

## Article

# Development of Vehicle Emission Model Based on Real-Road Test and Driving Conditions in Tianjin, China

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**Abstract:** Based on the demand of vehicle emission research and control, this paper presents the development of a portable vehicle measurement system (PEMS) based on SEMTECH-DS and ELPI+, the vehicle emission tests carried out on actual roads, and the data obtained for the establishment and validation of a vehicle emission model. Based on the results of the vehicle emission test, it was found that vehicle driving conditions (speed, acceleration, vehicle specific power (VSP), etc.) had a significant impact on the pollutant emission rate. In addition, local driving cycles were generated and the frequency distribution of VSP-bin under different cycles was analyzed. Then, through the establishment of an emission rate database, calculation of emission factors and validation of the emission model, a vehicle emission model based on actual road driving conditions was developed by taking VSP as the “surrogate variables”. It showed that the emission factor model established in this study could better reflect the vehicle transient emissions on the actual road with high accuracy and local adaptability. Through this study, it could be found that due to the great differences in traffic development modes and vehicle driving conditions in different cities in China, the emission model based on driving conditions was a better choice to carry out the research on vehicle emission in Chinese cities. Compared with directly applying international models or quoting the recommended values of relevant macroscopic guidelines, the emission factor model established in this study, using actual driving conditions, could better reflect the vehicle transient emissions on the actual road with high accuracy and local adaptability. In addition, due to the rapid development of China’s urban traffic and the rapid change of driving conditions, it was of great significance to regularly update China’s urban conditions to improve the accuracy of the model, no matter which model was chosen.

**Keywords:** vehicle emission model; vehicle emission factor; on-board test; real road driving conditions; VSP; PEMS



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## 1. Introduction

In recent years, with the rapid development of social economy and urbanization, as well as the continuous improvement of people’s living standard and travel demand, the number of vehicles in China has shown an explosive growth [1,2]. The huge number of vehicles and their high activity level have led to the increasing contribution rate of vehicle pollutant emissions to haze pollution represented by a high fine particle (PM<sub>2.5</sub>) concentration, and photochemical pollution represented by high ozone (O<sub>3</sub>) concentration, especially in urban areas [3,4]. In addition, because most of the vehicles are driven in densely populated areas, the impact of the emissions of CO, HC, NO<sub>x</sub> (a general term for

all types of nitrogen oxides such as NO and NO<sub>2</sub>), PM and other pollutants on people's health is more direct and serious [5].

Facing the increasingly severe situation of vehicular pollution, China has taken a series of measures and achieved great success, including conformity inspection of new vehicle production, environmental protection inspection of in-use vehicles, elimination of old vehicles, accelerated implementation of higher emission standards, promotion of clean-energy vehicles, etc. [6]. However, vehicle emission control is a relatively complex decision-making process, which needs a series of technical methods as support. Among these supporting means, vehicle source emission characterization is one of the most core basic contents [7].

At present, for the estimation of vehicle exhaust emissions, Chinese researchers mainly draw lessons from and refer to mature models developed by the US and Europe, such as the MOBILE model [8] and the MOVES model [9], developed by the US Environmental Protection Agency, and the COPERT model [10], developed by the Joint Research Centre of the European Commission. Most of these models are developed on the basis of vehicle emission in the US and Europe [11]. However, there are great differences between China's domestic vehicle types, real road driving characteristics, fuel quality, etc. and those of foreign countries [12]. Therefore, when the above models are applied in China, a large amount of localization-correction work needs to be carried out, and their applicability needs to be evaluated [13].

In order to guide the domestic vehicle pollutant accounting and emission inventory preparation, China's Ministry of Ecological Environment issued the Technical Guide for the Compilation of Air Pollutant Emission Inventory of Road Vehicles (Trial) in 2015, which filled in the gap of China's vehicle emission accounting basis from the official perspective [14]. However, because the data in the Guide was based on the national statistical average, it was more suitable for supporting the preparation of road vehicle emission inventory at the macro scales of cities, urban agglomerations and regions. However, it was very limited at the meso- and micro- scale and for refined vehicle emission simulation, and it was also difficult for the Guide to reflect the impact of actual road driving conditions on vehicle emissions.

In the latest research on the vehicle emission model, the driving conditions closely related to vehicle emission level are basically taken into account [15]. Compared with the macro emission model, the emission model based on driving conditions is able to analyze the impact of the real road driving state (such as uniform speed, acceleration, deceleration, idle speed, etc.) of vehicles on their emissions more comprehensively [16]. The driving-conditions-based mode emission model can more comprehensively consider the impact of vehicle driving characteristics on emissions, and its "substitute parameters" are more representative [17]. The modeling idea of the emission model based on driving conditions is to take the mathematical law embodied between the measured emission data and the "substitute parameters" as the core, and then use a mathematical means such as statistical regression to fit the mathematical function closest to the law [18]. In order to more accurately express the relationship, the emission model based on driving conditions will also rely on the physical relationship between vehicle emission and "substitute parameters" when establishing the mathematical function [19]. Furthermore, in recent years, with the continuous maturity of real road vehicle test methods and the rapid development of portable exhaust measurement technology, especially the improvement of measurement accuracy, so that it becomes more and more feasible to monitor the micro and transient emission characteristics of vehicles under real road driving conditions and to develop local emission models accordingly [19].

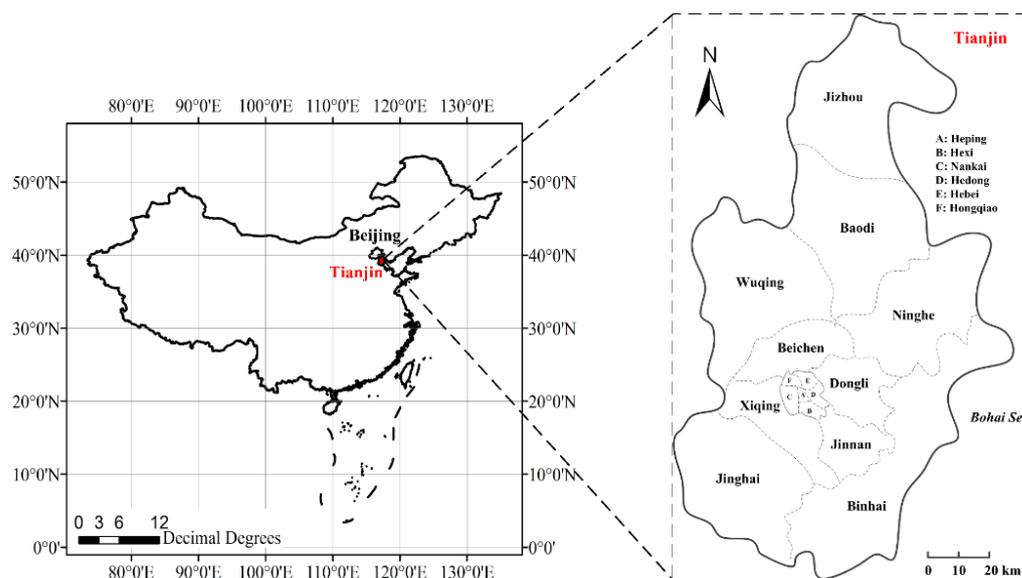
This study focuses on Tianjin, China, which has great pressure on vehicle emission reduction, as the research object [6]. Based on the demand of vehicle emission research and control, this paper selected the typical vehicles to carry out on-board emission tests on the local representative roads, developed the vehicle emission model based on the real-road driving conditions by taking vehicle specific power (VSP) as the "surrogate variables", and

completed the calculation and validation of emission factors. The research results were of great significance for the establishment of regional high spatial-temporal resolution and the refinement management of vehicle emission.

## 2. Materials and Methods

### 2.1. Study Area

Tianjin is one of China's four province-level municipalities, and it is also the National Center City and the economic center of Bohai Rim region. The location of Tianjin on the map of China is shown as Figure 1.



**Figure 1.** Location of Tianjin on the map of China.

By the end of 2020, Tianjin had built a road network structure including express road, artery road, secondary road and local road, with a total mileage of  $1.68 \times 10^4$  km, and the length proportion of each types of roads was 12.13%, 17.43%, 26.94% and 43.50%, respectively [20].

By the end of 2020, the number of motor vehicles in Tianjin had reached  $2.99 \times 10^6$  [20]. According to the classification of use and size, the proportion of light-duty vehicle (LDV) was the highest, up to 85.22%; according to the classification of fuel types and emission standards, most of the vehicles were gasoline vehicles, up to 90.47%; among the gasoline vehicles, the proportion of CHN IV (CHN refers to China's vehicle emission standards in this paper. For a long time, China has been learning from European emission standards equivalently. CHN IV and V are equivalent to Euro IV and V) vehicles was the highest, accounting for 46.90%, followed by the CHN V vehicles (19.16%) [20]. Therefore, the light-duty gasoline vehicles with the emission standards of CHN IV and CHN V were the mainstream vehicle types in Tianjin. Moreover, with the continuous improvement of new vehicle emission standards and the acceleration of the elimination of old vehicles in Tianjin, the proportion of gasoline vehicles with CHN V and above would be further increased, while the proportion of gasoline vehicles with CHN III and below would be rapidly reduced.

