Assessment of different methods in analyzing motor vehicle emission factors

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Abstract
To explore the emission characteristics of vehicle’s pollutants is of great significance to prevent and control the diffusion of pollutants. Limited by geographic location and economic condition, the model- and guideline-based studies on vehicle’s emission factor have become more concerned measures than the actual measurement. By analyzing the actual operating conditions of motor vehicles, this study obtains the emission factors of typical pollutants from different motor vehicles by adopting international vehicle emission (IVE) model and guideline method, respectively. Furthermore, the resulting emission factors by the above methods were compared and analyzed with on-road method. The results show that: (1) the emission factors of vehicle pollutants change regularly with velocity, emission standard, and accumulated mileage. Taking CO as an example, its emission factor shows a downward trend with the increase of velocity and emission standard and an upward trend with the increase of accumulated mileage; (2) compared with the actual measurement, the vehicle emission factor obtained by the guideline method has a large error, while the IVE model is close to the actual.

Keywords Vehicle emission factors · IVE model · Guideline method · Influencing factors · On-road test · Comparative analysis

Introduction
Transportation sector has posed various global challenges, including climate change and air pollution (Fan et al. 2018; Song et al. 2019), in rapidly developing countries such as China (Zheng et al. 2017; Adamiec et al. 2016). Chinese urbanization and increasing purchasing power have significantly stimulated the sharp increase in motor vehicle ownership. In 2019, vehicle ownership in China reached 340 million, with an average annual growth rate of 7.9% (MTPRC 2019). As a result, particulate matter (PM) emitted by motor vehicles in principal cities (such as Beijing, Tianjin, and Shanghai) contributed to 13.5% ~ 51.1% of the total PM emissions (BMEEB 2020; TEEB 2018; SMEEB 2020). Carbon monoxide, nitrogen oxides, and ammonia emitted by motor vehicles also seriously threaten people’s health and safety (Wu et al. 2017; Leung and Williams 2000). Therefore, it is of great significance to analyze the emission characteristics of vehicle pollutants to mitigate and manage the diffusion of pollutants.

Current research that analyzes emission characteristics of motor vehicles mainly focused on vehicle emission factors using measurement-based methods and model-based methods (Franco et al. 2013; Nesamani 2010), with the assistance of big data in the latest research (Deng et al. 2020). The measurement-based method involves laboratory test and on-road test. The former mainly uses benchmark tests, and the latter includes tunnel tests, remote sensing, and on-vehicle tests (Gao et al. 2019). With the increasing attention to the transient characteristics of emission factor of motor vehicles for actual roads, on-road test has gradually become a...
research hotspot in recent years. Hu et al. (2012) tested the emission factors of diesel taxis in Macao by using a portable test system and pointed out that better traffic planning was conducive to reducing pollutant emissions. With similar methods, emission factors of passenger cars were developed in Lombardia, Italy (Marina et al. 2013), Shanghai, Beijing, and Guangzhou, China (Huo et al. 2012a, b). Wang and Westerdahl (2009; 2010; 2011) analyzed the emission characteristics of Beijing’s motor vehicle, whose results implied that traffic control was an effective measure to effectively reduce pollutant emissions. By analyzing PM$_{2.5}$ emission factors of motor vehicles for Hong Kong, Cheng et al. (2010) were skeptical of Wang’s comments and pointed out that the test cycle and meteorological changes were not taken into account in Wang’s experiment. By establishing a black-box model based on actual measurement, Jamriska and Morawska (2001) analyzed the emission factors of motor vehicles in Queensland, which were higher than those of the actual emission factors. Other studies (Costagliola et al. 2014; Dong et al. 2014; Mamakos et al. 2013; Zhu et al. 2016; Liu et al. 2019; Ewen et al. 2009; Bhattacharjee et al. 2011) also analyzed emission factors of motor vehicles based on the measured method.

