, L., 2008. On-road vehicle emission inventory and its uncertainty analysis for Shanghai, China. Sci. Total Environ. 398 (1–3):60–67. https://doi.org/10.1016/j.scitotenv.2008.01.038.

Wang, F., Ketzel, M., Ellermann, T., Wåhlin, P., Jensen, S.S., Fang, D., et al., 2010. Particle number, particle mass and NOx emission factors at a highway and an urban street in Copenhagen. Atmos. Chem. Phys. 10 (6), 2745–2764.

Wang, X., Westerdahl, D., Wu, Y., Pan, X., Zhang, K.-M., 2011. On-road emission factor distributions of individual diesel vehicles in and around Beijing, China. Atmos. Environ. 45 (2): 503–513. https://doi.org/10.1016/j.atmosenv.2010.09.014.

Wang, Y., Yao, L., Wang, L., Liu, Z., Ji, D., Tang, G., et al., 2014. Mechanism for the formation of the January 2013 heavy haze pollution episode over central and eastern China. Sci. China Ser. D 57:14–25. https://doi.org/10.1007/s11430-013-4773-4.

Wenzel, T., 2001. Reducing emissions from in-use vehicles: an evaluation of the Phoenix inspection and maintenance program using test results and independent emissions measurements. Environ. Sci. Pol. 4 (6):359–376. https://doi.org/10.1016/S1462-9011(01)00032-6.

Wu, Y., Zhang, S., Hao, J., Liu, H., Wu, X., Hu, J., et al., 2017. On-road vehicle emissions and their control in China: a review and outlook. Sci. Total Environ. 574:332–349. https://doi.org/10.1016/j.scitotenv.2016.09.040.

Yang, H., Chien, S., Lo, M., Lan, J., Lu, W., Ku, Y., 2007. Effects of biodiesel on emissions of regulated air pollutants and polycyclic aromatic hydrocarbons under engine durability testing. Atmos. Environ. 41 (34):7232–7240. https://doi.org/10.1016/j.atmosenv.2007.05.019.

Yao, Z., Wei, H., Perugu, H., Liu, H., Li, Z., 2014. Sensitivity analysis of project level MOVES running emission rates for light and heavy duty vehicles. J. Traffic Transp. Eng. (Engl. Ed.) 1 (2): 81–96. https://doi.org/10.1016/S2095-7564(15)30092-1.

Zachariadis, T., Ntziachristos, L., Samaras, Z., 2001. The effect of age and technological change on motor vehicle emissions. J. Traffic Transp. Eng. 6 (3):221–227. https://doi.org/10.1016/S1361-9209(00)00025-0.

Zhang, Q., Wei, Y., Tian, W., Yang, K., 2008. GIS-based emission inventories of urban scale: a case study of Hangzhou, China. Atmos. Environ. 42:5150–5165. https://doi.org/10.1016/j.atmosenv.2008.02.012.

Zhang, Q., Sun, G., Fang, S., Tian, W., Li, X., Wang, H., 2013a. Air pollutant emissions from vehicles in China under various energy scenarios. Sci. Total Environ. 450–451:250–258. https://doi.org/10.1016/j.scitotenv.2013.01.098.

Zhang, S., Wu, Y., Liu, H., Wu, X., Zhou, Y., Yao, Z., et al., 2013b. Historical evaluation of vehicle emission control in Guangzhou based on a multi-year emission inventory. Atmos. Environ. 76: 32–42. https://doi.org/10.1016/j.atmosenv.2012.11.047.

Zhang, S., Wu, Y., Wu, X., Li, M., Ge, Y., Liang, B., et al., 2014. Historic and future trends of vehicle emissions in Beijing, 1998–2020: a policy assessment for the most stringent vehicle emission control program in China. Atmos. Environ. 89: 216–229. https://doi.org/10.1016/j.atmosenv.2013.12.002.

Zheng, L., Zhong, S.-q., Ma, S.-f., 2012. Controlling traffic jams on a two-lane road using delayed-feedback signals. J. Zhejiang Univ. Sci. A 13 (8):620–632. https://doi.org/10.1016/j.atmosenv.2010.07.059.

Zhou, Y., Wu, Y., Yang, L., Fu, L., He, K., Wang, S., et al., 2010. The impact of transportation control measures on emission reductions during the 2008 Olympic Games in Beijing, China. Atmos. Environ. 44 (3):285–293. https://doi.org/10.1016/j.atmosenv.2009.10.040.