### 2.2. Modeling Method of Vehicle Emission

#### 2.2.1. Surrogate Variables

- VSP

Because the driving state of vehicles in the real road network traffic flow was complex and variable, and there were many factors that affected it, in the modeling process, one or

more “surrogate variables” which were closely related to the emission level were usually selected to approximate the driving characteristics of the real road of vehicles [21]. At present, engine load was usually used as a surrogate variable in the mainstream emission models and the most representative engine load parameters was VSP, such as the IVE model [22–24] and MOVES model [25,26]. Considering the physical principle of vehicle emission, VSP could better describe the impact of vehicle transient driving characteristics on emission level, so it had higher accuracy [27]. Based on the development trend of vehicle emission model and the current demand of vehicle emission research, the VSP was also selected as a surrogate variable in this study.

VSP was defined as the engine power output per vehicle unit mass and first proposed by Jiménez Palacios from Massachusetts Institute of Technology [28]. The calculation of VSP took into account the changes of kinetic energy and potential energy in the actual vehicle driving process, as well as the work done by the engine to overcome the rolling friction and air resistance, which was closely related to the speed, acceleration, gradient, wind resistance, etc., with the unit of kW/t or  $\text{m}^2/\text{s}^3$ .

The calculation formula of VSP is as follows:

$$\begin{aligned} \text{VSP} &= \frac{\frac{d(\text{KE}+\text{PE})}{dt} + F_r v + F_A v}{m} = \frac{\frac{d[0.5 \times m(1+\varepsilon_i)v^2 + mgh]}{dt} + C_R mgv + 0.5 \times \rho_a C_D A (v+v_m)^2 v}{m} \\ &= v[a(1 + \varepsilon_i) + g \times \theta + g \times C_R] + \frac{0.5 \times \rho_a C_D A (v+v_m)^2 v}{m} \end{aligned} \quad (1)$$

where the following are defined: KE: kinetic energy of vehicle, N·m; PE: potential energy of vehicle, N·m;  $F_r$ : rolling friction resistance of vehicle during driving process, N;  $F_A$ : air resistance of vehicle during driving process, N;  $v$ : vehicle speed, m/s;  $m$ : vehicle mass, kg;  $\varepsilon_i$ : vehicle quality factor, dimensionless;  $g$ : acceleration of gravity,  $9.81 \text{ m/s}^2$ ;  $h$ : the altitude at which the vehicle is traveling, m;  $C_R$ : the rolling damping coefficient of vehicular tire and road surface during driving process, which is related to vehicular tire type and road surface material, dimensionless, 0.0085–0.016;  $\rho_a$ : ambient air density,  $1.207 \text{ kg/m}^3$  at  $20^\circ\text{C}$ ;  $C_D$ : the coefficient of wind resistance during driving process, dimensionless;  $A$ : windward area of vehicles,  $\text{m}^2$ ;  $v_m$ : wind speed, m/s;  $a$ : vehicle transient acceleration,  $\text{m/s}^2$ ;  $\theta$ : road slope.

After further arrangement, the calculation formula of VSP can be simplified as:

$$\text{VSP} = v\{1.1a + 9.81[\text{atan}(\sin\theta)] + 0.132\} + 0.000302v^3 \quad (2)$$

- VSP interval (VSP-bin)

Referring to the IVE model and the MOVES model, the vehicle transient conditions were divided into 38 VSP intervals (VSP-bins) according to the vehicle operation state (deceleration, idling, acceleration and uniform speed) and the calculated values of VSP, shown as Table 1. Each VSP-bin corresponded to an emission level, according to which the subsection corresponding relationship between vehicle transient condition and emission could be established.

### 2.2.2. Generation of Driving Cycle

The vehicle driving condition directly affected the emission. Therefore, before the calculation of vehicle emission factors, the actual vehicle driving characteristics in study area should be analyzed comprehensively to generate local driving cycle.

At present, the widely used means to generate vehicle driving cycle was to establish a 900–1200 s speed-time ( $v$ - $t$ ) curve as a typical urban driving cycle by using the characteristic parameters method [15]. This method was to use the statistical method to analyze and extract 11 commonly used vehicle driving characteristic parameters from the overall sample of actual measurement data (Table 2), which were used to describe the driving condition characteristics of the overall sample completely [22].

**Table 1.** The division standard of 38 VSP-bins according to the vehicle operation state and the calculated values of VSP.

Deceleration Idling VSP (kW/t)	bin0 ( $a < -1 \text{ m/s}^2$ ) bin1 ( $0 \leq v < 1.6 \text{ km/h}$ )		
	Low Speed ( $1.6 \text{ km/h} \leq v < 40 \text{ km/h}$ )	Middle Speed ( $40 \text{ km/h} \leq v < 80 \text{ km/h}$ )	High Speed ( $v \geq 80 \text{ km/h}$ )
$\leq -8]$	bin2	bin14	bin26
$(-8, -6]$	bin3	bin15	bin27
$(-6, -4]$	bin4	bin16	bin28
$(-4, -2]$	bin5	bin17	bin29
$(-2, 0]$	bin6	bin18	bin30
$(0, 2]$	bin7	bin19	bin31
$(2, 4]$	bin8	bin20	bin32
$(4, 6]$	bin9	bin21	bin33
$(6, 8]$	bin10	bin22	bin34
$(8, 10]$	bin11	bin23	bin35
$(10, 12]$	bin12	bin24	bin36
$> 12$	bin13	bin25	bin37

Annotation:  $a$  is acceleration,  $v$  is speed.

**Table 2.** The vehicular driving characteristic parameters.

No.	Vehicle Driving Characteristic Parameters	Abbreviation
1	Average speed (including idle process), km/h	$V_1$
2	Average speed (excluding idle process), km/h	$V_2$
3	The average acceleration of all accelerated states, $\text{m/s}^2$	$A$
4	The average deceleration of all decelerated states, $\text{m/s}^2$	$D$
5	Percentage of idle state time, %	$P_i$
6	Percentage of accelerated state time, %	$P_a$
7	Percentage of uniform state time, %	$P_c$
8	Percentage of decelerated state time, %	$P_d$
9	Positive acceleration kinetic energy, $\text{m/s}^2$	PKE
10	Relative positive acceleration, $\text{m/s}^2$	RPA
11	The number of times of speed oscillations per 100 m	FDA

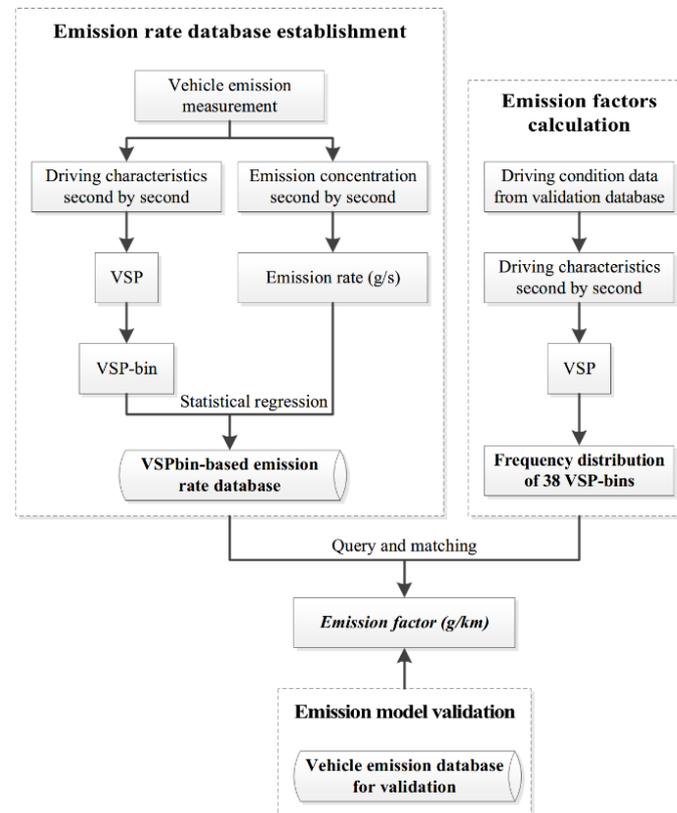
Annotation: Accelerated state: acceleration  $> 0.1 \text{ m/s}^2$ ; Uniform state:  $-0.1 \text{ m/s}^2 \leq$  acceleration or deceleration  $\leq 0.1 \text{ m/s}^2$ ; Decelerated state: deceleration  $< 0.1 \text{ m/s}^2$ .

The generation of local driving cycle mainly included the following three steps:

- Selection of alternative driving cycle  
A continuous data range of 900–1200 s is randomly selected from all the data of vehicle on-board test as the alternative cycle.
- Calculation of judgment criteria  
Taking 11 vehicular characteristic parameters as the judging criterion number, the characteristic parameters of the alternative driving cycle and the overall driving cycle were calculated, and the coincidence degree between them was judged by MATLAB software developed by MathWorks Company, Massachusetts, USA.
- Evaluation of coincidence degree  
If the coincidence degree between the alternative driving cycle and the overall driving cycle was not good enough, the interval of alternative driving cycle should be re-selected and the driving characteristic parameters should be re-calculated until their coincidence degree meet the expectation, then the re-selected alternative driving cycle could be considered as a typical driving cycle.

### 2.2.3. Modeling Steps

The development of emission factor model based on driving condition included three parts: the establishment of emission rate database, the calculation of emission factors and the validation of emission model. The technical route of the development of emission factor model based on driving condition is shown as Figure 2.



