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Research Article

Vehicle Emission Factors for Particulate and Gaseous Pollutants in an Urban Tunnel in Xi'an, China

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Urban tunnels are generally used to measure traffic-related particles and gas pollutant concentrations. To understand on-road vehicle emissions and update emission factors (EFs), traffic volume data and emissions of particulate matter smaller than 2.5 μm ($PM_{2.5}$), carbon monoxide (CO), nitrogen oxides (NO_X), hydrocarbon (HC), and volatile organic compounds (VOCs) for mixed vehicles were investigated at the Wenchang Gate-Peace Gate Tunnel in Xi'an over 11 days. An average fleet of 14,199 vehicles with mean speeds that ranged from 18 $km{\cdot}h^{-1}$ to 46 $km{\cdot}h^{-1}$ passed through the tunnel during the sampling period each day. A mass balance model and linear regression analysis were adopted to derive pollutant EFs for mixed vehicles, cars, and taxis, respectively. The results demonstrated that EFs during the night were higher than those during the day because goods vehicles are only allowed to travel from 22:00 to 07:00. Averaged EFs of $PM_{2.5}$, CO, NO_X, HC, and VOCs for the total fleet were 0.006 ± 0.005, 1.097 ± 0.398, 0.159 ± 0.092, 0.179 ± 0.089, and 0.317 ± 0.172 $g{\cdot}veh^{-1}{\cdot}km^{-1}$, respectively, lower than those reported from other literatures owing to the strict requirements of emission standards and improvements in vehicle technology. This method provides an approach to measure the EFs for different types of vehicles in urban traffic and evaluate traffic pollution in distinct areas.

1. Introduction

Vehicle exhaust is a threat to both the living environment and human health [1]. Emissions of particulate and gaseous pollutants from exhaust pipes in motor vehicles, tire and brake wear, and dust on the road have become important contributors to air pollution [2]. Most cities are subject to severe smog pollution whose main composition is fine particles such as particulate matter smaller than 2.5 μm ($PM_{2.5}$) during winter and ozone pollution whose primary precursors are nitrogen oxides (NO_X) and volatile organic compounds (VOCs) during summer [3–5]. Pollutants reduce visibility resulting in an increase in the risk of traffic accidents [6, 7]. In addition, vehicle emissions have adverse impacts on health according to epidemiological studies [8]. During recent years, many metropolis cities have implemented vehicle restriction policies in which some types of vehicles are not allowed at certain times or must travel on required roads [9]. In Xi'an, a midwestern city in China, goods vehicles are forbidden to travel inside the Second Ring Road during the day considering environmental quality and traffic safety. Moreover, beginning in 2016, on-road vehicles except public transportation are limited by license number during the weekdays during winter when the smog is serious on the basis of the air quality index forecast, while during weekends and holidays, there are no limitations. For example, vehicle tail numbers of 1 and 6 are restricted on Monday if the forecast shows air quality would be mild pollution, and an odd-even car ban could be applied when a red alert for air pollution is issued by the government. The purpose of the aforementioned policies and measurements is to reduce traffic-related air pollution. These measures all rely on accurate studies of emission factors (EFs) and corresponding emission inventories [10].

EFs refer to the emitted mass of pollutant per driven distance per vehicle and can be defined for a fleet as well as single vehicle [11]. Various techniques have been applied to measure EFs, and these can be classified into three categories: laboratory tests, on-road measurements, and model simulations. Chassis dynamometer methods were initially the most popular laboratory tests [12]. A single vehicle under standard driving cycles in laboratories is used to obtain tailpipe emissions. However, emissions of a traffic fleet are difficult to test because of the high expense, and real-world traffic conditions are too complex to simulate [13]. Real-time and on-road emission measurements that reflect the real conditions of traffic include single vehicle on-road cycles, remote sensing, and tunnel measurement [14]. Single vehicle on-road cycles are usually equipped with measuring facilities such as an emission analyzer, portable emissions measurement systems (PEMS), and Global Positioning System (GPS) in the testing vehicle, and then the vehicle is driven along a designated road to measure emissions and speed [15, 16]. Nevertheless, the cost is high if too many vehicles are involved, and the result is also related to a driver's behavior. Remote sensing is applied to evaluate gaseous pollutants, while particulate matter is difficult to investigate [17]. Tunnel measurement has its advantages in studying a real-world fleet of vehicles by monitoring pollutant concentrations as well as meteorological and traffic parameters at the inlet and outlet of an urban tunnel [18]. The differences in concentrations between the two sites are considered as the emissions from mobile sources in the tunnel where ventilation is closed. Moreover, mass balance model or carbon mass balance is often used to estimate EFs [19, 20]. Compared to other methods, a tunnel test is more accurate in measuring average EFs that represent the comprehensive level of urban traffic [21]. Furthermore, new techniques have been developed in using simulated EF models such as MOBILE, COPERT, IVE, CEME, and MOVES [22, 23]. These models have been established by European and American researchers, and the EFs can be obtained directly by inputting the required data such as vehicle type, age distribution, driving distance, and ambient temperature [24, 25]. To apply these models well and meet the needs of practical conditions, some parameters need to be localized, particularly for an area in China. Therefore, it was assumed that tunnel measurement is a basic method to compare and correct the results of estimated EF models, and it is still necessary to do so.