The model-based methods involve mathematical and physical models. At present, MOBILE, COPERT (Computer Programme to Calculate Emissions from Road Transport), and IVE (International Vehicle Emission) model are widely used to study emission factors of motor vehicles. The IVE model is widely used because of its strong adaptability in developing countries and regions. For example, Gao et al. (2020) established the vehicle emission inventory of Harbin-Changchun megalopolis by using the IVE model and simulated the emission inventory of different scenarios. The results show that the elimination of old vehicles was the most effective measure to reduce the emission of pollutants. Guo et al. (2007a) conducted a comparative analysis on the vehicle emission factors between the IVE model and remote sensing method in a case study of Hangzhou city and found that emission factors obtained from the IVE model were overestimated. Furthermore, they made a fuel-based emission inventory (Guo et al. 2007b). Wang et al. (2008) established the vehicle emission inventory of Shanghai based on the IVE model and concluded the error of emission factor obtained by the IVE model was within 10% compared with the actual situation. By analyzing vehicle emission inventory in Tehran, Shafie-Pour and Tavakoli (2013) found that fine and reasonable public transport system, land use, and urban spatial planning were very important to reduce pollutant emissions in this area. Besides, Andreo et al. (2020) established Brazil’s vehicle emission inventory. Oga et al. (2020) established Isfahan’s high-resolution spatial and temporal vehicle emission inventory and found that motorcycles have largest CO and VOC emission factor, and diesel heavy-duty vehicles and buses mainly contribute to particulate matter emissions.

However, there is a knowledge gap in the comparison of vehicle emission factors obtained by different methods. In addition, there are some deficiencies in the uncertainty analysis. In this paper, Changchun City is selected as a typical city with low temperature for motor vehicle emission factor analysis. Performing the analysis is based on the IVE model and the “technical guideline for the preparation of road vehicle–air pollutant emission list (hereinafter referred to as the “guideline method”).” Furthermore, we analyze the influencing factors of emission factors and do a comparative analysis.

**Methods**

**Route for vehicle testing**

This paper takes Changchun City in Northeast China as an example to explore the vehicle emission factors calculated by different methods. We sampled from Chaoyang and Erdao Districts on weekdays and weekends, including peak hours and off-peak hours. Chaoyang and Erdao Districts are selected as representatives of urban commercial and residential districts, respectively (Fig. 1). This paper further analyzed vehicle emissions from different types of roads, including expressway, main roads, secondary roads, and residential roads (Ericsson 2000; Liu and Barth 2012).

**Operating conditions**

Light gasoline vehicles (Toyota pra), light CNG vehicle (Volkswagen Jetta), and buses were tested at 7:00 ~ 9:00 and 11:00 ~ 13:00 on expressway, main roads, secondary roads, and residential roads. Two portable vehicle-mounted locators equipped with Beidou and GPS positioning systems were used to determine the position and speed of the vehicle. Monitoring points were set on different types of roads, including the expressway, main roads, secondary roads, and residential roads, respectively. The HT3000-E mobile high-definition capture instrument was used to obtain the vehicle types in different periods on typical roads. Information of vehicles (including vehicle age, pollutant control technology, mileage, fuel type, and hot soak time) was obtained through online and offline questionnaires. In addition, local information and oil quality were derived from monitoring or investigation.

**IVE model**

The IVE model was developed by the International Sustainable Systems Research Center and the University of
California, Riverside for precisely estimating vehicle emissions, especially in developing countries with various technical parameters (Guo et al. 2007a). Compared to MOBILE 6 model, the IVE model allows an efficient estimation of the vehicle emission factors under various driving conditions (Davis et al. 2005; Rakha et al. 2003; Wang et al. 2014).

The IVE model has 1372 kinds of technical parameters including vehicle type, fuel, engine size, driving mileage, evaporation control, exhaust purification technology, and 45 parameters defined by the users themselves (Shafie-Pour and Tavakoli 2013). The emission factor $EF_t$ is calculated as follows:

$$EF_t = \frac{BEF_t \times \prod K_{xt}}{\text{unit220F.s1}}$$

where, $EF_t$ is the calibrated emission factor in start-up and running, g/km. $BEF_t$ represents the basic emission factor of start-up and running, g/km. $K_{xt}$ is the correction factor, including local information (e.g., temperature, humidity, altitude, road slope, fuel quality, velocity, mileage, starting times, specific power, and hot soak time), fuel quality, and driving parameters. Fuel quality and driving parameters vary with vehicle technologies (such as different engine, mileage, exhaust control system, and air fuel control system) and various fuels that power the vehicles.