**Figure 2.** The technical route of the development of emission factor model based on driving condition.

- Establishment of emission rate database

- (a) Vehicle emission measurement on real road

Typical vehicles were selected to carry out on-board test of vehicle emissions on typical roads in Tianjin, and the transient driving characteristic parameters and pollutant concentration data of vehicles were collected second by second.

- (b) VSP-bin number determination

The second-by-second VSP values of the tested vehicle were calculated according to the transient driving characteristic data, and then the VSP-bin numbers corresponding to the second-by-second driving conditions of the vehicles were determined according to the VSP-bin division standard shown in Table 1.

- (c) Statistical regression of emission rate based on VSP-bin number

By using the method of statistical regression, the emission results of the same type of vehicle under the driving condition with the same VSP-bin number were analyzed to obtain the correlation between the VSP-bin numbers and the emission rates, and the VSP-bin-based vehicle emission rate (g/s) database was constructed. In this study, the database was divided into two parts: modeling database (used to build emission model) and validation database (used to verify emission model). The modeling database was composed of 80% measurement times randomly selected from the test routes, and the remaining 20% was put into the validation database. Both databases needed to be tested by K-S hypothesis to ensure that they had similar distribution of vehicle operating parameters.

- Calculation of emission factor:

- (a) The VSP-bin frequency distribution statistics

Firstly, the input transient condition data was analyzed and the second-by-second VSP was calculated. According to the VSP-bin division standard shown in Table 1, the VSP-bin number corresponding to the second-by-second driving condition of vehicle was determined, and then the VSP-bin frequency distribution of this condition data was computed.

- (b) Calculation of emission factor

In the vehicle emission rate database, the emission rate corresponding to each VSP-bin number of the input driving condition was founded. Additionally, then the emission factor (g/km) of this driving condition was calculated by combining the previous result of VSP-bin frequency distribution.

The calculation formula of emission factor is as follows:

$$EF_p = \frac{\sum_{n=0}^{38} (E_{n,p} \times f_n)}{v/3600} \quad (3)$$

where the following are defined:  $p$ : pollutants, including CO, HC, NO<sub>x</sub>, and PM;  $EF_p$ : emission factor of pollutant  $p$ , g/km;  $n$ : VSP-bin number, dimensionless;  $E_{n,p}$ : emission rate of vehicular pollutant  $p$  under the driving condition with VSP-bin No.  $n$ , g/s;  $f_n$ : distribution frequency of VSP-bin No.  $n$  in the input condition, dimensionless;  $v$ : average speed of the input condition, km/h.

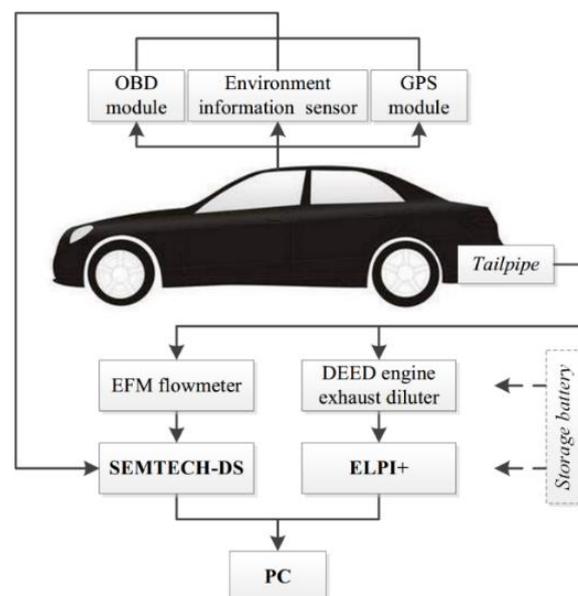
- Validation of emission factor

A section of driving condition data was randomly selected from the validation database to calculate the emission factors. Then, the calculated results were compared with the measured emission data corresponding to the driving condition of this section, so as to verify the simulation results of the model.

### 2.3. Real Road Measurement of Vehicle Emission

#### 2.3.1. PEMS Establishment

A portable vehicle measurement system (PEMS) was built based on SEMTECH-DS vehicle exhaust analysis system made by SENSORS Inc, Saline MI, US, ELPI+ electrostatic low pressure impactor made by DEKATI Ltd, Kangasala, Finland and notebook computer. The composition of PEMS and its real installation example were shown as Figure 3.



**Figure 3.** The composition of PEMS and its real installation example.

### 2.3.2. Experimental Design

- Tested vehicle

Based on the development status and future trend of various types of vehicles, 48 typical vehicles were selected for on-board test, which could represent the vehicle types with high ownership and activity level in Tianjin. Table 3 shows the types of vehicles selected for on-board test. Figure 4 shows part of tested vehicles equipped with PEMS.

**Table 3.** The types of vehicles selected for on-board test.

Emission Standards	CHN IV	CHN V	SUM
Light-duty vehicle (LDV)	10	10	20
Middle-duty vehicle (MDV)	2	2	4
Heavy-duty vehicle (HDV)	3	3	6
Light-duty truck (LDT)	3	3	6
Middle-duty truck (MDT)	4	4	8
Heavy-duty truck (HDT)	2	2	4
SUM	24	24	48



**Figure 4.** Part of tested vehicles equipped with PEMS.

- Test period

Each vehicle was tested for 2–4 days. Considering that the endurance time of on-board battery was about 3.5 h, the duration of single trip test task was controlled within 3 h in order to ensure the normal operation of instruments and equipment. Relevant research showed that the test of a single vehicle for three hours could contain more than 95% of the variation of exhaust gas [29]. In addition, in order to collect vehicle emission data under different traffic flow states as much as possible, the test time covered both peak hours (including early peak (7:00–9:00) and late peak (17:00–19:00)) and off-peak hours (other times).

- Test indicators

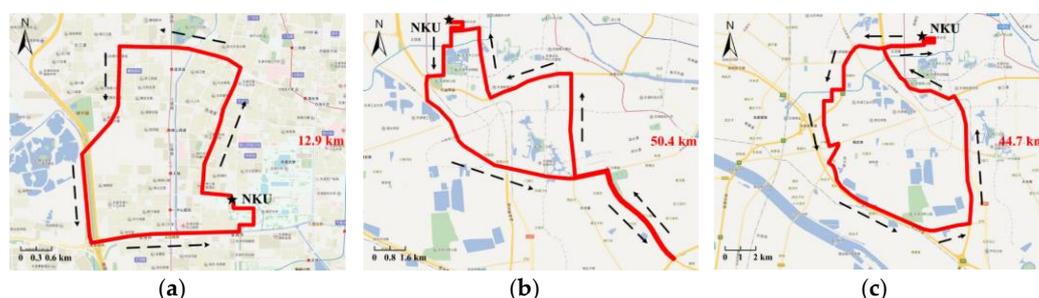
The main test indicators of on-board test included the longitude and latitude, altitude, speed, fuel consumption of vehicles in the real road driving process, as well as the concentrations of CO, HC, NO<sub>x</sub> and PM in the exhaust gas, second by second.

- Driver selection

The drivers with stable driving style were chosen to operate the tested vehicles, that is, to follow the traffic in the real road.

- Test routes

In order to make the on-board test results more comprehensively reflect the influence of different types of roads, slopes, traffic flow characteristics and other factors on the vehicular emission level, three corresponding test routes according to the actual activity characteristics of different types of vehicles were developed, including Route A for LDV, MDV and LDT, Route B for LDV, MDV and HDV, and Route C for HDV, MDT and HDT. The three test routes completely covered typical express roads, artery roads, secondary roads and local roads, as well as plane or three-dimensional intersections of various types of roads. Additionally, the proportion of express roads and artery roads with large traffic flow had also been appropriately increased in the determination of the routes. The test routes for different types of vehicles are shown as Figure 5.



**Figure 5.** The test routes for different types of vehicles; (a) Rout A for LDV, MDV and LDT; (b) Route B for LDV, MDV and HDV; (c) Route C for HDV, MDT and HDT.

### 3. Results and Discussion

#### 3.1. Analysis of Vehicle Emission Measurement Results

##### 3.1.1. Relationship between Driving Condition and Emission Rate

- Relationship between vehicular speed, acceleration and pollutant emission rate

The typical relationship between vehicle speed, acceleration and pollutant emission rate is shown as Figure 6. The vehicle speed and acceleration had an obvious influence on pollutant emission rate. When vehicle speed and acceleration were larger (speed > 30 km/h, acceleration > 0.5 m/s<sup>2</sup>), pollutant emission rate increased significantly. In this case, the vehicle engine was in the state of rich combustion in order to provide enough output power, and the fuel was not fully burned, which could lead to a sharp increase in the emission level.

