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Construction of Heavy-Duty Diesel Vehicle Atmospheric Pollutant Emission Inventory Based on Onboard Diagnosis Data

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Abstract: Motor vehicles emit a large amount of air pollutants. NOx and particulate matter (PM) account for 53.2% and 74.7%, respectively, of vehicle emissions in China. Using the technical guidelines for compiling road vehicle emission inventories, the emission factors based on the onboard diagnostics (OBD) system of heavy-duty diesel vehicles are obtained. The trajectory of heavy-duty diesel vehicles is corrected using big data interpolation, and the correction coefficients for different vehicle speeds are fitted to calculate the corresponding correction factors. Simultaneously, the Weather Research and Forecasting model is used for the meteorological correction of emissions, a heavy-duty diesel vehicle emission inventory under the community multiscale air quality model is established, and the distribution characteristics of pollution emissions from heavy-duty diesel vehicles in Chengdu are analyzed at the time and space levels. Overall, the pollutant gasses emitted by heavy-duty diesel vehicles in Chengdu are largely concentrated at the city center. In 2023, the total annual emissions of the pollutants NOx, CO, fine PM, and volatile organic compounds from heavy-duty diesel vehicles in Chengdu were 10,590.60, 28,852.90, 686.18, and 657.60 tons, respectively. NOx and CO have the highest proportions among the major pollutants, accounting for 70.7% and 26%, respectively.

Keywords: onboard diagnosis data; emission inventory; heavy-duty diesel vehicles; emission characteristics

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1. Introduction

With the economic growth, urbanization development, and significant improvement in living standards in recent years, the number of motor vehicles in Chengdu has been increasing every year, with Chengdu becoming the number one city in China in 2023. The Sichuan Basin, to which Chengdu belongs, has a unique topography with a relatively low terrain. The surrounding mountains have a higher altitude, making the stability of the atmospheric structure in the boundary layer of the basin higher than that in other areas at the same latitude. In addition, the frequency of static winds in the basin is high, and the diffusion conditions of atmospheric pollutants are poor, resulting in the continuous accumulation and high concentration of atmospheric pollutants in the basin [1]. Motor vehicles emit a large amount of air pollutants, with heavy-duty diesel vehicles accounting for 5.4% of the total number of automobiles. NOx and particulate matter (PM) account for 53.2% and 74.7%, respectively, of all motor vehicle emissions, particularly from heavy-duty diesel vehicles, such as diesel trucks and buses. The emitted pollutants not only enter the human body directly through respiration, but also form acid rain and react chemically with other pollutants in the air, producing photochemical smog under specific conditions and participating in the formation of haze, thus affecting air quality and endangering human health. Chengdu has the highest number of motor vehicles and poor conditions for air pollution diffusion. Therefore, establishing a pollutant emission list for Chengdu is necessary.

In recent years, local and foreign research institutions have given high attention to the problem of air pollution caused by motor vehicle emissions, and an endless stream of research has been conducted on pollutant emission inventories. Politarpo et al. [2] used a bottom-up emission factor method to estimate the air pollutant emissions from motor vehicles in Fortaleza, Brazil, from 2010 to 2015. Zhang et al. [3] used the motor vehicle emission simulator (MOVES) model for analysis and found that the total fine PM ($PM_{2.5}$) emissions from heavy-duty diesel vehicles account for more than 83.2% of the total diesel vehicle emissions, and these vehicles are the major contributor to $PM_{2.5}$. Sun et al. [4] calibrated the MOVES model based on the corresponding data on traffic flow, meteorological conditions, vehicle carbon emissions, and driving characteristics on typical roads in Shanghai and Wuxi in Jiangsu; then, they analyzed traffic carbon emissions. Simayi et al. [5] used a bottom-up approach to establish the 2016 Chengdu county-level anthropogenic specific volatile organic compound (VOC) emission inventory, with vehicle emissions as the major source of anthropogenic VOCs in Chengdu (31% and 37%). Fan et al. [6] tested 12 types of construction machineries (excavators, bulldozers, loaders, and forklifts) by using a portable emission measurement system (PEMS) under idle, mobile, and working modes. They established a typical construction machinery exhaust emission inventory in Chengdu in 2018 in accordance with the recommended method. Liu et al. [7] used floating vehicle data to calculate traffic flow speed on all types of roads in various regions of Foshan City. Wang et al. [8] developed the integrated air quality modeling system coupling regional urban/street areas for Beijing, which combined real-time road emission models and improved prediction performance for NO, NO_2, and O_3. Sun et al. [9] used the computer program to calculate emissions from the road transport model and the geographic information system tool ArcGIS to construct a high-resolution emission inventory of motor vehicles in Qingdao from 2000 to 2014. Their study considered the driving ratios of different types of motor vehicles in cities, suburbs, and highways and then analyzed the spatial distribution characteristics of pollutants. They found a gradually decreasing trend from the central urban area to the surrounding areas, with highways showing a clear strip distribution.

The current implementation of China's National Emission Standard VI (GB17691-2018) [10] clearly requires all heavy-duty diesel vehicles that meet the emission stage of National VI b to have onboard terminals for reading onboard diagnosis (OBD) data; this requires the collection of information to be uploaded to the management department, including monitoring fuel consumption and other data [11]. Therefore, using onboard terminal equipment to collect and upload vehicle operation data by collecting vehicle OBD data exhibits considerable advantages in achieving the noninterference monitoring and emission assessment of heavy-duty diesel vehicles on actual roads. Tan et al. [12] used OBD technology to read the operating data and NOx emission data of 72 heavy-duty trucks, verifying the reliability of the data. Simultaneously, they analyzed the characteristics of NOx emissions and found a significant difference between the actual NOx emissions of heavy-duty diesel vehicles and certified NOx emissions. Cheng et al. [13] used onboard sensing (OBS) and PEMS to synchronously collect NOx emission data. They found that OBS can effectively and accurately read the NOx emissions of diesel vehicles in use. OBD data accurately reflect the emission situation of diesel vehicles. The simulation of pollutant diffusion using OBD data can simulate the impact of heavy-duty diesel vehicles on the spatial distribution of pollutants. The simulation results can be used to evaluate the environmental benefits of energy substitution for diesel vehicles, as well as to guide the route planning of diesel vehicles under heavy pollution weather conditions.

Although local and foreign researchers have made significant progress in the study of vehicle air pollutant emission inventories, some problems persist. First, basic and statistical data on motor vehicles that can be subdivided into regions below the city level are limited. In particular, Chengdu, which belongs to the top three western central cities in terms of motor vehicle ownership in China, has experienced rapid economic development in recent years, with an annual growth rate of over 12% in motor vehicle ownership and severe air pollution [14]. Some scholars have conducted research on the emission inventory of motor vehicles in Chengdu. For example, Chen et al. [15] performed emission research on light buses, but did not complete the spatiotemporal allocation of the motor vehicle inventory. Mao et al. [16] used the same time and space allocation parameters for all vehicle models when conducting spatiotemporal allocation of the motor vehicle emission inventory. They did not consider that the spatiotemporal allocation parameters should not be completely consistent due to the varying driving characteristics of different types of vehicles. Overall, research on the high-spatiotemporal-resolution road moving source emission inventory in Chengdu is still lacking. Second, given the difficulty in obtaining extremely accurate data on motor vehicle emissions and driving mileage, researchers frequently use the emission factor method and combine it with the Technical Guidelines for the Compilation of Road Motor Vehicle Air Pollutant Emission Inventory (Trial) to estimate the emissions of motor vehicle pollutants. However, research has shown that this method can lead to low spatiotemporal resolution and the overestimation of emissions in undetermined areas. The method typically requires field research, vehicle following collection, or reference to similar city activity level information to improve accuracy and spatiotemporal resolution; these tasks are time-consuming, labor-intensive, and exhibit small data volume and poor representativeness [17,18].