**Guideline method**

In this session, we refer to the Technical Guidebook for On-Road Vehicle Air Pollutant Emissions (the Guidebook) from the Ministry of Environmental Protection of China to quantify on-road vehicle emissions in Northeast China in 2014 (MEP 2014). Based on the comprehensive benchmark emission coefficient ($BEF$) proposed from the Guidebook, we calibrated the emission coefficient with various inputs such as local information, mileages, vehicle type, and fuel quality, as follows:

$$EF_{ij} = BEF_i \times \varphi_j \times 

\text{region j; } \theta_i \text{ is the other correction factor of vehicle } i. \text{Fig. 1 Test route} \]
On-road test

In this study, SEMTECH-DS vehicle–exhaust gas analysis system was used to test vehicle emission factors. This instrument is designed according to the EPA 40CFR Part 1065 Subpart J standard, including the main control computer, vehicle-mounted gas emission analyzer, portable power supply, positioner, and gas flow meter. Its core analysis module is miniaturized and shockproof, and its accuracy can be sufficient and meet the experimental requirements. This equipment uses non-dispersive infrared analysis method to measure CO and CO₂, non-dispersive ultraviolet analysis method to measure NO and NO₂, electrochemical method to measure O₂ content, and Pitot flowmeter to measure exhaust gas flow.

Results and discussion

Operating condition analysis

Light gasoline vehicle

1. Velocity distribution

The hourly average velocities of light gasoline vehicles in different functional areas and road types of Changchun City are shown in Fig. 2. The average velocity on expressway on weekdays is the highest in the business district, which is 41.69 km/h, followed by the main roads (19.57 km/h), secondary roads (10.65 km/h), and residential roads (12.53 km/h). The velocities on expressway and main roads show typical bimodal distribution over time.

For the working days in residential areas, the maximum velocities occurred on expressway (48.5 km/h), main road (26.5 km/h), secondary road (24.8 km/h), and residential road (17.9 km/h) are 16.3%, 35.5%, 132.9%, and 43.1% higher than the same type of road in commercial areas, respectively. This means that the traffic condition of residential area is better than that of the commercial area.

2. Acceleration distribution

The acceleration distribution of the motor vehicle during the running stage is shown in Fig. 3. From left to right, the driving states are fast deceleration (a < −1.5), high deceleration (−1.5 ≤ a < −1.0), medium deceleration (−1.0 ≤ a < −0.6 and −0.6 ≤ a < −0.3), slow deceleration (−0.3 ≤ a < −0.1), uniform velocity (−0.1 ≤ a < 0.1), slow acceleration (0.1 < a ≤ 0.3), medium acceleration (0.3 < a ≤ 0.6 and 0.6 < a ≤ 1.0), high acceleration (1.0 < a ≤ 1.5), and fast acceleration (a > 1.5), respectively.

From the perspective of space, the acceleration distribution on different roads is obviously different. For example, the temporal distribution of uniform velocity on the secondary roads is the largest (57%), followed by
main roads (54%), residential roads (49%), and expressway (43%). The acceleration distribution is also different in different periods. During the rush hour, most of the vehicles drive at a constant velocity or slow acceleration and deceleration.

Light CNG vehicle and bus

For light CNG vehicle, the vehicle’s average velocity shows a wavy distribution over time, among which the average velocity in uniform velocity driving is the largest (44.66 km/h), followed by deceleration driving (36.09 km/h) and acceleration driving (29.38 km/h), respectively. The velocity maxima mainly occur at 11:00, 21:00, 5:00, and 8:00. The vehicle’s acceleration is mainly concentrated in uniform velocity and slow acceleration and slow acceleration, accounting for 37.7% and 29.4%, respectively, followed by medium acceleration, accounting for 27.8%.

The operating conditions of buses are related to road types and urban functions. Generally speaking, the operating conditions of buses in the rural are better than those in the urban. The experiment shows that the average velocity of buses in Changchun is 17.88 km/h. The operating conditions of acceleration and deceleration frequently occur on buses in Changchun, accounting for 85.4%. This is related to the frequent entry and exit of passengers.

Fleet composition and technical distribution

Fleet composition

Figure 4 shows the hourly traffic flow and fleet composition on typical roads.