Vehicle EFs are different in distinct areas at different times and change all the time because of many dynamic factors, such as road characteristics (tunnel dimensions, structure, and gradient), traffic conditions (traffic volume, fleet speed, vehicle type, and age), vehicle performance (engine, fuel, and accumulating mileage), driving behavior (acceleration and deceleration), environmental factors (temperature, wind speed, and pressure), and emission standards. All of the aforementioned result in dramatic changes in EFs, and therefore, it is important to update EFs to reflect the real emission situation of an area.

During recent years, many cities have conducted EF studies. The types of vehicles were mainly classified into light-duty vehicles and heavy-duty vehicles [26]. Nevertheless, few researchers have focused on cars and taxis because goods vehicles are limited in numerous cities during the day such that the major vehicles on the roads were these two types and public transport. In addition, the only tunnel test conducted in Xi'an, China, was undertaken in 1996 [27], and there has been no further study in the city since. The EFs must have changed because of the increasing number of vehicles and the different emission standards of today. This study aimed to measure traffic-related pollutants in the Wenchang Gate-Peace Gate Tunnel and update the average EFs of $PM_{2.5}$, carbon monoxide (CO), NO_X, hydrocarbon (HC), and VOCs for the total fleet, cars, and taxis in Xi'an. The results not only present the latest vehicle emission conditions in Xi'an but also provide a sound reference for traffic pollutant assessments and policymaking for the government.

2. Materials and Methods

2.1. Tunnel Description. The Wenchang Gate-Peace Gate Tunnel consists of two unidirectional bores that are 992 m in length and that have no internal curves. Both bores have two lanes with one entrance and one exit. The posted speed limit is $50\,\mathrm{km{\cdot}h^{-1}}$. The tunnel is on Ring Road in the Beilin District and is also the longest urban tunnel in Xi'an, China. The tunnel is a direct transportation link between the Wenchang Gate and Peace Gate as well as the main road access to the City Wall which is the center of Xi'an. Restricted by policy, goods vehicles are not allowed in the tunnel from 07:00 to 22:00.

In general, there is a ventilation system in the tunnel to supply fresh air; however, to avoid the effect of ventilation, the vent pipes were all closed during our tests, such that the condition of the tunnel could only be considered a result of traffic-induced pistons and natural forces. Similarly, ambient air pollutants were generated only by the vehicles.

2.2. Measurements. The main vehicle of the traffic fleet in the urban tunnel was gasoline car of which most emissions were $PM_{2.5}$, CO, and NO_X [28]. Thus, two on-road monitoring points were set 200 m from the inlet and outlet with a cross-sectional area of $39\,\mathrm{m}^2$ and a height of 1.5 m above the platform inside the eastbound bore as shown in Figure 1. The pollutants $PM_{2.5}$, CO, NO_X, and HC (including methane and nonmethane total hydrocarbons) and VOCs (including nonmethane total hydrocarbons, benzene, toluene, and xylene) were measured in the Wenchang Gate-Peace Gate Tunnel simultaneously in this study. Sampling occurred from July 17 to July 27, 2015 (including seven weekdays, two Saturdays, and two Sundays). Considering the number and functions of the measuring devices, as well as the different concentrations between inlet and outlet, the devices at sampling sites 1 and 2 were not exactly the same in terms of the accuracy of the tests, as summarized in Table 1.

Measuring devices were used to acquire particulate pollutant $PM_{2.5}$ and gaseous pollutants (CO, NO_X, HC, and VOCs). The sampling periods were split into morning transit (07:00–10:00), afternoon period (12:00–15:00), evening transit (17:00–20:00), and night period (22:00–24:00). A TSI Q-Trak was used for probing the ambient temperature, relative humidity, barometric pressure, and air velocity (V). Additionally, a video camera was installed at the exit at the same time to record traffic data. The traffic volume and the number of different types of vehicles were manually counted every 15 min from video tapes directly such that the hourly average indexes were calculated. The types of vehicles were classified into five major categories, namely, cars, taxis, buses (including