To address these shortcomings, a more convenient and reliable method is provided for studying the actual road pollution emission calculation of heavy-duty diesel vehicles in Chengdu. The emission inventory of heavy-duty diesel vehicles established using OBD data is closer to reality. Then, the accuracy of this method is verified to create a real and reliable pollutant emission inventory. This study is based on OBD equipment data and uses the linear interpolation (LINE) and big data interpolation (GFX) methods for path completion. These two methods solve the problem of missing data in OBD data. After speed and meteorological corrections, the emission balance of heavy-duty diesel vehicles is calculated, and spatial and species allocations are performed. Finally, a grid emission inventory of $0.02^\circ \times 0.02^\circ$ for NOx, CO, $PM_{2.5}$, and VOCs is obtained, providing basic data for studying air quality management and pollutant control in Chengdu.

2. Study Area

Chengdu is located in the central part of Sichuan Province (Figure 1), in the western part of the Sichuan Basin and on the eastern edge of the Qinghai–Tibet Plateau. As of 2021, Chengdu has jurisdiction over twelve municipal districts, five county-level cities, three counties, and three urban functional zones. The seventh national population census shows that in 2020, the permanent population of Chengdu was 20.9378 million, and the number of motor vehicles has been increasing every year. Simultaneously, Chengdu is a heavily polluted area with frequent hazy weather, and the concentrations of major pollutants, such as SO_2, NO_2, coarse PM (PM_{10}), and $PM_{2.5}$, often remain high, particularly during winter [8].

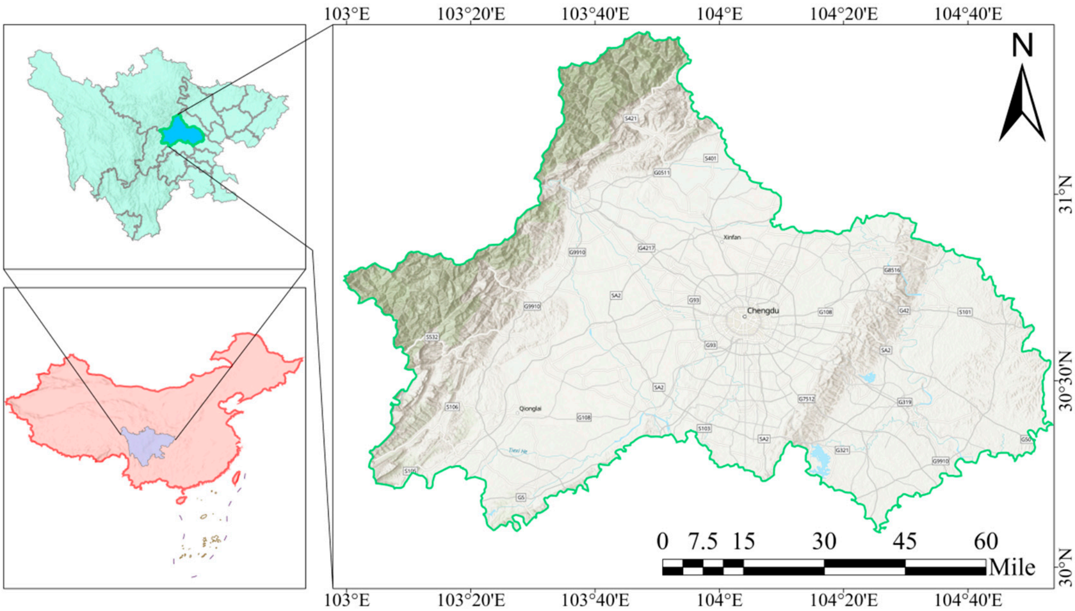

Figure 1. Overview of the research area.

3. Materials

This study used the OBD data of heavy-duty diesel vehicles in Chengdu. The data were cleaned and processed, and available fields are listed in Table 1. OBD is provided by the Key Laboratory of Motor Vehicle Pollution Control and Simulation of National Environmental Protection.

Table 1. OBD data available fields.

Field	Describe	Field	Describe
Time	Data collection time	Speed of a motor vehicle	GPS instantaneous vehicle speed
Total nitrogen oxide emissions	Accumulated emissions	Longitude	GPS longitude
Latitude	GPS latitude		

4. Methods

The research mainly utilizes OBD data to establish a CMAQ emission inventory. However, due to the impact of OBD data quality, the OBD data trajectory was first completed and quality controlled, and meteorological data were used to calibrate the OBD data emissions.

4.1. OBD Data Quality Control and Trajectory Data Completion

The longitude and latitude information in OBD data are extremely important for this study. On the one hand, the longitude and latitude data provide the spatial location of heavy-duty diesel vehicles. On the other hand, the longitude and latitude data at different times can be calculated to obtain the driving mileage of heavy-duty diesel vehicles, and thus, emissions are calculated.

After analysis, the OBD data obtained in this study exhibit certain quality issues due to factors, such as data collection stability. These issues are mostly reflected in the interruption of data collection. Simultaneously, problems with NOx emissions in OBD data still occur. These problems are mostly reflected in data errors caused by data collection failures, such as irregular zeroing.

4.1.1. OBD Data Quality Control

The time of data is decided, and the time interval between the two data points is calculated based on the data points. The length of time that the two data points have passed through is obtained. The distance between the two data points is calculated based on the longitude and latitude data, i.e., the distance traveled during that time.

The time interval of the data is determined. The driving distance of data is set with a time interval that is excessively large (10 min or 600 s in this study) to avoid a significant difference between the distance calculated through two points of latitude and longitude and the actual situation after data interruption for an extremely long period.

On the basis of the distance and time interval calculated by the latitude and longitude, the vehicle speed for this segment is calculated. The calculated vehicle speed is set to $\geq$200 to 0 and compared with the instantaneous speed recorded in OBD data to analyze the relationship between the calculated driving speed and instantaneous speed.

4.1.2. Trajectory Path Completion

Considering the missing data collection and the continuous driving trajectory of heavy-duty diesel vehicles, supplementing the trajectory is necessary to reflect the actual operating trajectory of heavy-duty diesel vehicles as much as possible. This study employed two trajectory correction techniques, namely LINE and GFX.

LINE: Equidistant trajectory points are added between two Global Positioning System (GPS) data points with a long span to extend a certain segment of the running trajectory. This completion method directly connects the disconnected distance with a straight line, which has the advantage of convenient calculation, but the disadvantage is that it does not consider the actual road network and underestimates the completion of the disconnected distance.

GFX: This method first collects the recorded paths of diesel vehicles. When there is a discontinuity in the route, it considers possible paths that already exist in the big data and selects the shortest path from the existing paths. First, the possible path that a heavy-duty diesel vehicle may pass through is determined by combining GPS trajectories over a certain period. Then, the minimum distance method is used to connect two GPS data points with a long span. On this basis, the running trajectory is further connected through LINE. On the one hand, reflecting the driving trajectory of heavy-duty diesel vehicles is better. On the other hand, conducting subsequent grid work and reducing the phenomenon of emission grid jumping are better. When GFX performs path completion, all sample routes are used as a large database. When a heavy-duty diesel vehicle experiences a route interruption, the shortest route that can connect to the interruption point is selected from the large database.

4.2. Emission Accounting of Heavy-Duty Diesel Vehicles

To calculate the exhaust emissions of heavy-duty diesel vehicles, obtaining the emission factors, activity levels, and motor vehicle mileage of these vehicles is necessary. In accordance with the Technical Guidelines for "Compiling Road Motor Vehicle Emission Inventory (Trial)", the emission factor is calculated using the following formula:

$$EF_{i,j} = BEF_i \times \varphi_j \times \gamma_j \times \lambda_i \times \theta_i, \tag{1}$$

where $EF_{i,j}$ is the emission factor of class i vehicles in region j, BEF_i is the comprehensive benchmark emission factor of class i vehicles, φ_j is the meteorological correction factor of region j, γ_j is the average speed correction factor of region j, λ_i is the deterioration correction factor of class i vehicles, and θ_i is the other usage conditions of class i vehicles. For this study, the meteorological correction factor φ_j is determined through meteorological data obtained from the Weather Research and Forecasting (WRF) model, and γ_j is determined through the driving speed in OBD data. The benchmark emission factor (BEF) for heavy-duty diesel vehicles at different emission stages is provided in Table 2.

Table 2. Benchmark emission factors for heavy-duty diesel vehicles.