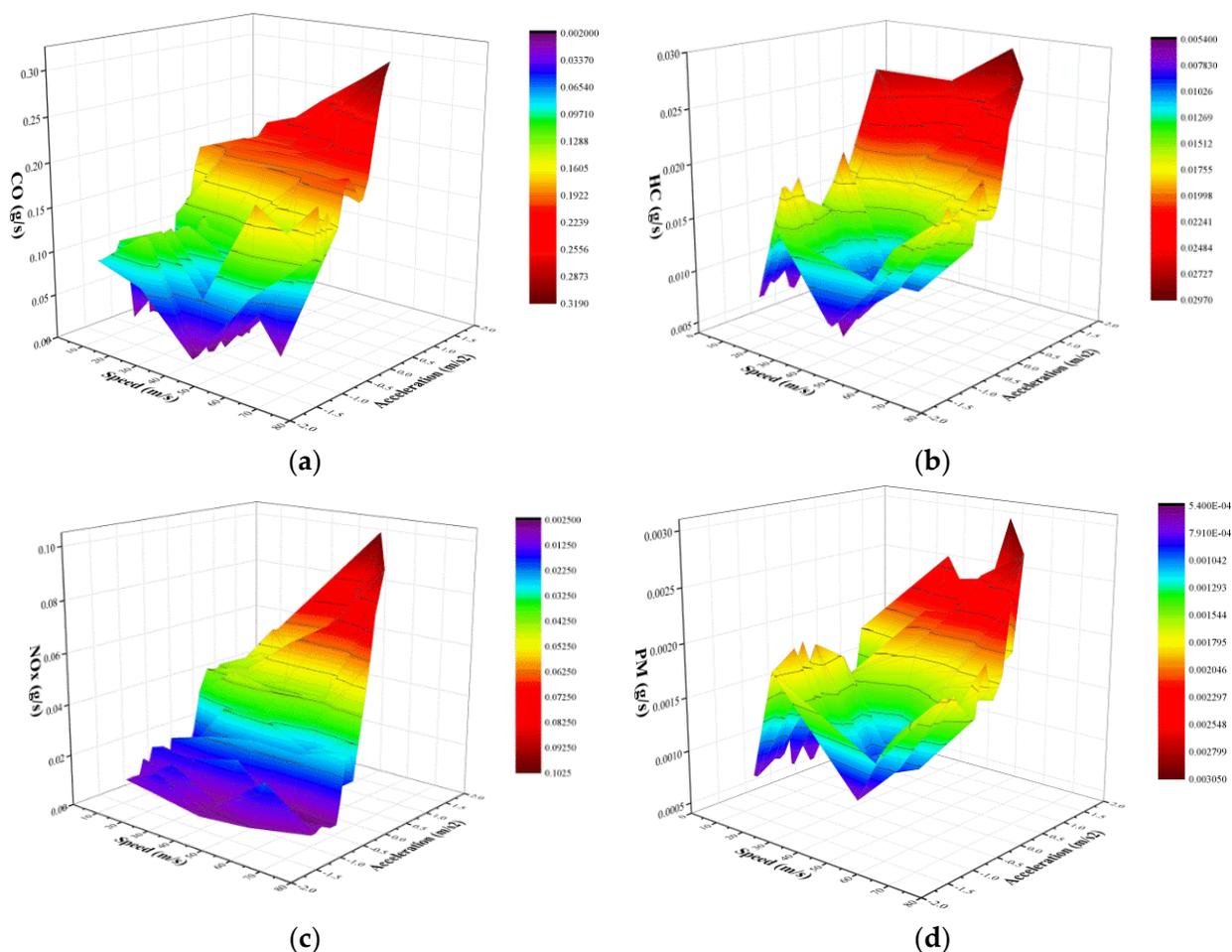
- Relationship between vehicular VSP and pollutant emission rate

The typical relationship between vehicle VSP and pollutant emission rate is shown as Figure 7. The emission rate of different types of vehicle pollutants increased with the increase in VSP, that is, when the vehicle accelerated rapidly or the instantaneous output power was high, the emission level of pollutants would also increase significantly.

##### 3.1.2. Generation of Localized Driving Cycle

- Distribution of speed acceleration driving condition points

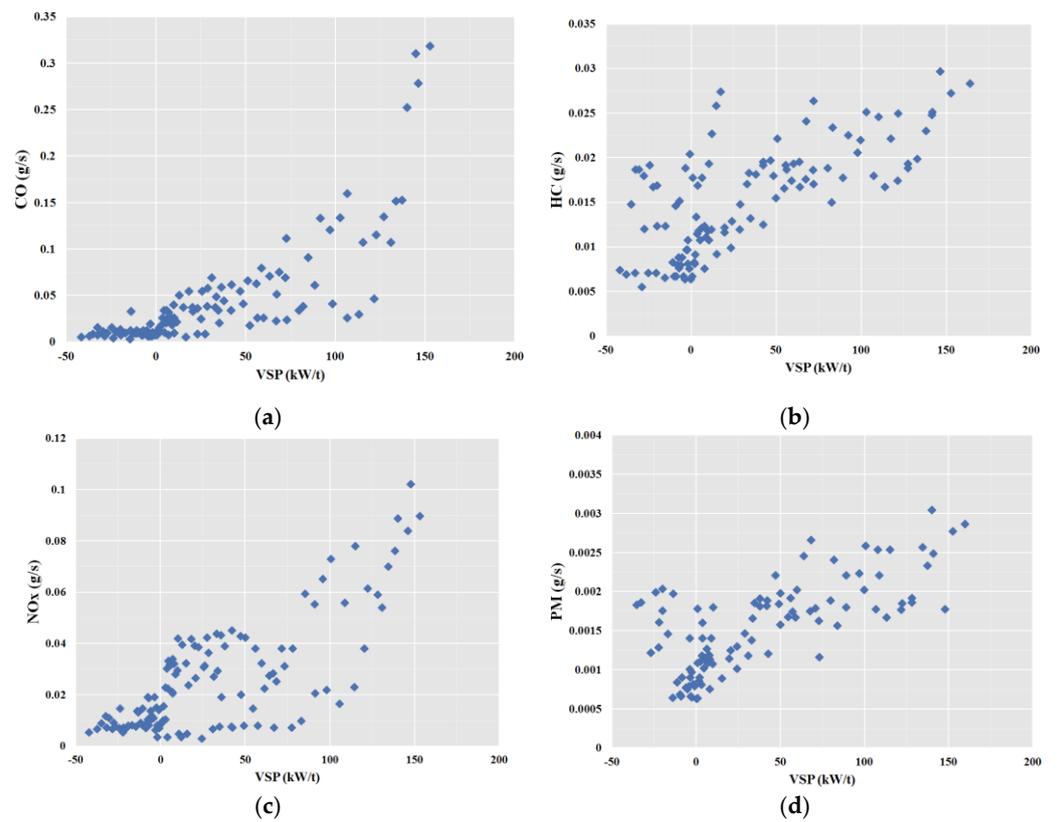
According to the vehicle on-board data of the real roads in different periods of time, the distribution of speed acceleration driving condition points in Tianjin was obtained, shown as Figure 8. For the test vehicles on the test routes, the speed of peak hours was mostly concentrated in 0–40 km/h, and the speed of the off-peak hour was mostly concentrated in 0–70 km/h, with a relatively uniform distribution; the acceleration was mostly concentrated in  $-1-1$  m/s<sup>2</sup>.



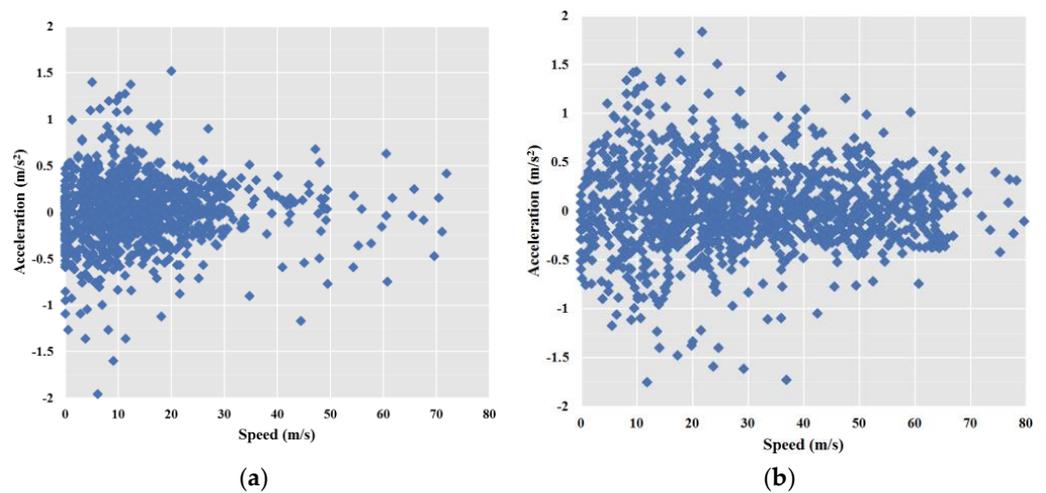
**Figure 6.** The typical relationship between vehicular speed, acceleration and pollutant emission rate; (a) Relationship between vehicular speed, acceleration and CO emission rate; (b) Relationship between vehicular speed, acceleration and HC emission rate; (c) Relationship between vehicular speed, acceleration and NOx emission rate; (d) Relationship between vehicular speed, acceleration and PM emission rate.

- Localized vehicle driving cycle in Tianjin

The localized vehicle driving cycle in Tianjin generated by using characteristic parameters method is shown as Figure 9. The comparison of vehicle driving characteristic parameters between Tianjin and Europe and the US is shown as Table 4. The New European Driving Cycle (European NEDC) and the Federal Test Procedure (American FTP75) were widely used in vehicle emission research in China. However, based on the real road test results, it was found that there were still certain differences between Tianjin's driving cycle and NEDC and FTP cycles. For instance, the average speed ( $V_1$ ) in Tianjin was 17.77% lower than that in NEDC, while the number of times of speed oscillations per 100 m (FDA) was 694.12% higher than NEDC, and both the percentage of accelerated state time ( $P_a$ ) and the percentage of decelerated state time ( $P_d$ ) in Tianjin were higher than those in Europe and the US. These differences also indicated that there would be a greater error in the simulation of China's local vehicle emissions by directly using European and American driving cycles. Therefore, it was more necessary to develop a vehicle emission model based on local driving conditions.