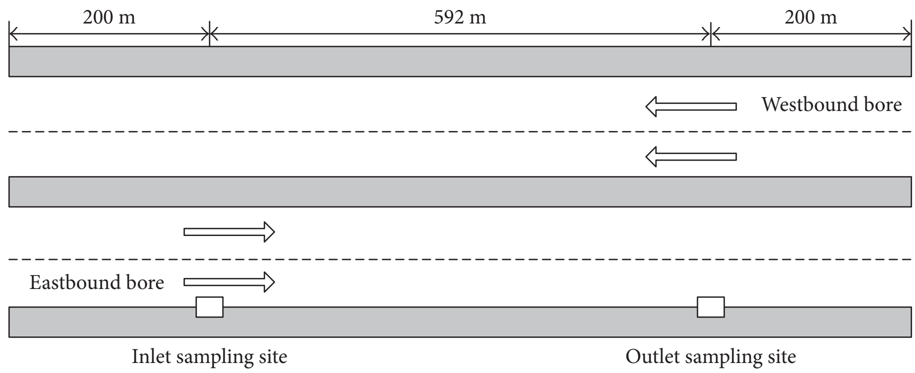


FIGURE 1: Sampling sites in the tunnel. The inlet sampling site was set 200 m from the inlet, and the outlet sampling site was set 200 m from the outlet in the eastbound bore.

TABLE 1: Measuring devices in the tunnel.

	Device at site 1	Device at site 2	Company, country	Time resolution	Technical parameter
$PM_{2.5}$	E-BAM($PM_{2.5}$)		Met One, USA	1 min	0–10 mg·m^{-3}; 2.5 μg
CO	Thermo 48i (CO)	Ecotech 9830	Ecotech, Australia	1 min	0–200 ppm; 0.1 ppm
NO_X	Airbags, Interscan (NO_X)	Ecotech 9841B	Ecotech, Australia	5 min	0–100 ppm; 1 ppb
HC	Airbags	55C Methane-NMHC analyzer	Thermo, USA	5 min	0–50 ppm; 0.1 ppm
VOCs	PPb RAE 3000VOC		RAE, USA	1 min	1 ppb–10000 ppm; 1 ppb
Meteorological parameters	Q-Trak, V-Trak 7575		TSI, USA	1 min	TP: 0–50°C, 0.1°C; RH: 5%~95% rh, 0.1% rh; BP: 0.1 kPa; V: 0.1 m·s^{-1}
Traffic parameters	Camera, Simi-motion			Continuous	1 h; 0.01 m·s^{-1}

Note. VOCs were measured using PPB RAE in this study. The reported VOC was a relative value based on the VOC used to calibrate the instrument and thus was not comparable to the HC measurement.

public buses; coach buses; and light, medium, and heavy buses), goods vehicles (GVs) (including light, medium, and heavy goods vehicles), and others (including tricycles, motorcycles, and special cars such as ambulances and clean cars). Furthermore, the speed and acceleration of vehicles were obtained using the Simi-motion software indirectly.

2.3. Quality Control. $PM_{2.5}$ was measured using an online method, and a beta-ray attenuation method was used in E-BAM. In this study, the cut particle size was 2.5 μm and flow rate was 16.7 L·min^{-1}. Examining the state of devices daily was necessary to ensure sound operation. More importantly, the work of downloading and data checking was carefully completed daily. Backup battery and the power contact of the instrument were checked regularly to avoid power outages.

For measurement of CO, the devices must be fully warm and stable for 30 min prior to measurement. In addition, the fan filter was cleaned and the sampling filter was periodically replaced. The calibration points were divided into low range and high range, and each range consisted of three points (80%, 50%, and 20% of the range). The first was zero check; a test was conducted for at least 5 min, the average time of the instrument was set at 300 s to obtain the best accuracy, and then a span check was conducted.

Similar precautions were taken for NO_X measurement. Adequate preheating, regular replacement of front filters, sintering the filter, and cleaning of the gas pipeline were necessary. A NO standard was used for calibration, and at least 10 min of zero air was needed.

As for measurement of HC, VOCs, and meteorological data, zero calibration was essential and the devices were started 15 min prior to sampling. Only when the devices were in a storage state and the operation was normal during the warm-up phase could the sampling start.

2.4. Emission Factors. The mass balance model is widely used to determine EFs in tunnels. Based on the principle of mass conservation, a tunnel is regarded as an ideal cylindrical piston, and the difference between the pollutants passing through the two sections is the total mass of pollutants between the two sections [29]. The model has two assumptions. First, except that the jet fan can accelerate the wind speed inside the tunnel, only one inlet and one outlet can be set; there are no other air inlets or outlets. Second, the measured contaminants cannot deposit, decompose, or transform during the sampling time. As a result, average EFs can be calculated as follows [30]:

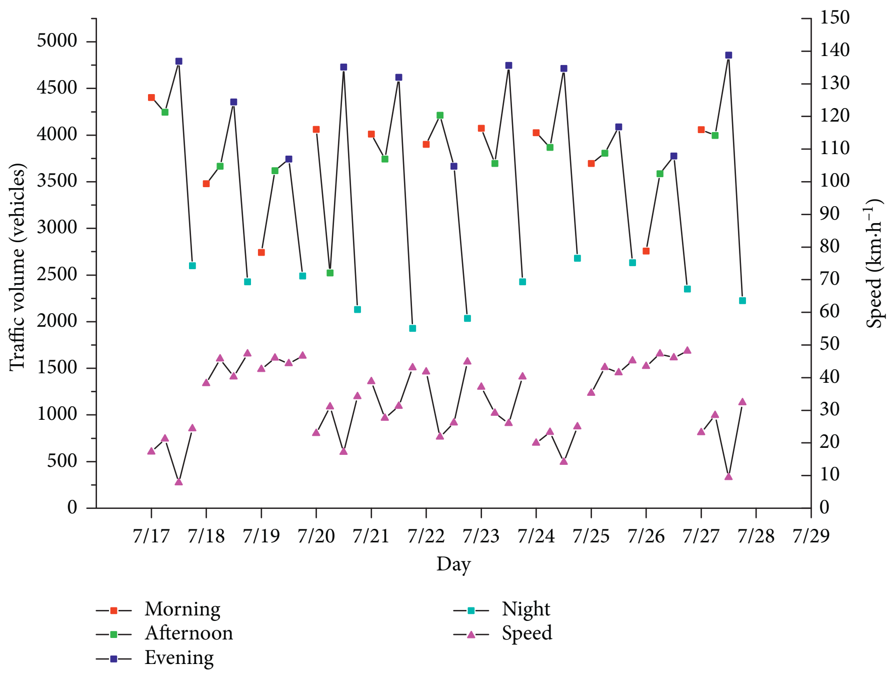


Figure 2: Diurnal variations in traffic volume and speed during the sampling period. Left axes show the number of vehicles during the morning transit (07:00–10:00), afternoon period (12:00–15:00), evening transit (17:00–20:00), and night period (22:00–24:00) from July 17 to July 27, 2015. The right axes show the corresponding average speed of the total fleets.

$$\text{EFs} = \frac{(C_{\text{outlet}} - C_{\text{inlet}}) \cdot V \cdot T \cdot A}{N \cdot L}, \quad (1)$$

where EFs (mg·veh^{-1}·km^{-1}) are the average emission factors for mixed vehicles; C_{outlet} and C_{inlet} (mg·m^{-3}) are the concentrations of the pollutants at the outlet and inlet inside the tunnel, respectively; V (m·s^{-1}) is the air velocity inside the tunnel; T (s) is the time interval; A (m^2) is the cross-sectional area in the tunnel; N (veh) is the number of vehicles; and L (m) is the length from the sampling inlet site to the outlet site.

Mean EFs reflect the level of pollutant emissions from all motor vehicles passing through the tunnel at different sampling times. They represent a combination of mean vehicle speed, vehicle type, age distribution, and mileage distribution. If the vehicles traveling within the tunnel could reflect the actual situation of traffic in a city, the calculated average EFs would represent the vehicles EFs in that area. Additionally, the average EFs for different types of vehicles can be calculated via linear regression [11]. In this study, the majority of vehicles were cars and taxis such that only these two types were considered in the calculation of EFs. The following equation can be used according to the linear regression model:

$$\text{EFs} = \sum_i \text{EF}_i \cdot X_i, \quad (2)$$

where EFs are the average emission factors for mixed vehicles; i is the different type of vehicles; EF_i (mg·veh^{-1}·km^{-1}) is the emission factor for the vehicle i; and X_i is the proportion for i.

3. Results and Discussion

3.1. Traffic Fleet Characteristics. Characteristics of the traffic fleets in the tunnel are related to traffic volume, fleet composition, and vehicle speed. In the eastbound bore where the sampling was conducted, 12,470–16,042 vehicles passed through the tunnel during the sampling periods per day. The traffic in this study presented distinct characteristics on workdays and weekends in that there was a higher volume on weekdays compared to that of weekends, as well as higher volume on Saturdays compared to that on Sundays. As for diurnal variations, the segmented traffic volume presented an N-type distribution on workdays and an inverted U-type distribution on weekends, as shown in Figure 2. Moreover, the traffic fleets had two peaks termed tidal flow at the rush hours of 07:00–09:00 and 17:00–19:00 during workdays, while two peaks occurred at 11:00–13:00 and 18:00–20:00 on the weekends [21]. During weekdays, the flow of the morning transit on Monday and Friday was the highest; correspondingly, the return flows of the evening transit were also high. Additionally, the traffic at every sampling time on Friday was heavier, which may be because of regular working meetings, business travel, and entertainment. The common trend that the highest number of vehicles occurred during the evening rush hours may be explained in that the eastbound bore was an out-of-city direction, and the second highest traffic flow appeared during the morning. In contrast, the lowest volume was found during the night at approximately 23:00.