STAGE	CO	HC	NOx	PM
Pre-National Emission Standard I	13.6	4.083	17.279	1.653
National Emission Standard I	5.79	0.897	9.589	0.623
National Emission Standard II	3.08	0.52	7.934	0.502
National Emission Standard III	2.79	0.255	7.934	0.243
National Emission Standard IV	2.2	0.129	5.554	0.138
National Emission Standard V	2.2	0.129	4.721	0.027

4.2.1. Speed Correction Based on OBD Data

The speed correction factors for heavy-duty diesel vehicles under different emission stages are provided in Table 3. To reflect the relationship between heavy-duty diesel vehicle emissions and vehicle speed, the correction coefficients for different vehicle speeds are fitted and a functional relationship between the vehicle speed and correction factors is established. Before conducting emission calculations, the fitted speed correction function is used to calculate the correction factors that correspond to driving speeds in different OBD data.

Table 3. Speed correction factors for heavy-duty diesel vehicles at different speeds.

POL	STAGE	15 m/s	25 m/s	35 m/s	45 m/s
PM	Pre-National Emission Standard I-Standard III	1.22	1.08	0.93	0.71
PM	National Emission Standard IV-Standard V	1.36	1.12	0.91	0.65
CO	Pre-National Emission Standard I-Standard III	1.43	1.14	0.89	0.54
CO	National Emission Standard IV-Standard V	1.29	1.1	0.93	0.7
HC	Pre-National Emission Standard I-Standard III	1.41	1.13	0.9	0.61
HC	National Emission Standard IV-Standard V	1.38	1.12	0.91	0.64
NOx	Pre-National Emission Standard I-Standard III	1.31	1.08	0.93	0.74
NOx	National Emission Standard IV-Standard V	1.39	1.12	0.91	0.6

4.2.2. Meteorological Correction Based on the WRF Meteorological Model

The emission factors of motor vehicles are influenced by meteorological factors, such as altitude, temperature, and humidity. Therefore, a meteorological correction factor that considers temperature, relative humidity, and altitude is proposed. In accordance with the

Technical Guidelines for "Compiling Road Motor Vehicle Emission Inventory (Trial)", the formula is as follows:

$$\varphi_j = \varphi_{Temp} \times \varphi_{RH} \times \varphi_{Height} \quad (2)$$

where φ_{Temp} is the temperature correction factor, φ_{RH} is the humidity correction factor, and φ_{Height} is the altitude correction factor.

The correction factors under different temperature conditions are provided in Table 4. The humidity correction factor only corrects the NOx emission factor. In low-temperature environments (temperatures below 24 °C), when the relative humidity is below 50%, the NOx emission factor is regarded as 1.04; when the relative humidity is above 50%, this factor is regarded as 0.94. In high-temperature environments (temperatures above 24 °C), when the relative humidity is below 50%, the NOx emission factor is 1.12; when the relative humidity is above 50%, this factor is 0.88.

Table 4. Temperature correction factors for heavy-duty diesel vehicles.

Air Temperature	CO	HC	NOx	PM
<15 °C	1.0	1.0	1.06	1.70
>15 °C	1.3	1.06	1.15	0.74

The altitude correction factor is primarily aimed at environments with an altitude that exceeds 1500 m. At this moment, the correction factors for the emission factors of heavy-duty diesel vehicles are provided in Table 5.

Table 5. Correction factors for altitude of heavy-duty diesel vehicles.

Altitude	CO	HC	NOx	PM
>1500 m	2.46	2.05	1.02	1.00

4.2.3. Calculation of Emission Data for Heavy-Duty Diesel Vehicles

To adapt to the OBD emission data calculation method developed in this study, the calculation formula for the exhaust emissions E1 of heavy-duty diesel vehicles is modified as follows:

$$E_1 = \frac{\mathrm{P_t}}{\mathrm{n}} \times \sum_{i=1}^{n} EF \times VKT_i \times 10^{-6} \quad (3)$$

where Pt represents the driving volume of heavy-duty diesel vehicles obtained through the monitoring platform of the motor vehicle company; N represents the number of heavy-duty diesel vehicles in the OBD data sample obtained in this study; and EF is the revised emission factor that is determined by the vehicle speed calculated from heavy-duty diesel vehicle OBD data, meteorological data simulated by the WRF model, altitude of the simulation grid, and BEF. The mileage of the *i*-th heavy-duty diesel vehicle of VKTi is calculated using the longitude and latitude information in OBD data.

4.2.4. Grid-Based Emission Inventory Production

The emission information of heavy-duty diesel vehicles based on OBD data already has temporal and spatial attributes, and most operating paths of heavy-duty diesel vehicles are on the ground. Therefore, only spatial and species allocations based on emission data are necessary to obtain a grid-based emission inventory of NOx, CO, $PM_{2.5}$, and VOCs at 0.02° × 0.02°.

Space allocation combines GPS coordinate information to classify emission data into corresponding spatial grids. Species allocation refers to the chemical species characteristics of heavy-duty diesel vehicles in the literature. In accordance with the definition of the CB05 chemical mechanism, VOCs, NOx, and $PM_{2.5}$ are classified into species, and species allocation is performed based on the proportion of different species. The results are stored as chemical species. The composition spectra used in this study are provided in Table 6.

Table 6. Composition spectrum of VOCs, $PM_{2.5}$, and NOx model for heavy-duty diesel vehicles.

	Component	Proportion	Component	Proportion
VOCs	ALDX	0.00%	MEOH	0.00%
	CH_4	0.00%	NVOL	0.00%
	ETH	9.40%	OLE	7.95%
	ETHA	0.33%	PAR	50.17%
	ETOH	0.00%	TERP	0.00%
	FORM	0.30%	TOL	6.76%
	IOLE	2.11%	UNR	8.28%
	ISOP	0.00%	XYL	13.42%
	ALD_2	0.00%	BENZENE	0.00%
	Component	**Proportion**	**Component**	**Proportion**
$PM_{2.5}$	PEC	33.65%	PMG	0.24%
	PNO3	0.44%	PMN	0.02%
	POC	40.88%	PNA	0.33%
	PSO4	4.27%	PNH4	0.00%
	PH2O	0.01%	PAL	0.29%
	PCL	0.00%	PFE	1.31%
	PNCOM	16.35%	PTI	0.11%
	PCA	0.66%	PK	0.25%
	PSI	0.77%	PMOTHR	0.42%
NOx	NO	22.00%	NO_2	74.00%
	HONO	4.00%		

5. Results

5.1. Quality Control of OBD Data

The scatter distribution of the calculated and GPS instantaneous vehicle speeds in this study is depicted in Figure 2, with a correlation coefficient of 0.83. The calculated vehicle speed is basically consistent with the GPS instantaneous vehicle speed.

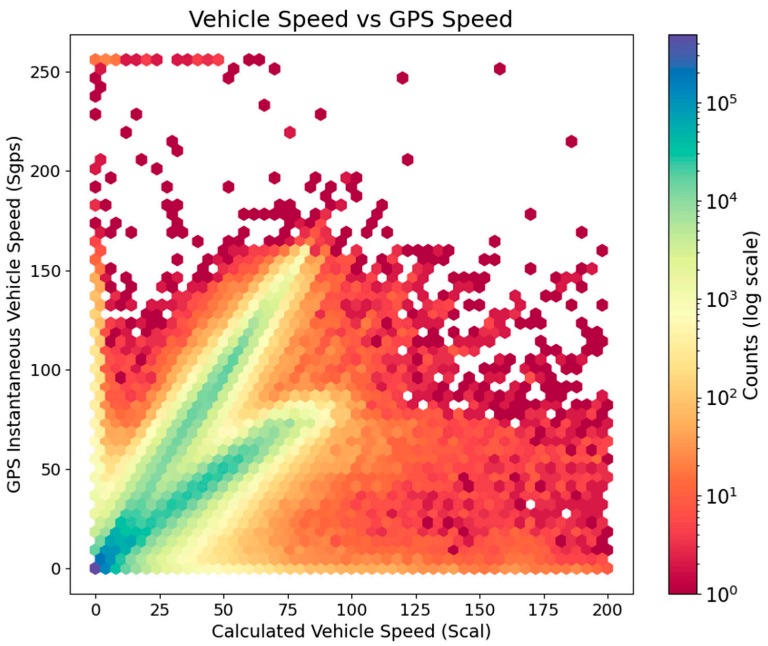

Figure 2. Scatter distribution of vehicle speed (x) and GPS instantaneous vehicle speed (y).