**Figure 7.** The typical relationship between vehicular VSP and pollutant emission rate. (a) The relationship between vehicular VSP and CO emission rate; (b) The relationship between vehicular VSP and HC emission rate; (c) The relationship between vehicular VSP and NOx emission rate; (d) The relationship between vehicular VSP and PM emission rate.



**Figure 8.** The typical distribution of speed acceleration driving condition points; (a) Peak hours (7:00–9:00, 17:00–19:00); (b) Off-peak hours (other time).

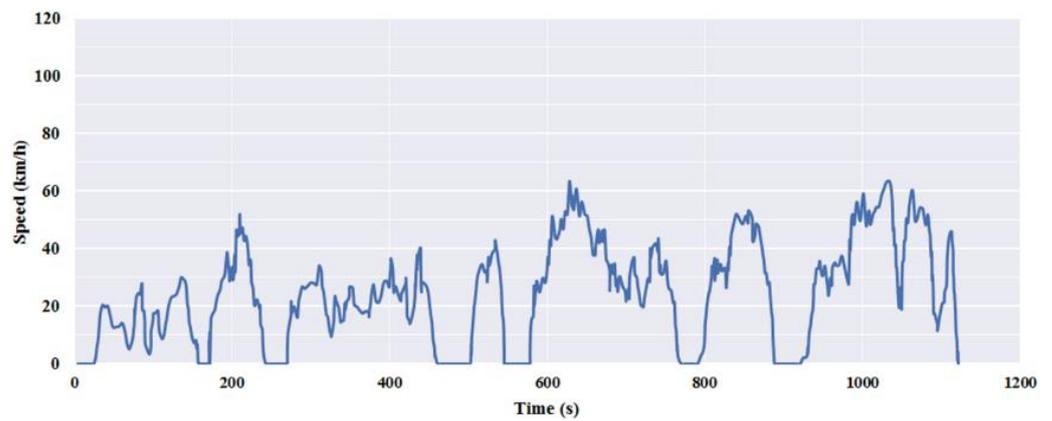


Figure 9. The localized vehicle driving cycle in Tianjin.

Table 4. The comparison of vehicle driving characteristic parameters between Tianjin and Europe and the US.

Driving Cycles	Driving Cycle in Tianjin	European NEDC	American FTP75
$V_1$ (km/h)	27.63	33.6	34.2
$V_2$ (km/h)	36.89	44.4	38.8
A ( $m/s^2$ )	0.51	0.48	0.56
D ( $m/s^2$ )	−0.51	−0.68	−0.67
$P_i$ (%)	12.98	25	19
$P_a$ (%)	36.85	27	36
$P_c$ (%)	21.27	29	16
$P_d$ (%)	33.18	19	30
PKE ( $m/s^2$ )	0.37	0.22	0.35
RPA ( $m/s^2$ )	0.18	0.12	0.18
FDA	1.35	0.17	0.59

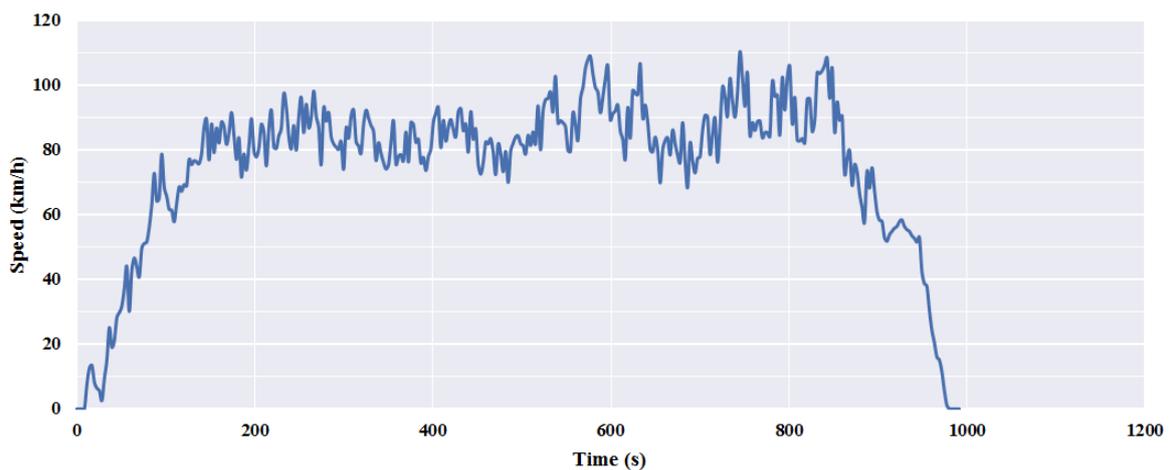
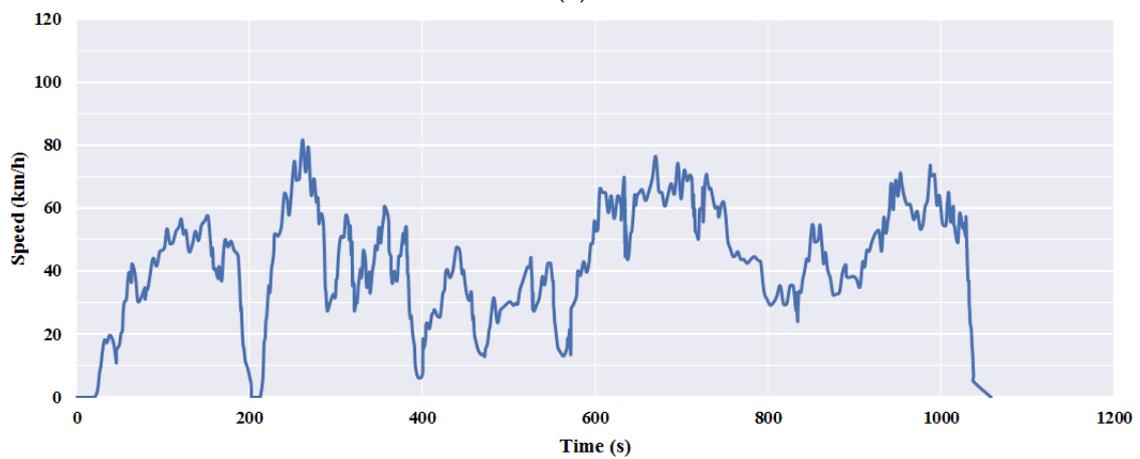
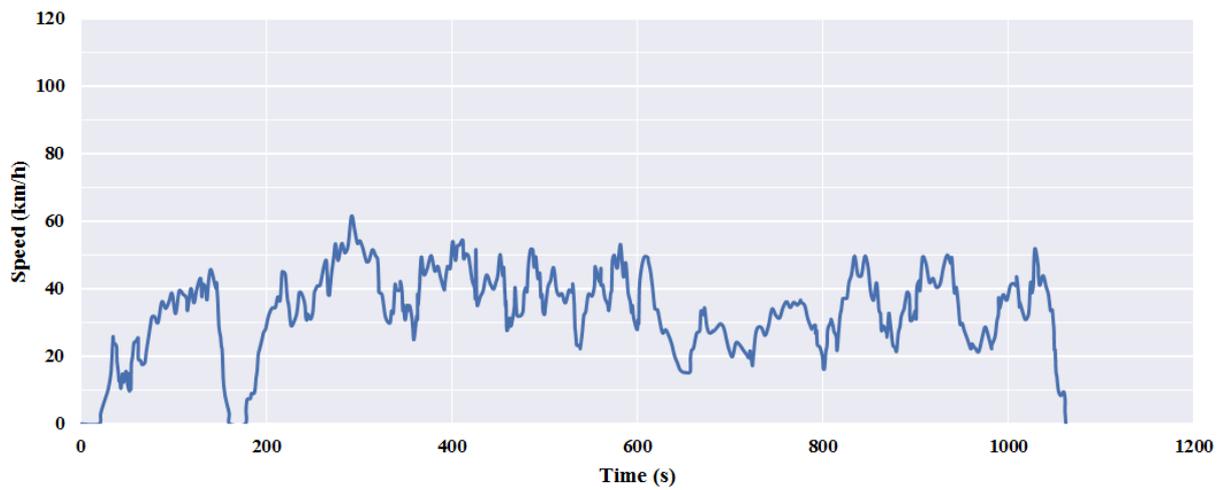
### 3.1.3. VSP-Bin Frequency Distribution of Driving Conditions