The traffic flow in Changchun City is wavy over time. The peak value of hourly traffic flow on weekdays is around 7:00 and 18:00, which is consistent with the peak time of commuting. The expressway has the largest traffic volume (5405 vehicles/h), followed by the main roads (3843 vehicles/h), secondary roads (1834 vehicles/h), and residential roads.
(1153 vehicles/h). The road traffic on weekends is less than weekdays. The average traffic flow of the expressway, main roads, secondary roads, and residential roads is 5073, 3422, 1875, and 1004 vehicles/h, respectively. Their peak value appears around 9:00, 15:00, and 18:00.

For the distribution of vehicle type, small passenger cars accounted for the largest proportion (70%), followed by taxis (15%), and buses (4%). The proportion of small passenger cars in the expressway is as high as 90.3%, and the proportion of buses and motorcycles is almost zero. The proportions of small passenger cars on the main roads and secondary roads are lower than that on the expressway, which are 76% and 61%, respectively. In addition, the proportion of motorcycles on the residential road and secondary road is significantly higher than the other two types of roads.

**Distribution of motor vehicle technology**

1. **Light gasoline vehicle and light CNG vehicle**
   Light gasoline vehicles are mainly medium-sized vehicles (78%), followed by light vehicles (21%) and heavy vehicles (1%). These vehicles are mainly national IV and V, of which the proportion of national IV and V is as high as 88%, and the proportion of national III models is only 12%. The proportion of accumulated mileage less than $79 \times 10^3$ km is the largest (84.4%) and that greater than $161 \times 10^3$ km is the smallest, only 4.2%. The average daily starts of light gasoline vehicles are about 3.4, among which the daily starts of the railway station are the most about 4.8.

   Control standards of exhaust emission of vehicles are mainly national IV and V, both of which are 50%. The registration time of these vehicles is mostly after 2011. The annual mileage is about $95 \times 10^3$ km~$120 \times 10^3$ km. The flameout time of light CNG vehicles is mainly 15–30 min (57%), followed by 0–15 min (14%), 30 min–1 h (14%), and 12 h–18 h (14%).

   The average age of light CNG vehicle is about 4.1 years. About 78% of vehicles are under 5 years old. The accumulated mileage of light gasoline vehicles is mostly within $100 \times 10^3$ km, and it gradually increases with the increase of service life.

2. **Buses**
   The fuel of Changchun City’s buses is mainly clean energy (CNG, LNG), accounting for about 80%. New energy vehicles (includes steam hybrid vehicles, plug-in
hybrid vehicles, and pure electric vehicles) only account for about 3%. Traditional gasoline buses account for about 17%. Medium-sized buses account for the largest proportion (58%), followed by heavy-duty buses (38%), and light buses (4%). The daily average mileage of buses is more than 200 km, and the cumulative average mileage is above $200 \times 10^3$ km. For the emission control standard, the national IV vehicles have the largest proportion, accounting for 48%, followed by the national V (31%) and III (21%) vehicles.

Emission factors and influencing factors based on the IVE model

Light gasoline vehicle

1. Emission factor

Fig. 5 shows the emission factors of light gasoline vehicles on different roads and in different periods.

The emission factor of vehicle emissions on residential roads is significantly higher than that of the other roads. The emission factors show a certain regularity over time, which is related to the operating conditions of vehicles. For example, the traffic conditions in the morning (7:00) and evening peak periods (17:00) are poor, and its emission factors are relatively large, while the flat valley period is relatively small.

2. Velocity effect

Fig. 6 shows emission factors of pollutant NH$_3$ at different velocities.
The emission factors of CO, NO\textsubscript{x}, VOC, PM, and NH\textsubscript{3} decrease with the increase of velocity. The changes in emission factors of these five pollutants are similar, which is that the decreasing trend gradually slows down. Besides, it is found that there is a good mathematical relationship between the pollutant emission factors and velocity by function fitting. Most of the characterization parameters $R^2$ are above 0.9.

3. Emission standard effect

Fig. 7 shows emission factors of different pollutants with different emission standards.

Except for NH\textsubscript{3}, with the improvement of control standards, the overall pollutant emission factors show a downward trend. Among them, the emission factors of CO, VOC, and NO\textsubscript{x} are significantly reduced. Taking CO as an example, the emission factors in national standards II, III, and IV are 64%, 78%, and 92% lower than those in national standards I, respectively. In other words, the potential for vehicle emission reduction is getting smaller and smaller with the improvement of emission standards.