Because GVs are not allowed to enter the tunnel from 07:00 to 22:00, GVs accounted for only approximately 0.6% of the total fleets while passenger vehicles accounted for 96.2%, and in particular, cars had the highest proportion at approximately 80%, and taxis were the second highest at 14%. The GVs mainly traveled from Thursday to Sunday, particularly on weekends. Different weekday-weekend patterns were also reflected in the vehicle type. On average, there were

Table 2: Mean mass concentrations of pollutants at the outlet and inlet.

Pollutants	Inlet concentration ($mg\cdot m^{-3}$)		Outlet concentration ($mg\cdot m^{-3}$)	
	Average	Standard deviation	Average	Standard deviation
$PM_{2.5}$	0.048	0.023	0.054	0.023
CO	1.804	1.054	3.895	2.205
NO_X	0.544	0.111	0.694	0.099
HC	3.615	0.277	5.129	0.289
VOCs	0.324	0.082	0.441	0.149

5% more cars on workdays than on weekends, and more passengers chose taxis during the weekends.

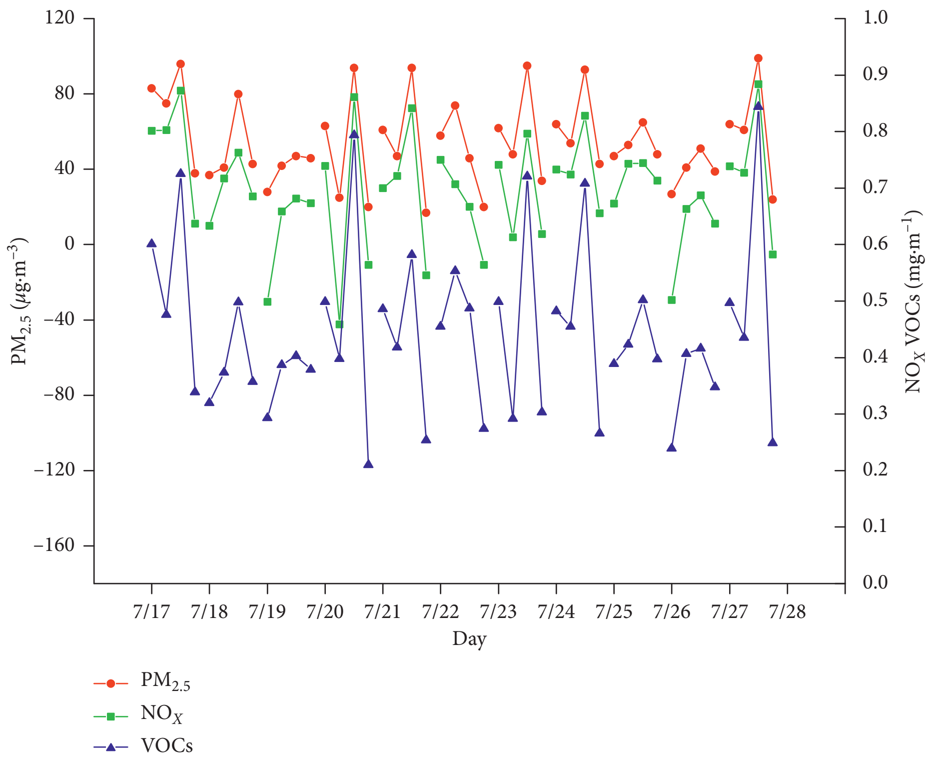
To a large extent, the speed of the vehicles was inversely proportional to the traffic volume [31]. The more the vehicles in the tunnel, the slower the speed of the fleets. Similarly, the vehicle speed on weekends was higher than that on workdays, and the segmented traffic speed presented an N-type distribution from Friday to Monday and a U-type distribution from Tuesday to Thursday. Noticeably, the mean traffic volume during the morning was higher than that in the afternoon during the workdays; nevertheless, the average speed during the morning was not slower but faster compared to that of the afternoon during the same period. It was found that commuters during the weekday morning were hurrying to work, even if in a traffic jam, and the speed of driving was also faster than the afternoon when people were driving more leisurely. Moreover, the calculated time referred to the morning from 07:00–10:00, not only the peak hours, thus the average speed of the vehicles was slightly faster. Furthermore, the traffic flow during the afternoon on weekends was higher than that during the morning, and the speed had the same trend. This phenomenon may be attributed to trip purpose, including leisure and shopping during the weekend afternoon rather than working or business during the morning. The destinations were so dispersed that the operation of the traffic near the tunnel worked well during the afternoon even though there was a high volume.

3.2. Mass Concentrations of Pollutants. The mean mass concentrations of the pollutants at the outlet and inlet are presented in Table 2. It is obvious that the values at the outlets were higher than those at the inlets owing to the accumulation of the pollutants [32]. Average mass concentrations of CO and HC at the exit were 2.16 and 1.42 times those at the entrance, respectively, suggesting that the cars exhausted a considerable amount of CO. Other pollutant mass concentrations at the exit were 1.13 to 1.36 times of those at the entrance.