- Driving cycles of different speed intervals

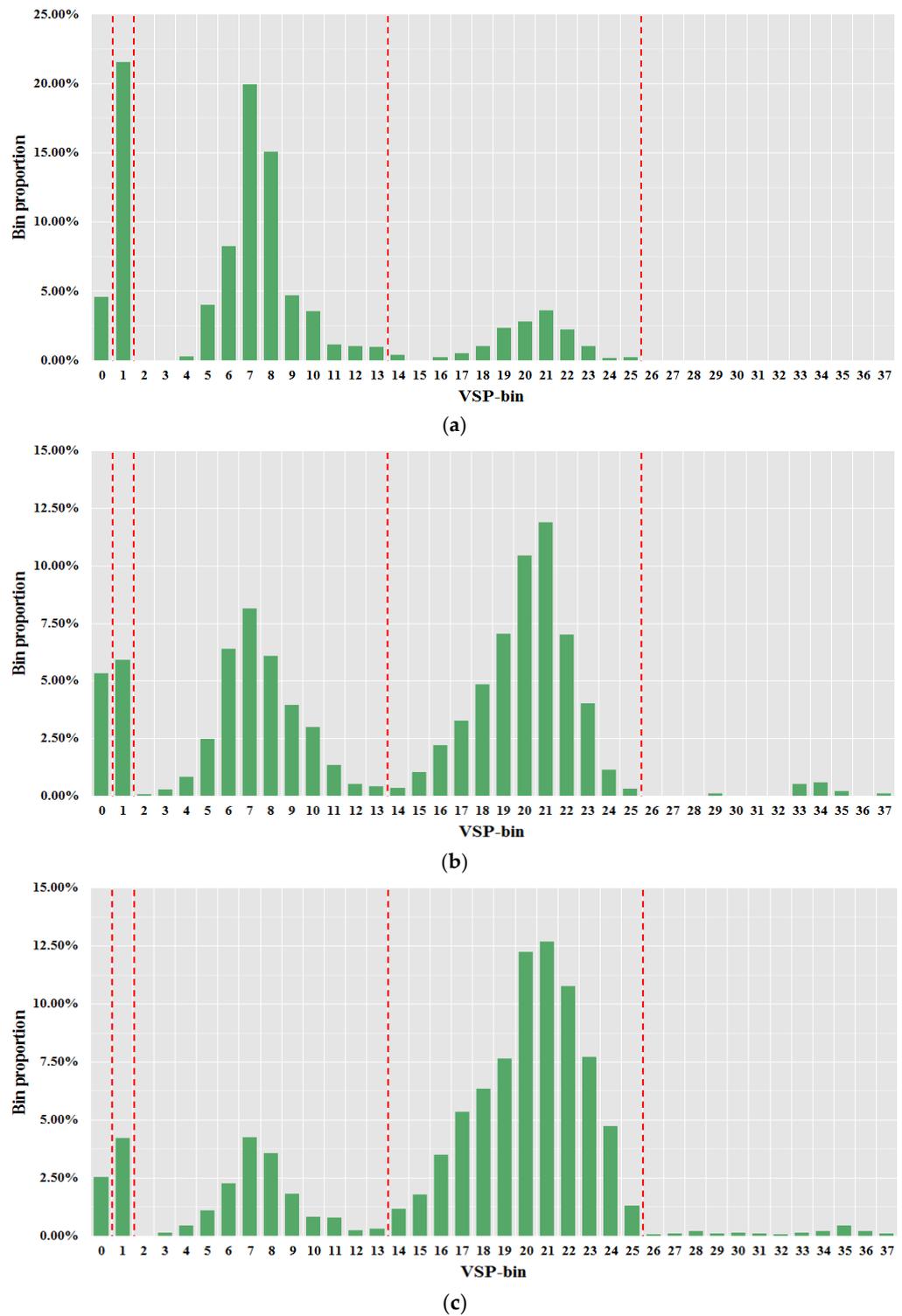
In order to analyze the VSP-bin distribution under different driving conditions, the vehicle driving conditions were further subdivided into low-speed driving conditions ( $1.6 \text{ km/h} \leq v < 40 \text{ km/h}$ ), middle-speed driving conditions ( $40 \text{ km/h} \leq v < 80 \text{ km/h}$ ) and high-speed driving conditions ( $v \geq 80 \text{ km/h}$ ) according to the definition of different speed intervals in the VSP-bin division standard of Table 1. Then, based on the characteristic parameters method and clustering the driving conditions with average speed values in the same interval, the typical vehicle driving cycles of different speed intervals in Tianjin were obtained, shown as Figure 10.

- VSP-bin frequency distributions of different typical driving conditions

Based on the results of vehicle driving cycles of different speed intervals, referring to the definition of different speed intervals in the VSP-bin division standard of Table 1, the VSP-bin frequency distributions of different typical vehicle driving cycles were determined, shown as Figure 11 and Table 5.



**Figure 10.** The typical vehicle driving cycles of different speed intervals; (a) The typical vehicle driving cycles under low-speed driving condition; (b) The typical vehicle driving cycles under middle-speed driving condition; (c) The typical vehicle driving cycles under high-speed driving condition.



**Figure 11.** The VSP-bin frequency distributions of different typical vehicle driving cycles; (a) The VSP-bin frequency distributions of low-speed driving condition; (b) The VSP-bin frequency distributions of middle-speed driving condition; (c) The VSP-bin frequency distributions of high-speed driving condition; the areas divided by 4 red dotted lines from left to right corresponds to 5 speed intervals (i.e., “Deceleration”, “Idling”, “Low speed”, “Middle speed”, and “High speed”) in VSP-bin division standard respectively.

**Table 5.** The distribution frequency of different vehicle typical driving cycles in different speed intervals of VSP-bins.

Speed Intervals of VSP-Bins	Low-Speed Driving Cycle	Middle-Speed Driving Cycle	High-Speed Driving Cycle
Deceleration (bin0)	4.60%	5.32%	2.53%
Idling (bin1)	21.58%	5.93%	4.22%
Low speed (bin2–bin13)	58.99%	33.52%	15.86%
Middle speed (bin14–bin25)	14.84%	53.64%	75.35%
High speed (bin26–bin37)	0.00%	1.51%	2.03%

According to Figure 11 and Table 5, the VSP-bin distribution under different typical driving cycles showed the following laws:

- The frequency distribution of VSP-bin in different typical vehicle driving cycles was different;
- The distribution frequency of different vehicle typical driving cycles was relatively high in bin0 (Deceleration), bin1 (Idling), bin6–bin8 (Low speed), bin19–bin23 (Middle speed);
- For the three speed intervals except Deceleration and Idling, the distribution frequency of VSP-bin in the middle of each interval was higher, and the distribution frequency of low VSP-bins and high VSP-bins were less, showing the characteristics of “high in the middle and low at both ends”;
- The low speed interval (bin2–bin13) had the highest distribution frequency for low-speed driving cycle, while the middle speed interval (bin14–bin25) had the highest distribution frequency for middle- and high-speed driving cycles. The frequency of the three driving cycles distributed in the high speed interval (bin26–bin37) was very small or even zero.

### 3.2. Establishment of Vehicle Emission Model

#### 3.2.1. Establishment of Emission Rate Database

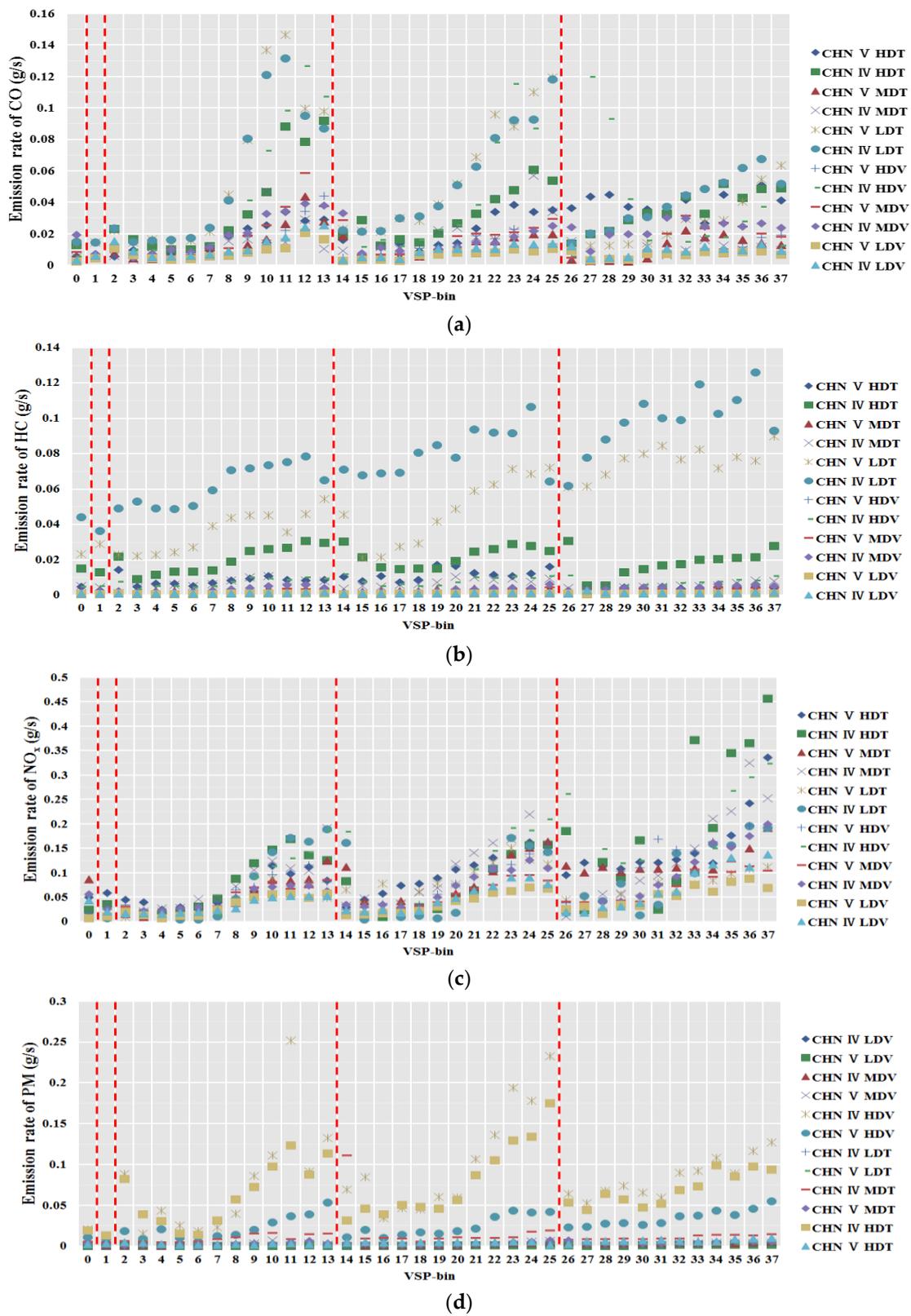
Firstly, all vehicle on-board test results were clustered according to vehicle types, and the emission results of the same type of vehicle under driving cycle with the same VSP-bin number were analyzed. Then, by using the method of statistical regression, the correlation between the number of VSP-bin and the emission rate was analyzed, so as to build the vehicle emission rate (g/s) database based on VSP-bin, shown as Figure 12.