4. Accumulated mileage effect

Taking the light gasoline vehicle with national standard IV as an example, the impact of accumulated mileage on emission factors is shown in Fig. 8.

Except for NH\textsubscript{3}, the emission factors of other pollutants increase with the increase of accumulated mileage, that is, the deterioration coefficient of vehicles increases gradually. Taking CO as an example, the degradation rate of emission factors in $80 \times 10^3$ km and $160 \times 10^3$ km is 0.048 g/km and 0.081 g/km, respectively, which indicates that the degradation rate of vehicles increases gradually with the increase of driving mileage.

Light CNG car

1. Emission factor

Fig. 9 shows the emission factors of light CNG vehicles on different roads and in different periods. In general, the highest emission factors occur in residential roads, followed by secondary roads, main roads, and expressway. Taking CO as an example, the emission factor on the expressway is 7.243 g/km, which is 2.0, 2.4, and 3.0 times of the main road, secondary road, and residential road, indicating that the road type is an important factor affecting emission factors of light CNG vehicles.

The five emission factors have similar trends in time distribution. The peak value mainly occurs at 9:00,
15:00, and 19:00, which is related to the high traffic density, low velocity, and aggressive driving. The average emission factors of CO, VOC, NOx, PM, and NH3 are 12.152 g/km, 0.029 g/km, 1.297 g/km, 0.004 g/km, and 0.067 g/km, respectively. By comparing the emission factors between daytime (9:00–19:00) and nighttime (20:00–8:00), it is found that emission factors of CO, VOC, NOx, PM, and NH3 at daytime are 12.776, 0.031, 1.373, 0.004, and 0.070 g/km, respectively, which are 10.8%, 10.6%, 12.6%, 9.8%, and 9.8% higher than that of nighttime. The traffic flow at nighttime is small and the velocity is large, which is opposite to the traffic condition at daytime. The latter results in incomplete combustion of the engine, and a large number of pollutants are emitted.

2. Velocity and emission standard effect

The emission factors of light CNG vehicles decrease with the increase of velocity, which is similar to the emission rules of light gasoline vehicles, so it will not be discussed here. Besides, since the light CNG vehicles in Changchun are mostly oil to gas vehicles, the tail gas treatment technology of gasoline vehicles is not suitable for CNG fuel vehicles. Therefore, this paper does not discuss the effect of emission standards.

3. Accumulated mileage effect

Fig. 10 shows emission factors of different pollutants with different accumulated mileages. Except NH3, the emission factors of other pollutants gradually increase with the increase in accumulated mileage. Like light gasoline vehicles, the deterioration rate of light CNG vehicles increases with the increase of accumulated mileage. Taking CO and NOx as examples, the degradation rate of $80 \times 10^3$ km and $160 \times 10^3$ km is 0.655, 0.970, 0.023, and 0.035 g/km, respectively. It shows that the degradation rate of light CNG vehicle increases with the increase in mileage.

![Fig. 9 Emission factors of light CNG car on different roads and in different periods. (a) Emission factors of light CNG car on different roads. (b) Emission factors of light CNG car in different periods](image-url)
Bus

1. Emission factor
   The pollutant emission factors of buses at different velocities are shown in Fig. 11. The emission factors are generally decreasing with the increase of velocity. The average emission factors of CO, NOx, VOC, PM, and NH3 are 4.835, 0.200, 0.032, 0.005, and 0.036 g/km, respectively.

2. Fuel type
   About 80% of buses in Changchun use clean energy. But about 20% of the buses are gasoline vehicles, which results in a large contribution rate of pollutant emission in public transportation. The emission factors of CO, NOx, VOC, PM, and NH3 of gasoline buses are 31.002, 1.557, 2.461, 0.023, and 0.029 g/km, respectively, which are 6.4, 7.8, 75.9, 4.3, and 0.8 times of those of CNG fuel vehicles. It can be seen that CNG fuel can significantly reduce pollutant emissions, especially VOC emissions.