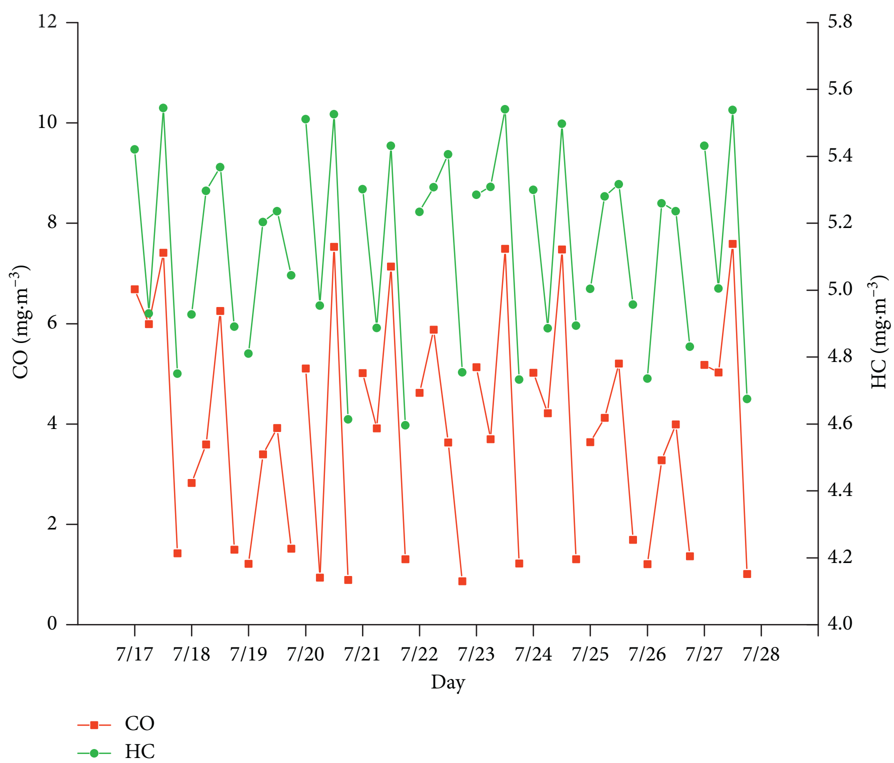
Figure 3 demonstrates the variations in average mass concentrations at the outlet among different pollutants during the four sampling periods for 11 days. The pollutant mass concentrations were proportional to the traffic volume and inversely proportional to the fleet speed. It is shown that traffic volume had a distinct impact on pollutant concentrations. Moreover, a slower speed and a greater acceleration of vehicles resulted in a higher accumulation of pollutants [33]. All the curves show similar diurnal variations, with high values during the day and the highest occurring during the evening period (17:00–20:00) because of a great many vehicles in the evening rush hours. $PM_{2.5}$ and NO_X concentrations had a similar trend with a correlation coefficient of 0.922. HC and CO concentrations also had high correlation with a coefficient of 0.853. However, the change rates in the CO and HC were higher than those of the other pollutants. This may be attributed to CO and HC mainly originating from cars and taxis, and the number of these types of vehicles during the night was significantly lower than that during the day, while the other pollutants were related to heavy-duty vehicles such as GVs that only operated in the tunnel during the night. The weekday-weekend pattern is shown in Figure 4. The average mass concentrations during weekends were lower than those during workdays, which was because of the lower volume and higher speed of the vehicles during the weekends. The concentrations during the night on weekends were higher than those during working days because of the high emissions of the GVs.

3.3. Average Emission Factors. The average EFs for the mixed vehicles during the different sampling periods are shown in Table 3. The night period had the highest values during the sampling time for the proportion of GVs. This comparison between the day and night suggests that the number of GVs is a decisive factor in the emissions of pollutants; most notably, the EFs of $PM_{2.5}$, NO_X, and VOCs during the night were nearly twice as high as those during the day. High EFs emerged during the evening during the daytime, corresponding well to a high traffic volume with a low fleet speed. In contrast, the values in the afternoon were the lowest because of the high speed and low volume. The gradient in the variation in CO and HC was greater than that in the other pollutants, which can be explained to a certain extent in that CO and HC are mainly generated by cars and taxis, which accounted for a large proportion of the traffic volume.