5.2. Trajectory Data Completion Based on LINE and GFX

As presented in Table 7, using the OBD data sample from October 2022 as an example, the data sample includes 286 vehicle OBD data, and differences exist in the quality of data collection for different heavy-duty diesel vehicles. After reading the OBD data and quality control, the driving mileage was 289,000 km. After performing LINE on the missing data within X min, the driving mileage increased to 355,000 km. After using GFX for completion, the driving mileage further increased to 416,000 km. Compared with RAW, driving mileage increased by 43.7%, improving the accuracy of the heavy-duty diesel vehicle emission calculation and pollution emission spatial distribution to a certain extent.

Table 7. Differences in driving range for different OBD data completion methods.

Data Processing Methods	RAW	LINE	GFX
Mileage driven (km)	289,241.6	354,771.2	415,705.3

A specific driving trajectory is selected, and the differences in the driving trajectories obtained by various data processing methods are depicted in Figure 3 (the blue dots in the figure represent the original trajectory points of the OBD data, while the red dots represent the corrected trajectory points, which overlap when directly read).

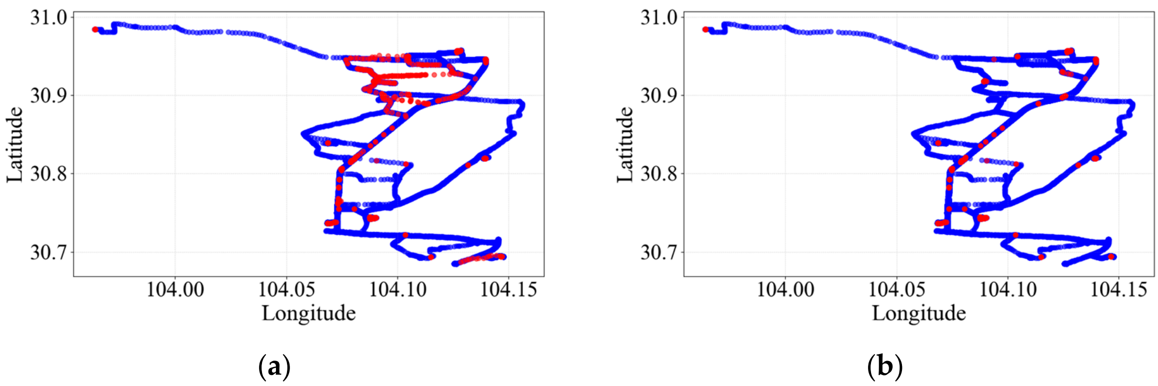

Figure 3. OBD data of GFX and RAW (**a**) and LINE and RAW (**b**) (the blue dots in the figure represent the original trajectory points of the OBD data, while the red dots represent the corrected trajectory points, which overlap when directly read).

As shown in the graph, compared with the directly read OBD trajectory data, the trajectory after LINE is extended, while the trajectory after GFX is extended again. Considering the actual situation, the final result is more accurate than the original data. Therefore, in terms of driving trajectory, the effect after GFX is better than that after LINE and RAW. This finding is in line with the real situation.

5.3. Hourly, Daily, and Day Night Emissions of Pollutants Based on OBD Data

Using October OBD data, the daily variation analysis of pollutant emissions was conducted using LINE and GFX methods (Figure 4). Overall, the variation characteristics of the four pollutants exhibit two "first rising and then falling" processes. During the National Day holiday, heavy-duty diesel vehicles had frequent activities, and pollutant emissions had rapidly increased since 1 October. Emissions remained high on 2–5 October. Then, emissions rapidly decreased, reaching their lowest point on 8 October. After 8 October, emissions continued to rise to their highest point on 10 October, and then continued to decline slowly. In the daily variation in pollutant emissions, GFX is similar to the original data values, while LINE differs significantly.

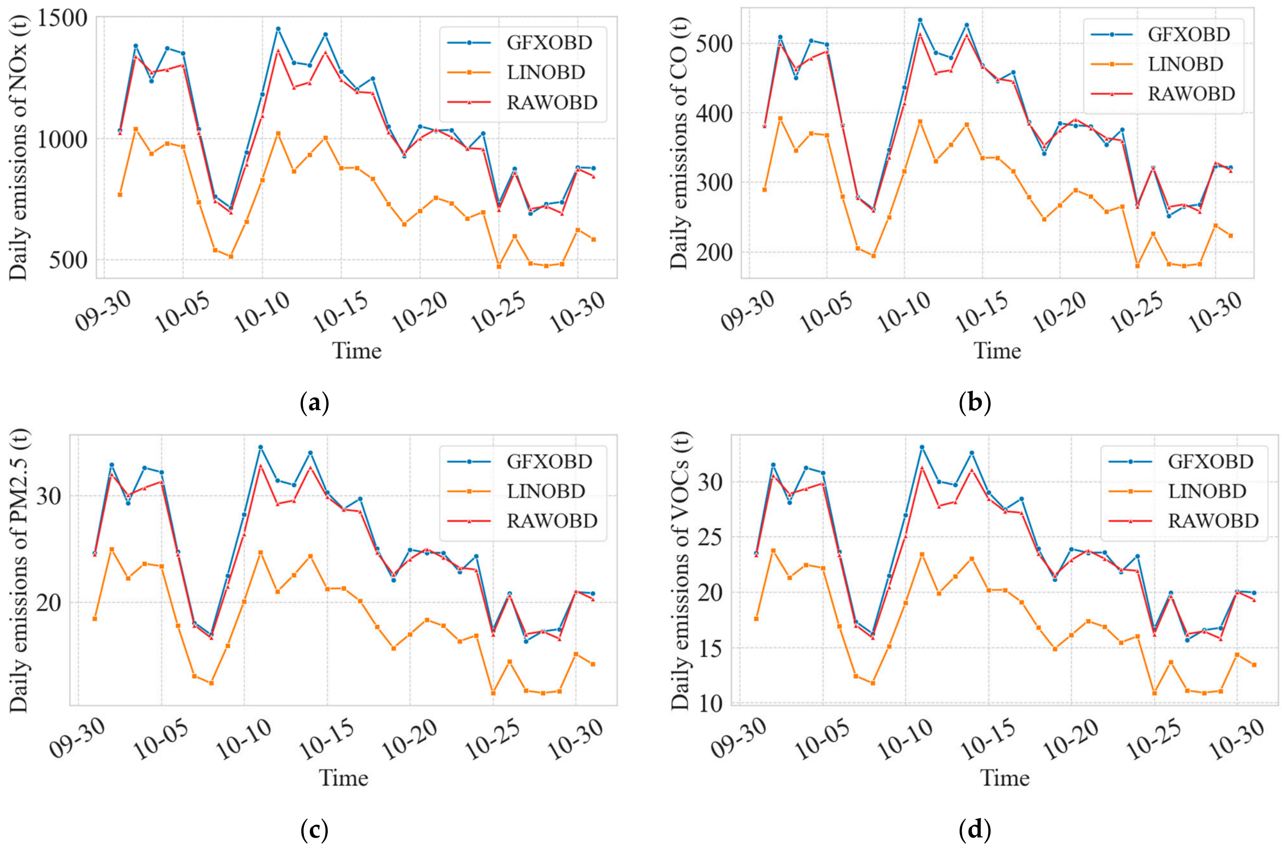

Figure 4. Daily variation in pollutant emissions under different interpolation methods.(**a**) NO_x, (**b**) CO, (**c**) $PM_{2.5}$, (**d**) VOC_S.

Setting 08:00–20:00 as daytime and the rest of the time as nighttime, the OBD data for October were analyzed for the diurnal variation in pollutant emissions by using the LINE and GFX methods (Figure 5). The four pollutants exhibit similar spatial distributions; however, in terms of numerical values, heavy-duty diesel vehicles are frequently active at night, and pollutant emissions are considerably higher than that during the day. In addition, the emissions of the four pollutants in descending order are NOx, CO, $PM_{2.5}$, and VOCs. The four pollutants emissions obtained through GFX are the highest, while the LINE results are the lowest.