3. Emission standard effect
   Fig. 12 shows emission factors with different emission standards. With the improvement of emission standards, the emission factors of pollutants gradually decrease. When the emission standard is raised from national II to V, the emission factors of CO, VOC, NOx, and PM are reduced by 69%, 68%, 66%, and 66%, respectively. It can be seen that with the improvement of emission standards, the effect of pollutant emission reduction is more obvious.

4. Accumulated mileage effect
   Emission factors of buses under different accumulated driving mileage are shown in Table 1. Except for NH3, the emission factors of other four pollutants increased with the increase in accumulated mileage, that is, the deterioration coefficient of vehicles increased gradually. Taking gasoline bus with the national standard V as an example, the degradation rate of CO with $80 \times 10^3$ km and $160 \times 10^3$ km is 0.483 and 0.746 g/km, respectively, and the latter is 1.54 times of the former.

Emission factors based on the guideline method

Figure 13 shows the pollutant emission factors of light gasoline vehicles with national standard V, gasoline bus with national standard V, and CNG-fueled passenger vehicle.

For light gasoline vehicles, the emission factors of different pollutants are similar to the change of velocity, as shown in Fig. 13(a). When the velocity is less than 80 km/h, the pollutant emission factor decreases with the increase...
in velocity. The emission factors of gasoline buses with national V standards are similar to those of light gasoline vehicles, as shown in Fig. 13(b). The average emission factors of CO, VOC, NO\textsubscript{x}, and PM\textsubscript{10} are 4.640, 0.527, 0.814, and 0.037 g/km, respectively. The emission factor of buses is much higher than that of light vehicles, as shown in Fig. 13(c). The emission factors of CO, VOC, NO\textsubscript{x}, and PM of CNG fuel buses are 4.570, 1.192, 3.728, and 0.049 g/km, which are 0.6, 1.2, 3.5, and 0.7 times of those of gasoline bus, respectively.

### Comparative analysis

#### Comparison of on-road measurement and guideline method

A comparison of emission factors between on-road measurement and guideline method is shown in Table 2. For the gasoline vehicle with national standard V, the measured results of CO and VOC emission factors are similar to the guidelines, with only 3 and 11\% difference. However, NO\textsubscript{x}-measured are about three times those of the guideline method, indicating that the NO\textsubscript{x} emission factor of Changchun City for gasoline vehicles with national V standard based on the guideline is somewhat underestimated.

For the gasoline vehicle with national standard VI, the actual emissions of CO and NO\textsubscript{x} are significantly higher than the guideline, which are about 4 and 12 times that of the guideline, respectively, while the VOCs are closer.

For the CNG vehicle with national standard VI, the measured emission factors of CO, VOC, and NO\textsubscript{x} are about 2, 5, and 40 times that of the guideline, respectively. On the one hand, light CNG vehicles are mostly modified vehicles, resulting in insufficient combustion. On the other hand, long-term driving, high-load driving, irregular maintenance, and insufficient combustion lead to the pollutant emission exceeding the standard.

#### Comparison of on-road measurement and IVE model

The comparative results on emission factor between the on-road measurement and the IVE model are presented in Table 3. The emission factors of different emission standards and fuel types are different. Even at the same pollutant, the emission factor is different at different velocities. The simulation results of emission factors of light gasoline vehicles with national standard IV and V are close to the actual measured results, while the simulation results of emission factors of light CNG vehicles with national standard V are far from the actual measured results, which are related to the lag of technical parameters of vehicles in the IVE model.

### Conclusions

By analyzing the operating conditions, fleet composition, and technology distribution of three typical vehicles, this study obtained the emission factors of typical motor vehicles based on the IVE model and guideline method, and
then analyzed their influencing factors. At last, comparative analysis between the on-road measurement and the guideline method and the IVE model was conducted. The following conclusions were drawn.