According to Figure 12, vehicle emission rate based on VSP-bin showed the following laws:

- The corresponding relationship between emission rate of different types of vehicles and VSP-bins was different;
- For the three speed intervals except deceleration and idling, the emission rate of each type of vehicle increased with the increase in VSP-bin;
- CHN IV vehicle emission rate was generally higher than the same type CHN V vehicle;
- The emission rate of CO and HC of passenger car was generally higher than that of freight car, and the emission rate of NO<sub>x</sub> and PM of freight was generally higher than that of passenger car.

#### 3.2.2. Calculation of Emission Factors

The vehicular pollutant emission (g) of a certain driving cycle was obtained by multiplying the frequency distribution of VSP-bin and the corresponding emission rate based on VSP-bin in the database. Then, the average emission factor (g/km) of this driving condition could be obtained by dividing the emission (g) by the mileage (km). The average pollutant emission factors of tested vehicles through model calculation in this study are listed in Table 6. For comparative analysis, the table also includes the model operation results under NEDC and FTP75 cycles.



**Figure 12.** The vehicle emission rate (g/s) based on VSP-bin. (a) CO emission rate (g/s) based on VSP-bin; (b) HC emission rate (g/s) based on VSP-bin; (c) NO<sub>x</sub> emission rate (g/s) based on VSP-bin; (d) PM emission rate (g/s) based on VSP-bin; the areas divided by 4 red dotted lines from left to right corresponds to 5 speed intervals (i.e., “Deceleration”, “Idling”, “Low speed”, “Middle speed”, and “High speed”) in VSP-bin division standard respectively.

**Table 6.** The average pollutant emission factors of tested vehicles (unit: g/km).

Vehicles Types	CO			HC			NO <sub>x</sub>			PM		
	Simulation	NEDC	FTP75	Simulation	NEDC	FTP75	Simulation	NEDC	FTP75	Simulation	NEDC	FTP75
CHN IV LDV	0.681	0.496	0.545	0.077	0.061	0.057	0.031	0.021	0.025	0.003	0.002	0.002
CHN V LDV	0.455	0.276	0.379	0.059	0.038	0.046	0.017	0.013	0.014	0.003	0.002	0.002
CHN IV MDV	2.060	1.351	1.555	0.105	0.070	0.080	0.197	0.128	0.167	0.007	0.005	0.006
CHN V MDV	1.990	1.197	1.537	0.102	0.069	0.083	0.153	0.104	0.123	0.007	0.005	0.006
CHN IV HDV	2.250	1.776	1.799	0.106	0.083	0.082	5.040	3.960	3.865	0.277	0.176	0.212
CHN V HDV	1.660	1.213	1.287	0.084	0.056	0.067	4.000	2.535	3.393	0.140	0.109	0.110
CHN IV LDT	2.400	1.804	1.819	0.169	0.103	0.123	2.240	1.728	1.734	0.007	0.006	0.005
CHN V LDT	2.350	1.418	1.947	0.165	0.103	0.121	2.170	1.501	1.740	0.007	0.004	0.005
CHN IV MDT	1.720	1.302	1.340	0.105	0.076	0.081	4.310	3.203	3.652	0.107	0.076	0.084
CHN V MDT	1.610	1.253	1.324	0.105	0.079	0.082	3.620	2.776	2.983	0.021	0.016	0.018
CHN IV HDT	2.210	1.672	1.874	0.134	0.097	0.098	5.380	4.217	4.387	0.149	0.112	0.122
CHN V HDT	2.170	1.472	1.818	0.126	0.098	0.099	4.620	3.463	3.887	0.030	0.021	0.024

It can be seen from Table 6 that the emissions of the same vehicle type under different driving conditions were quite different. Compared with the model operation results of NEDC and FTP75, the emission factors of all types of vehicles under actual driving conditions were higher. At present, China take the European NEDC cycle as the national standard test condition. If the standard test condition was directly used to calculate the emission of urban vehicles, large errors would be introduced. Therefore, when determining the emission factors of urban motor vehicles, we should not simply use the emission factors under standard test conditions, but first synthesize the actual driving conditions of the target city, and then use the emission model based on driving conditions or laboratory test to determine the local emission factors of the city.

In order to facilitate the subsequent nested coupling with the developed vehicle emission inventory model [3], this study further subdivided the typical vehicle conditions into 8 intervals according to the speed (i.e., 5–15 km/h, 15–25 km/h, 25–35 km/h, 35–45 km/h, 45–55 km/h, 55–65 km/h, 65–75 km/h, 75–85 km/h). Then, by using the least square method and polynomial fitting, the vehicle emission factors of different speed intervals were calculated. The fitting results of vehicle emission factors are shown as Figure 13. According to Figure 3, emission factors of different types of vehicles generally decreased with the increase in speed.

### 3.2.3. Validation of Emission Model

A section of driving condition data (Figure 14) was randomly selected from the validation database composed of 20% of the original on-board test data, which was input to the vehicle emission model to calculate the emission factor of this section of condition. Then, the calculated results were compared with the measured emission data corresponding to the driving condition of this section, so as to verify the simulation results of the model.

The comparison of measurement and simulation values of instantaneous pollutant emission rate under the selected driving condition for validation are shown as Figure 15. For the measurement values and simulation values of CO, HC, NO<sub>x</sub> and PM, the relative errors were 5.01%, 5.06%, 5.18% and 4.89%, respectively, showing that both of them were basically the same and the changing trend was very consistent. Therefore, it also showed that, compared with applying international models directly or quoting the recommended values of relevant macroscopic guidelines [14], the emission factor model established in this study could better reflect the vehicle transient emissions on the actual road with high accuracy.