Consequently, the mean EFs of the mixed vehicles in Xi'an, China, were 0.006 ± 0.005, 1.097 ± 0.398, 0.159 ± 0.092, 0.179 ± 0.089, and $0.317 \pm 0.172\ g\cdot veh^{-1}\cdot km^{-1}$ for $PM_{2.5}$, CO, NO_X, HC, and VOCs, respectively. On the basis of linear regression, the EFs of cars which accounted for nearly 80% of the total fleet and taxis which were the second highest at 14% were calculated as shown in Table 4 during the daytime except night sampling period. The taxis had higher EFs than those of the cars for all pollutants. The EF of CO for the taxis was only slightly higher than that for the cars (1.1 times), while the other pollutants between them were dramatically different, particularly $PM_{2.5}$ and NO_X; the taxi EFs were 10 times and 7 times those of the cars, respectively. EFs of the taxis were higher than the cars perhaps because of the high fuel consumption and large changes in speed among taxis, as well as the tighter control of tail gas and the better vehicle condition of cars compared to that of taxis. The continuous operation of taxis will result in greater losses, which will lead to high pollutant emissions and thus an increase in the EFs of the pollutants. Moreover, the proportion of cars exceeds 80%, which is much greater than that of taxis and may result in lower EFs than the actual values.



(a)



(b)

Figure 3: Diurnal variations in five pollutants at site 2 during the sampling period. (a) Diurnal variations in $PM_{2.5}$ (left axes) and NO_X and VOCs (right axes) for 11 days. (b) Diurnal variations in CO (left axes) and HC (right axes) for 11 days.

A comparison of the EFs among this study and other studies is shown in Table 4. The calculated EFs were the highest in the North Ring Road Tunnel in Xi'an [25], in which the CO, NO_X, and HC EFs were approximately 20, 25, and 30 times higher than those of the current study, respectively. This could be attributed to the model year 1996

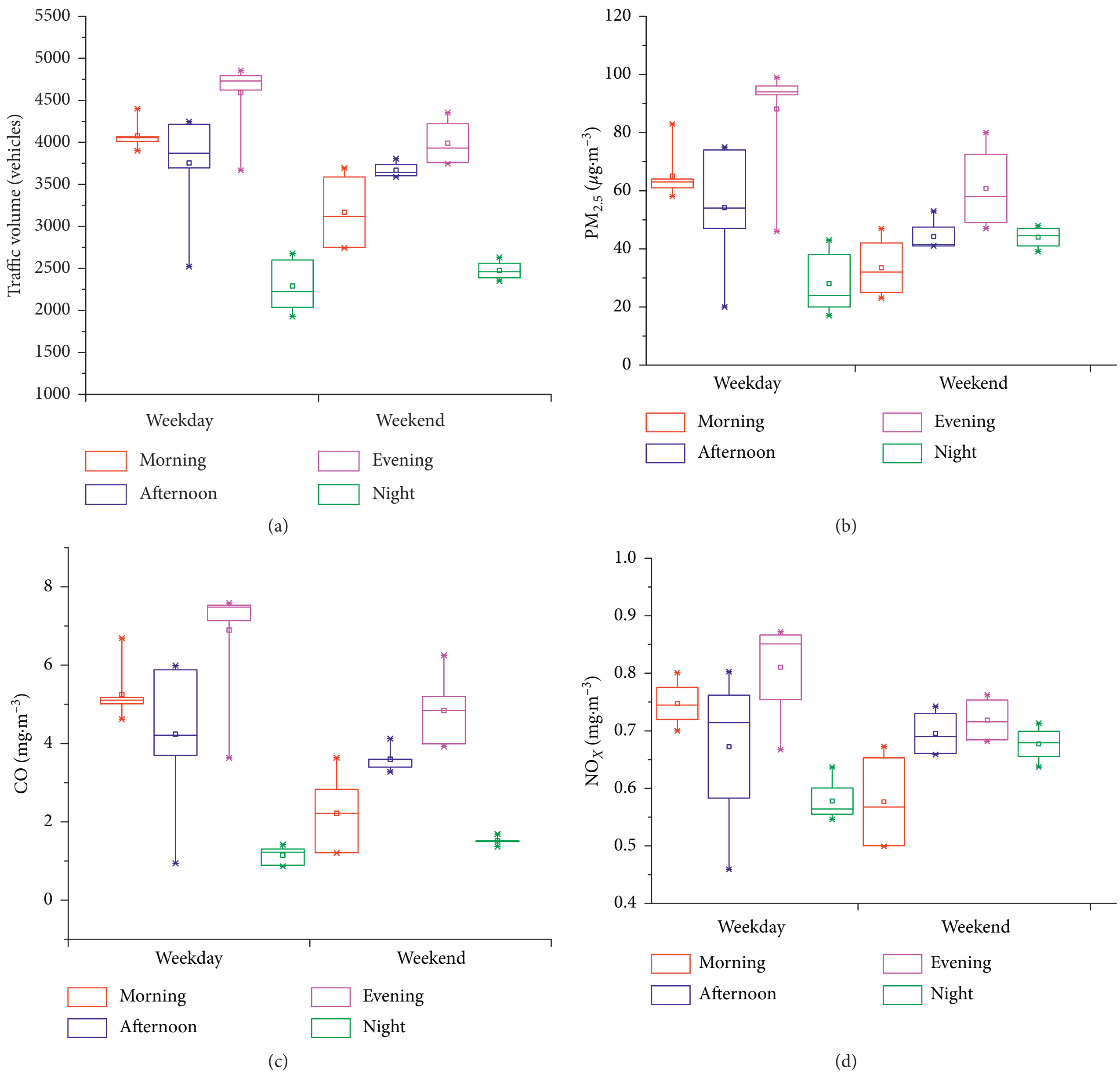
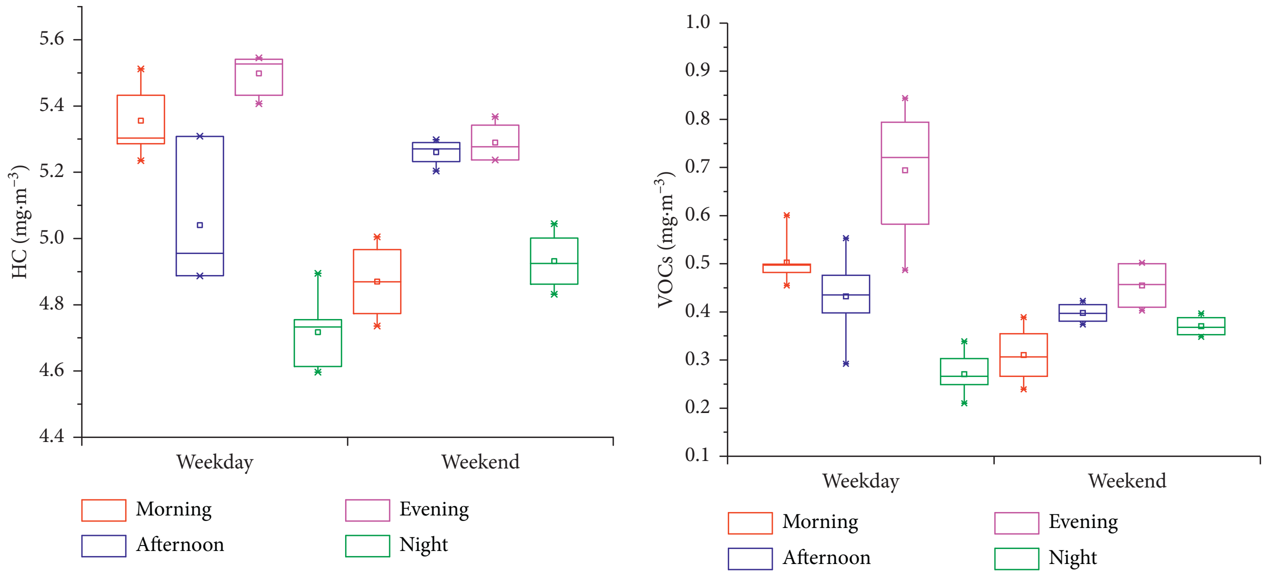