1. Regarding the operating conditions of motor vehicles, taking light gasoline vehicles as an example, its average velocity occurs on expressways at most (48.5 km/h). The proportion of motor vehicles with uniform vehicle on the

**Fig. 13** Emission factors of light gasoline vehicles with national standard V, gasoline bus with national standard V, and CNG fuel passenger vehicle. (a) Light gasoline vehicles with national standard V. (b) Gasoline bus with national standard V. (c) CNG-fueled passenger vehicle

**Table 2** Comparison of measurement and guideline method

| Methods          | Gasoline vehicles with national V standard/(g/km) | Gasoline vehicles with national VI standard/(g/km) | CNG vehicles with national VI standard/ (g/km) |
|------------------|--------------------------------------------------|--------------------------------------------------|-----------------------------------------------|
|                   | CO   | VOC  | NOx  | CO   | VOC  | NOx  | CO   | VOC  | NOx  |
| Guideline method  | 0.416| 0.048| 0.019| 0.615| 0.064| 0.039| 0.500| 0.091| 0.027|
| On-road test      | 0.334| 0.036| 0.060| 2.600| 0.060| 0.465| 1.007| 0.461| 0.937|
secondary roads is the highest (57%). The highest traffic density occurs at 9:00 and 17:00 on weekdays.

2. With the increase of velocity and emission standards, most emission factors of vehicles decrease. With the increase of accumulated mileage, most emission factors of vehicles increase.

3. Compared with the actual emission factors, the emission factors of light gasoline vehicles with national V standard are overestimated, while those of other types of vehicles are underestimated. Compared with the actual emission factors, the emission factors of light duty-gasoline vehicles obtained by IVE model are close to the actual ones, while the emission factors of light CNG vehicles with national standard V have great errors with the actual measurement.

4. Improving the road environment, strengthening vehicle pollutant emission control, eliminating low-standard emission vehicles, and promoting the use of new energy vehicles are of great significance to reducing vehicle pollutant emissions.

Author contribution Chengkang Gao and Hongming Na conceived and designed the study. Chengkang Gao critically revised the manuscript and approved the final version. Kaihui Song critically edited and revised the manuscript. Qingjiang Xu executed the experiment and compiled the data collection.

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Data availability Data and material are available for research purpose and for reference.

Table 3 Comparison results between the on-road test and the IVE model

| Velocity/(km/h) | Correction factor of the IVE model |
|----------------|-----------------------------------|
|                | Light gasoline vehicles with national standard IV | Light gasoline vehicles with national standard V | Light CNG vehicles with national standard V |
|                | CO₂   | CO     | NOₓ    | VOC | CO₂  | CO   | NOₓ    | VOC | CO₂  | CO   | NOₓ    | VOC |
| 10             | 1.33  | 2.18   | 4.02   | 1.71 | 1.27 | 0.51 | 0.42   | 4.49 | 0.56 | 0.02 | 0.34   | 11.93 |
| 20             | 1.27  | 2.33   | 3.54   | 1.67 | 1.19 | 0.52 | 0.76   | 3.82 | 0.60 | 0.02 | 0.42   | 13.58 |
| 30             | 1.08  | 3.51   | 2.89   | 1.76 | 1.20 | 0.30 | 0.60   | 4.21 | -    | -    | -      | -    |
| 40             | 1.21  | 3.33   | 2.65   | 1.85 | 1.20 | 0.85 | 0.78   | 3.84 | 0.68 | 0.07 | 0.56   | 9.63  |
| 50             | 1.18  | 2.84   | 3.01   | 1.63 | 1.17 | 0.72 | 0.81   | 3.45 | -    | -    | -      | -    |
| 60             | 1.21  | 3.14   | 2.42   | 1.36 | 1.16 | 0.61 | 0.68   | 3.61 | 0.69 | 0.18 | 0.45   | 10.69 |
| 70             | 1.14  | 3.09   | 2.70   | 1.81 | 1.18 | 1.30 | 0.86   | 4.05 | -    | -    | -      | -    |
| 80             | 1.15  | 3.04   | 2.14   | 2.16 | -    | -    | -      | -    | -    | -    | -      | -    |
| Average        | 1.25  | 2.95   | 2.89   | 1.86 | 1.20 | 0.85 | 0.78   | 3.84 | 0.68 | 0.07 | 0.56   | 9.63  |

Declarations

Ethical approval Ethical approval was taken from the SEP Key Laboratory of Eco-Industry, Northeastern University to conduct the study, and no animal was harmed in this study. This manuscript has not been published or presented elsewhere in part or in entirety.

Consent to participate Not applicable

Consent for publication All the authors agreed to publish this article in Environmental Science and Pollution Research.

Competing interests The authors declare no competing interests.

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