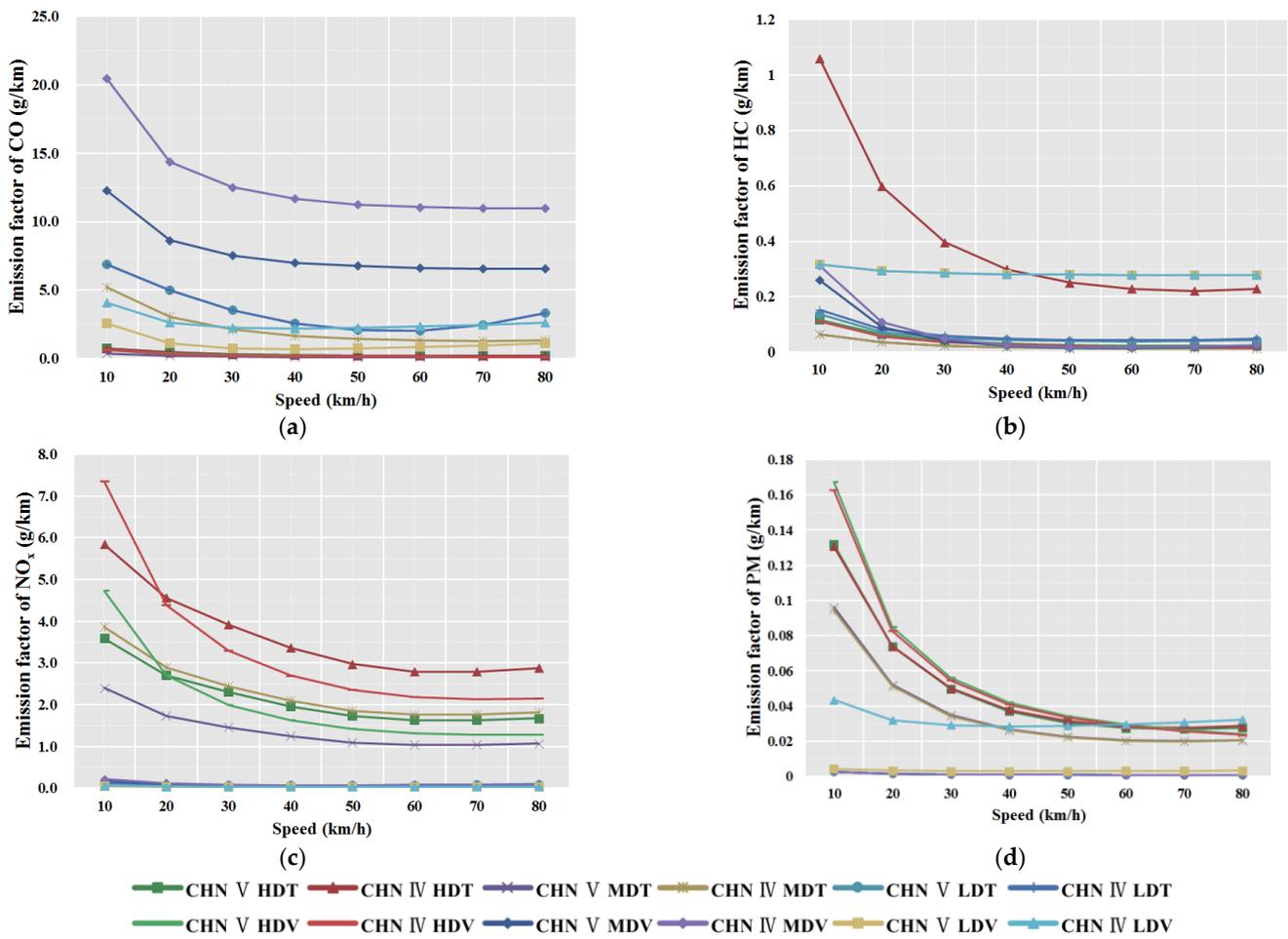


Figure 13. The emission factors of different tested vehicles; (a) Emission factors of CO; (b) Emission factors of HC; (c) Emission factors of NO<sub>x</sub>; (d) Emission factors of PM.

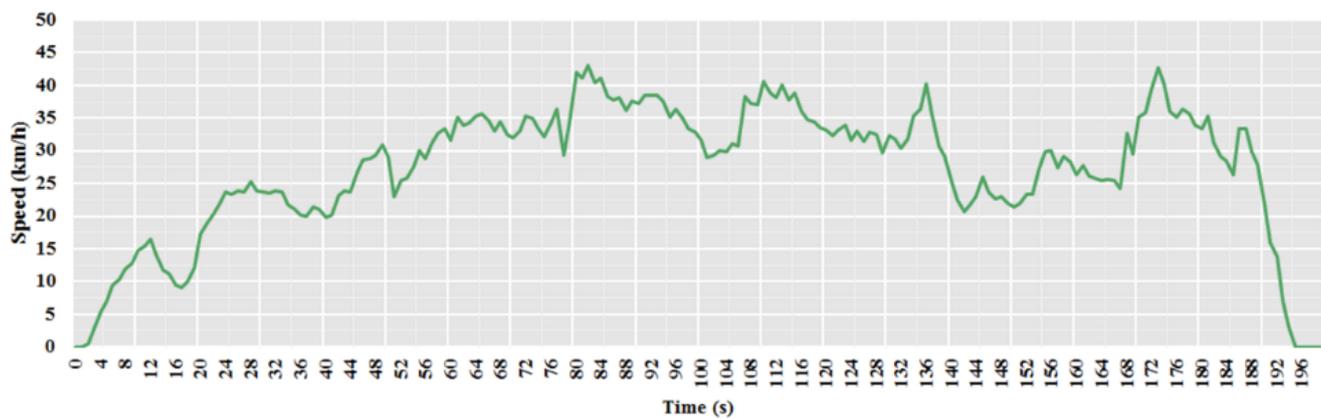
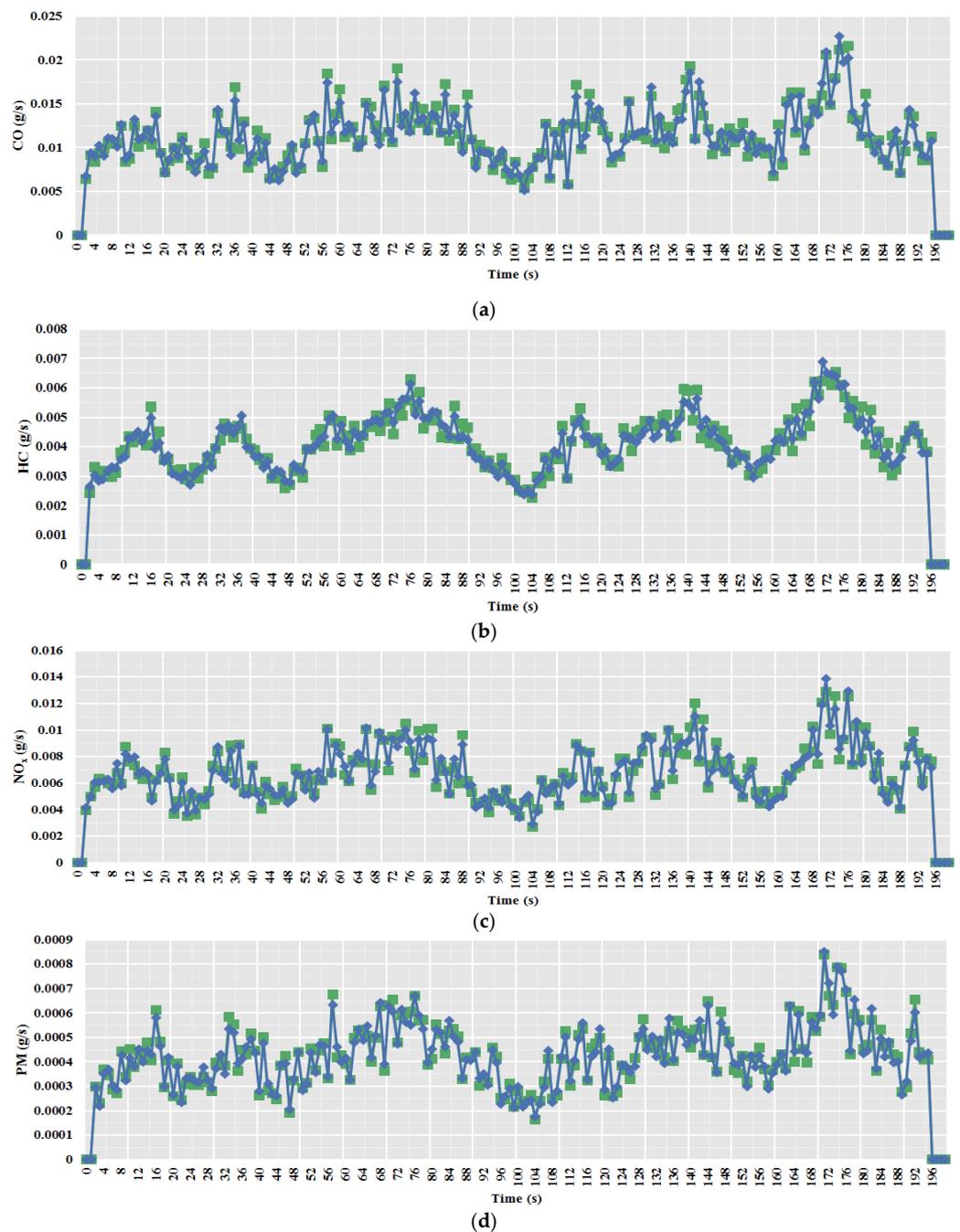


Figure 14. A section of driving condition data was randomly selected from the validation database.



**Figure 15.** Comparison of measurement and simulation values of instantaneous pollutant emission rate under the driving condition for validation; (a) Comparison of measurement and simulation values of in-stantaneous CO emission rate; (b) Comparison of measurement and simulation values of instantaneous HC emission rate; (c) Comparison of measurement and simulation values of instantaneous NO<sub>x</sub> emission rate; (d) Comparison of measurement and simulation values of instantaneous PM emission rate.

#### 4. Conclusions

Based on the demand of vehicle emission research and control, this paper selected the typical vehicles to carry out on-board emission testing on the local representative roads in Tianjin, and then developed the vehicle emission model based on real road driving conditions by taking VSP as the “surrogate variables”, and completed the calculation and validation of emission factors. The research results were of great significance for the

establishment of regional high-resolution inventory and the refinement management of vehicle emission.

In addition, through this study, it could be found that due to the great differences in traffic development modes and vehicle driving conditions in different cities in China, the emission model based on driving conditions was a better choice to carry out the research on vehicle emission in Chinese cities. On the other hand, it should be noted that when using the existing international driving-conditions-based models (such as IVE, MOVES, etc.) to directly simulate China's vehicle emissions, the technical differences and maintenance status differences between Chinese and foreign vehicles would introduce certain errors. This part of the error could be reduced by carrying out field test based on PEMS and correcting the international model emission factor database. In this sense, the establishment of China's local working condition emission model can more accurately study the vehicle emission characteristics of Chinese cities. From this perspective, the establishment of an emission model based on local driving conditions could more accurately study the vehicle emission characteristics of Chinese cities.

However, it should also be clear that, like all emission models, the accuracy of emission models based on driving conditions would also be affected by the systematic error of test instruments and the representativeness of test samples. For the mature model based on a large number of test samples, these effects were far less than the emission model with a small number of samples. Therefore, the international mature models had obvious advantages in test samples and should be fully utilized. In addition, due to the rapid development of China's urban traffic and the rapid change of driving conditions, it was of great significance to regularly update China's urban conditions to improve the accuracy of the model, no matter which model was chosen.

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