The hourly variation analysis of pollutant emissions is performed using the GFX method on October OBD data (Figure 6). The emissions of NOx, CO, $PM_{2.5}$, and VOC pollutants from heavy-duty diesel vehicles tend to be low during the day and high at night. The overall emissions of heavy-duty diesel vehicles from 00:00 to 01:00 exhibited a continuous upward trend, reaching a higher level by 03:00. This result is related to the traffic characteristics of heavy-duty diesel vehicles and the driving behavior of drivers. The emissions of heavy-duty diesel trucks sharply decreased from 00:00 to 05:00 and then surged to a peak at 06:00. From 07:00 to 18:00, the emissions of heavy-duty diesel trucks demonstrated a steep decline followed by a slow decline, primarily due to the daytime restrictions imposed by urban roads and bridges on heavy-duty diesel vehicles. Evidently, heavy-duty diesel vehicles had significantly different peak travel times from other motor vehicles in the morning and evening, and their emissions exhibited a clear two-stage distribution. The emissions were lower from 14:00 to 23:00 and higher at other times.

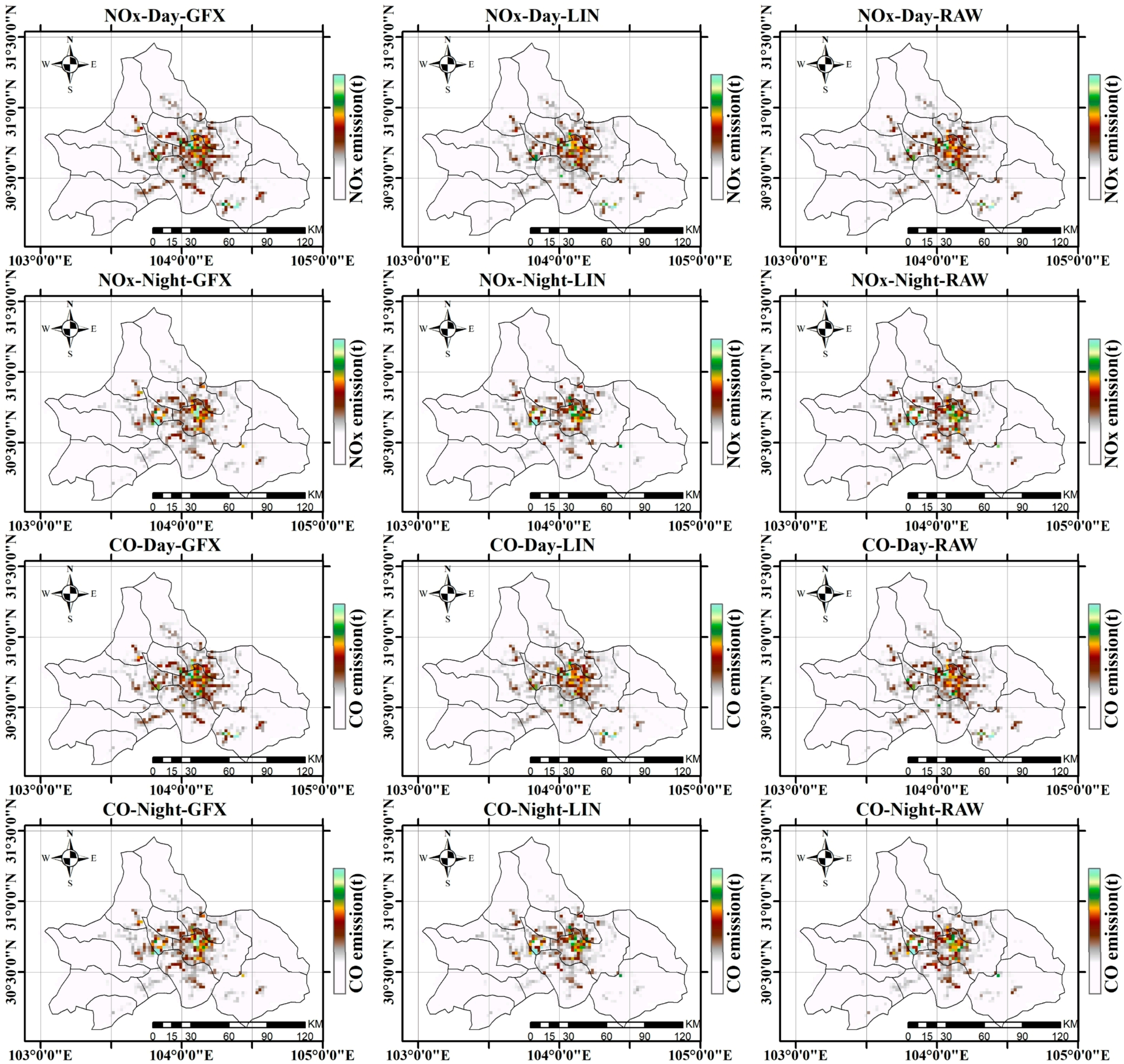

Figure 5. *Cont.*

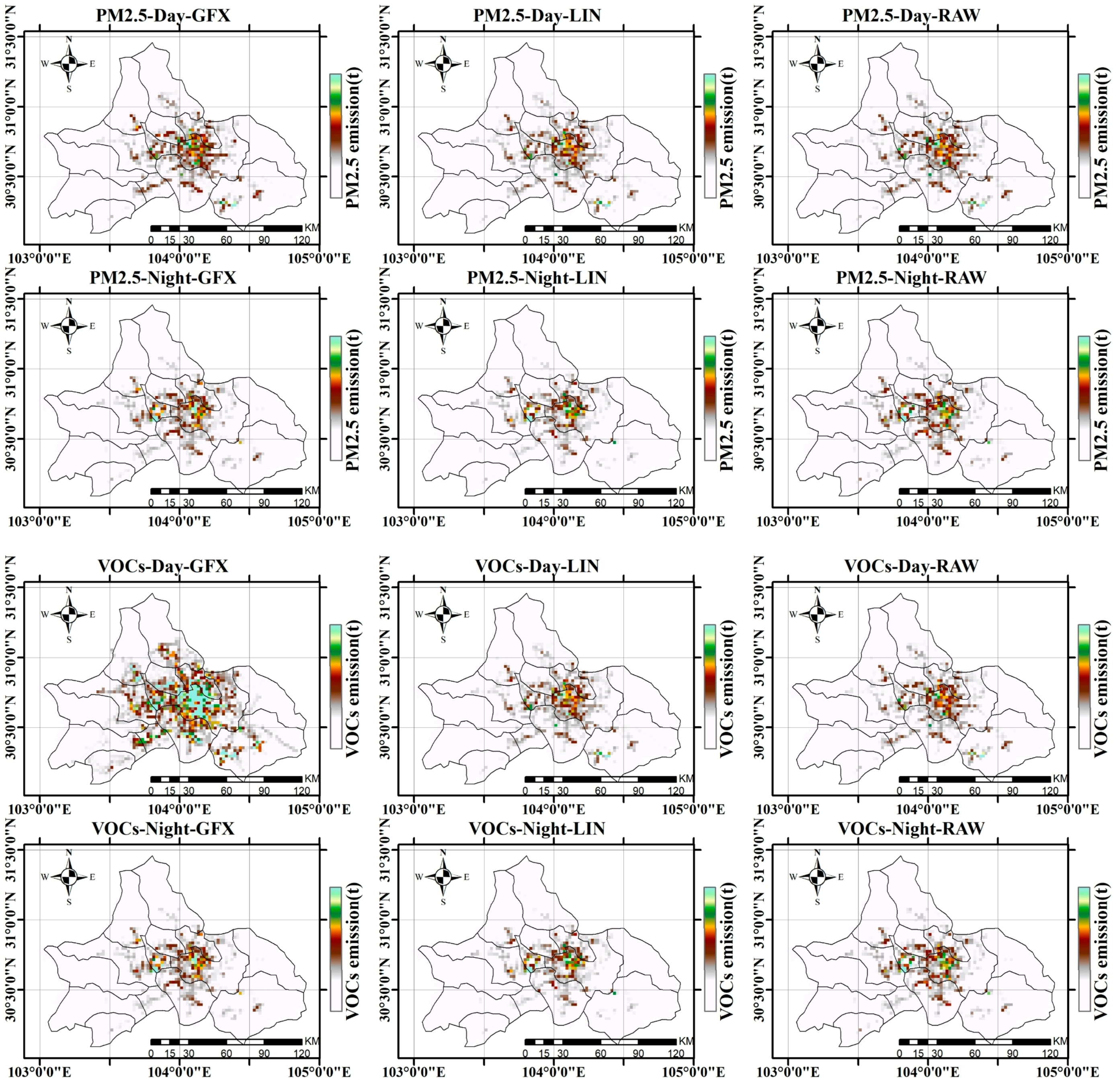

Figure 5. Diurnal variation in pollutant emissions under different interpolation methods.

5.4. Grid-Based Emission Inventory

The spatial distribution results of grid-based NOx, CO, $PM_{2.5}$, and VOC emissions obtained using different OBD data processing techniques based on the aforementioned methods are shown in Figures 7–9. Overall, regardless of its type, the pollutant is largely concentrated in the city center of Chengdu, such as Chenghua District, Chongzhou County, Dayi County, and other districts and counties adjacent to the city center, along with the main road network and expressways in Chengdu. The aforementioned regions are leading in economic development, with high traffic flow, frequent heavy-duty diesel vehicle traffic, and relatively high emission intensity. In other prefecture-level cities under the jurisdiction of Chengdu, such as Jianyang and Pengzhou, pollutants are also scattered at the city center but less distributed in other areas.

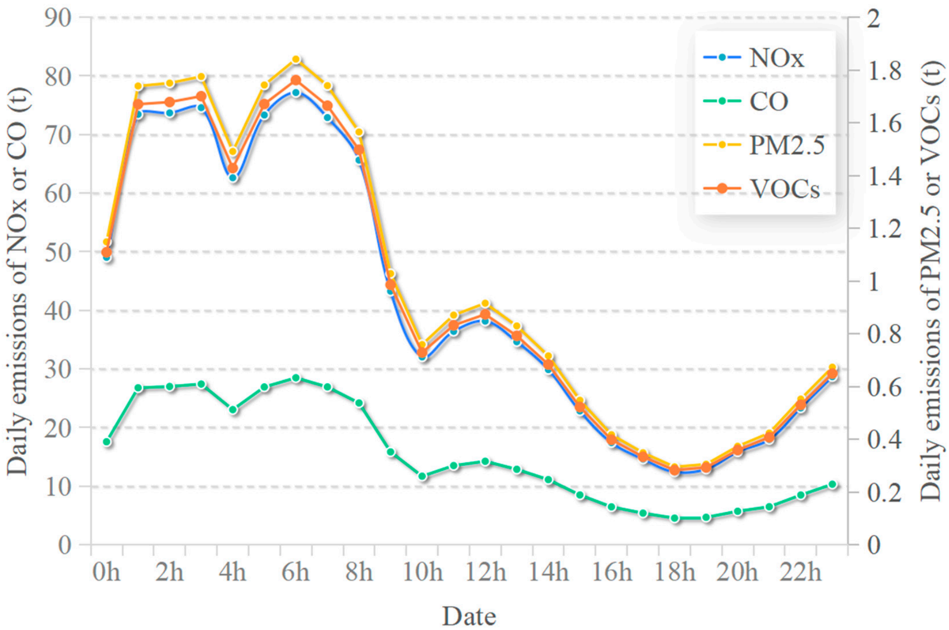

Figure 6. Hourly variation in pollutant emissions under GFX method.

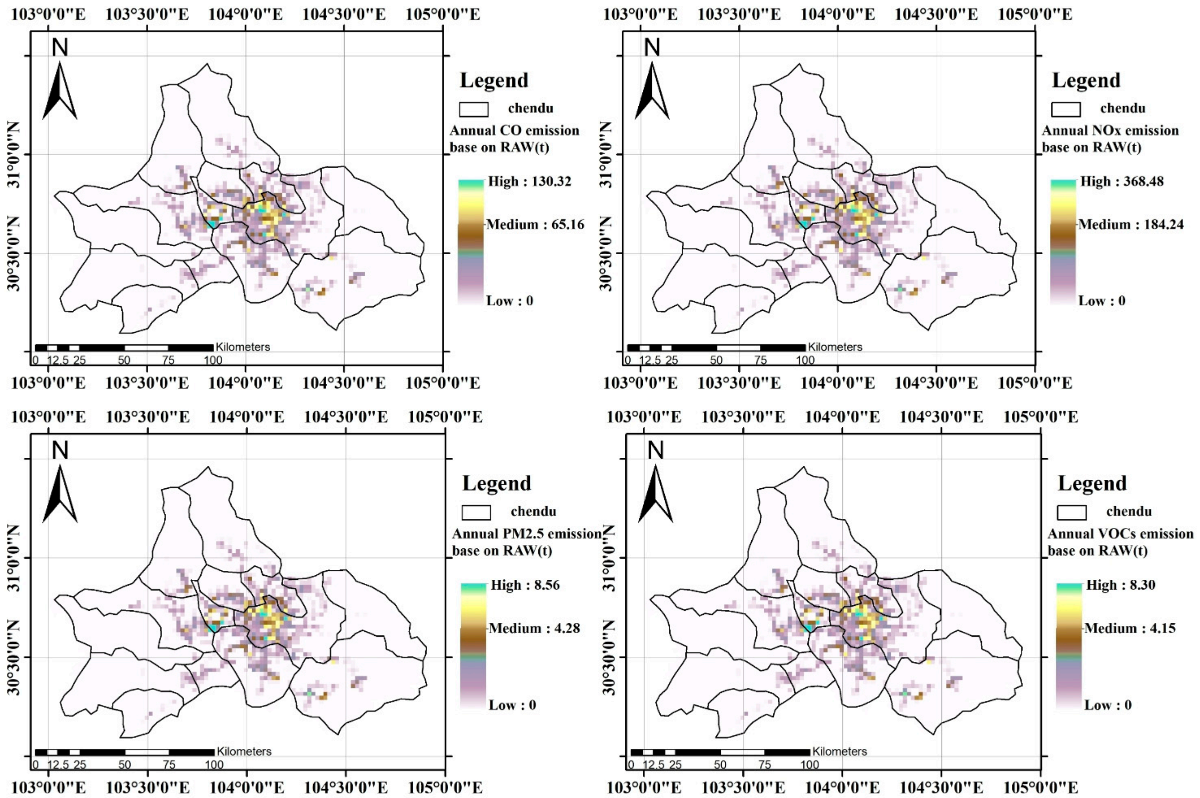

Figure 7. Spatial distribution of CO, NOx, $PM_{2.5}$, and VOC_S emissions calculated by RAW.

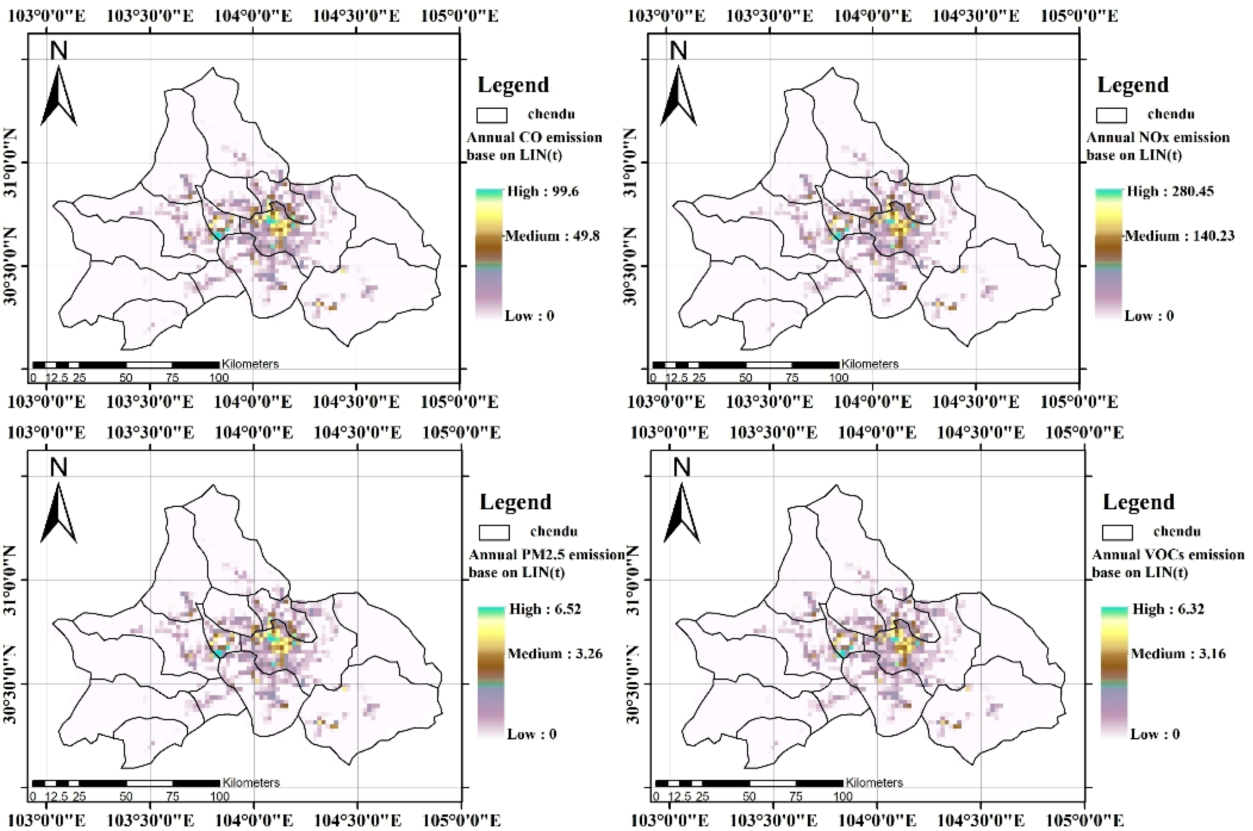

Figure 8. Spatial distribution of CO, NOx, $PM_{2.5}$, and VOC_S emissions calculated by LINE.

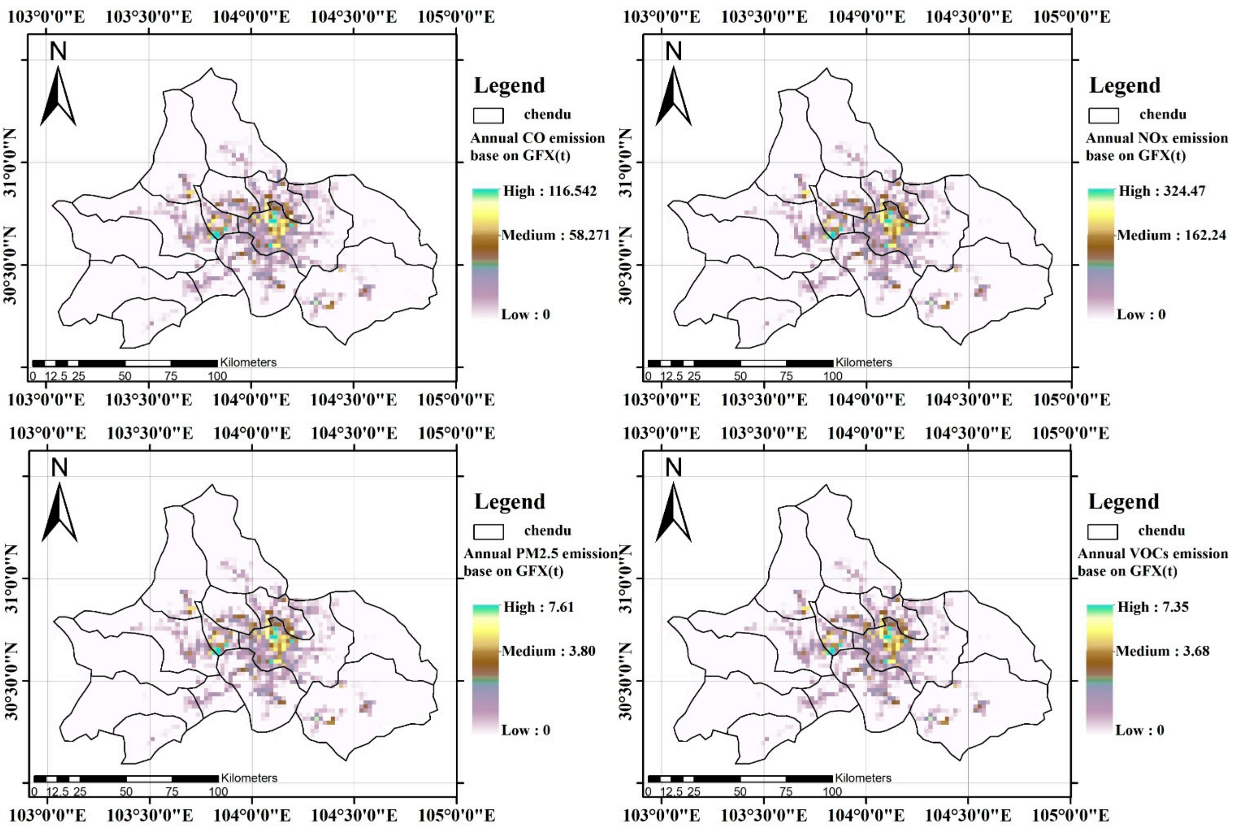

Figure 9. Spatial distribution of CO, NOx, $PM_{2.5}$, and VOC_S emissions calculated by GFX.

Further aggregation analysis was conducted on the emissions of various districts and counties in Chengdu, and the results are presented in Figure 10. Significant differences occur in pollutant emissions among various districts and counties, with an uneven distribution. Among them, Chenghua District exhibits the highest emissions, followed by Chongzhou County, Dayi County, and the Dujiangyan Irrigation Project. Compared with the aforementioned urban areas, the emissions in other urban areas, such as Jianyang and Jinniu, have significantly decreased. The cities with the lowest emissions are Wenjiang, Wuhou, Xindu, and Xinjin. Among all districts and counties in Chengdu, Xinjin has the lowest emissions of the four pollutants, with NOx, CO, $PM_{2.5}$, and VOC emissions of 94.91, 35.64, 2.29, and 2.18 tons, respectively. Compared with those of Chenghua District, the emissions of NOx, CO, PM2.5, and VOCs have decreased by 3453.28, 1260.12, 81.67, and 78.50 tons, respectively.

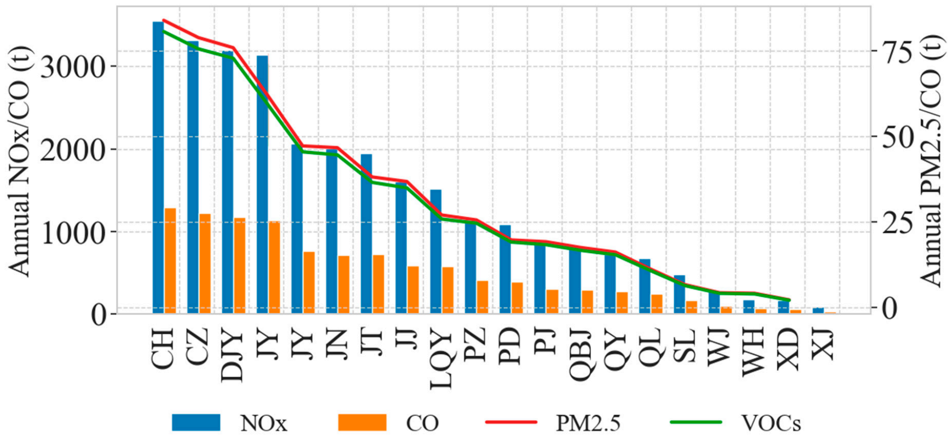

Figure 10. Total pollutant emissions from various districts and counties in Chengdu City.

No considerable difference is observed in the spatial distribution characteristics of pollutant grid emissions obtained by performing different interpolation methods, but a significant difference in numerical values is found. The overall annual emissions exhibit a characteristic of GFX > RAW > LINE (Table 8). Compared with LINE, the difference between the results of GFX and RAW is relatively small, indicating that the results of GFX are more authentic. In terms of the total annual emissions of NOx, CO, $PM_{2.5}$, and VOCs, the GFX results are 28,852.90, 10,590.60, 686.18, and 657.60 tons, respectively, which increased by 1068.90, 488.10, 19.06, and 21.44 tons compared with RAW. LINE decreased by 7603.8, 2445.98, 179.92, and 172.61 tons, respectively, compared with RAW. In accordance with the results of GFX, NOx is the major pollutant emitted by heavy-duty diesel vehicles, accounting for 70.7% of the four pollutants, followed by CO, $PM_{2.5}$, and VOCs, accounting for 26%, 1.7%, and 1.6%, respectively.

Table 8. Annual total emissions of four pollutants.

	NOx (t)	**CO (t)**	**$PM_{2.5}$ (t)**	**VOCs (t)**
RAW	27,784.00	10,102.50	667.12	636.16
LINE	20,180.20	7656.52	487.20	463.55
GFX	28,852.90	10,590.60	686.18	657.60

6. Discussion

6.1. Advantages of the GFX Method

Given the missing data collection and the continuous driving trajectory of heavy-duty diesel vehicles, this study used two trajectory correction techniques, LINE and GFX, to supplement the trajectory and reflect the actual operating trajectory of heavy-duty diesel vehicles as much as possible.

In terms of trajectory completion, the driving distance increased to 355,000 km when selecting a certain distance and using LINE, while using GFX for completion further increased driving distance to 416,000 km. Compared with RAW, driving distance increased by 43.7%, which improved the accuracy of THE heavy-duty diesel vehicle emission calculation and THE spatial distribution of pollution emissions to a certain extent (Table 8). Second, compared with the OBD trajectory data of RAW, the trajectory after LINE is extended and then further extended after GFX. Based on the actual situation, the final result is more accurate compared with the original data. Therefore, in terms of driving trajectory, the effect of GFX is better than those of LINE and RAW, and GFX is more in line with the real situation (Figures 3 and 4).

In terms of the grid-based emission inventory of pollutants, the total annual emissions of the four pollutants exhibit an overall trend of GFX > RAW > LINE (Table 8). Compared with the results of LINE, the results of GFX and RAW present a smaller difference, indicating that the results of GFX are more authentic.

6.2. Chengdu Grid Emission Inventory

To verify the authenticity and rationality of the results of this study, corresponding comparisons were made with vehicle emission inventories compiled by other scholars. In 2023, NOx, CO, $PM_{2.5}$, and VOC emissions in Chengdu were mostly concentrated spatially at the city center, surrounding industrial areas, such as Wenjiang, Qingbaijiang, and Xindu, and major road networks, such as main roads and expressways in Chengdu. This finding is consistent with previous research results [6,14,16,19]. The reason for selecting the Chengdu region for the study is that the Sichuan Basin, where Chengdu is located, has poor air pollution diffusion conditions and is one of the areas with severe air pollution in China. The research results in this region can be extended to other heavily polluted areas.

The total annual emissions of NOx, CO, PM2.5, and VOCs from heavy-duty diesel vehicles in Chengdu in 2023 are 28,852.90, 10,590.60, 686.18, and 657.60 tons, respectively. Among the four pollutants, NOx is the most important component, accounting for 70.7% of the total annual emissions of major pollutants. Li et al. [20] developed a high-resolution emission inventory for Northeast China. In 2020, the total emissions of CO, NOx, NO2, and PM in Northeast China were 172.2 kt, 531.5 kt, 11.2 kt, and 921.4 t, respectively. Among them, the proportion of CO and NOx is similar to the content of the current study. Das et al. [21] found that the emissions of CO, VOCs, NOx, SO2, PM10, and NH3 from mobile sources on roads in Chengdu reached 432.2, 44.8, 72.4, 0.4, 11.3, and 6.2 thousand tons, respectively, in 2016. The proportion of NOx has significantly decreased, largely because diesel vehicles are more prone to carbonization and the formation of carbon smoke during combustion compared with gasoline vehicles. In addition, the air in the combustion chamber at high temperatures can easily form NOx [22].

As one of the most severely polluted areas in China, the Chengdu region is mainly affected by poor air diffusion capacity, with pollutants easily accumulating and being difficult to diffuse. The current government has gradually relocated polluting industries and also encouraged tram travel. This study can be used to estimate the environmental benefits that heavy diesel vehicles can generate after energy substitution, and it can also be used as a reference for planning the driving routes of heavy diesel vehicles on heavily polluted days.

6.3. Uncertainty Analysis

OBD data are currently the most effective and accurate measure of diesel vehicle emissions, but there are some missing samples in the data. After multiple attempts, it is believed that GFX is currently the most reliable method based on the number of completion samples. In the future, more comparative analysis of other data will be used to evaluate the advantages and disadvantages of the completion method.

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Without considering the comprehensive effect of pollutants directly emitted by heavy-duty diesel vehicles in complex atmospheres and their migration and transformation processes on air quality, a third-generation air quality model can be used for research in the future. Through downscaling correction technology, the Multi-resolution Emission Inventory for China data at a national scale resolution of 10 km can be optimized to provide a benchmark emission inventory that is basically in line with the actual situation in Chengdu.

This simulation only considered the establishment of winter emission inventories. In the future, separate inventories for the four seasons will be established and simulated, possibly taking into account the impact of seasonal changes on pollutants from heavy-duty diesel vehicles, which will be more informative. The preliminary prediction shows that the pollution emissions caused by diesel vehicles in winter and summer will be more significant. After analyzing the four seasons, the impact of different meteorological conditions on emission diffusion will be further analyzed.

7. Conclusions

On the basis of OBD equipment data, path completion was performed using the LINE and GFX methods. After speed and meteorological corrections, the emission balance of heavy-duty diesel vehicles was calculated, and spatial and species allocations were conducted. Finally, a grid-based emission inventory of NOx, CO, $PM_{2.5}$, and VOCs for heavy-duty diesel vehicles in Chengdu in 2023 was obtained, with a value of $0.02^\circ \times 0.02^\circ$. The conclusion drawn is as follows.

The total annual emissions of NOx, CO, PM2.5, and VOCs from heavy-duty diesel vehicles in Chengdu in 2023 were 28,852.90, 10,590.60, 686.18, and 657.60 tons, respectively. Among the four pollutants, NOx is the most important component, accounting for 70.7% of the total annual emissions of major pollutants. VOCs and $PM_{2.5}$ only account for a small portion, with their combined annual emissions accounting for only 3.29% of major pollutants.

The total annual emissions of NOx, CO, $PM_{2.5}$, and VOCs from heavy-duty diesel vehicles in Chengdu City exhibit high values on a daily scale and persist for a certain period during the National Day holiday. On an hourly scale, a trend of low daytime and high nighttime is exhibited, and the rush hour travel time of heavy-duty diesel vehicles is completely different from that of other motor vehicles, with their emissions showing a clear two-stage distribution.

Heavy-duty diesel vehicle pollutants present a concentrated distribution at the city center of Chengdu, such as Chenghua District, Chongzhou County, Dayi County, and other districts and counties adjacent to the city center, along with the main road network and expressways of Chengdu. The pollutants in prefecture-level cities under the jurisdiction of Chengdu, such as Jianyang and Pengzhou, also demonstrate a certain amount of concentrated distribution at the city center. The distribution of pollutants in other areas is relatively small and does not exhibit a clear trend.

In terms of trajectory completion, the use of the GFX method is better than that of the LINE method. Compared with the original data, trajectory completion is more accurate and realistic. Moreover, in the final list of pollutants emitted by heavy-duty diesel vehicles, the results obtained by the GFX method are less different from the original data than the results of the LINE method and are more realistic.

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