FIGURE 4: Continued.



(e) (f)

Figure 4: Weekday-weekend pattern of pollutant emissions. The comparison of weekday and weekend traffic volume (a), $PM_{2.5}$ (b), CO (c), NO_X (d), HC (e), and VOCs (f) during the four sampling periods.

Table 3: Average EFs ($g\cdot veh^{-1}\cdot km^{-1}$) during different sampling periods.

Species	Morning	Afternoon	Evening	Night	Range
$PM_{2.5}$	0.006 ± 0.004	0.005 ± 0.003	0.06 ± 0.004	0.011 ± 0.010	0.001~0.018
CO	1.042 ± 0.152	1.041 ± 0.472	1.260 ± 0.678	1.243 ± 0.197	0.586~2.271
NO_X	0.122 ± 0.078	0.137 ± 0.067	0.143 ± 0.070	0.236 ± 0.115	0.052~0.438
HC	0.153 ± 0.066	0.135 ± 0.030	0.213 ± 0.145	0.224 ± 0.101	0.073~0.379
VOCs	0.265 ± 0.077	0.199 ± 0.050	0.365 ± 0.092	0.607 ± 0.184	0.125~0.868

when the fleets included both passenger cars and GVs during the day as well as the quality of the fuels, which was poor, and the emission standards, which were low. With the strict requirements of today's emission standards and improvements in vehicle technology, emission conditions have significantly changed EFs of CO and HC in the Zhujiang Tunnel [34] which had a considerable decreasing trend from 1999 to 2004 of four-fifths [30]. Although the Clem Jones Tunnel in Australia [35] and the Yingpan Road Tunnel in Changsha [31] had lower EFs than most of the other studied tunnels, they were slightly higher than those of this study. NO_X and VOCs in the Shing Mun Tunnel [29] and Taipei Tunnel [36] were one-half of those in this study. For the type of vehicle, cars and taxi EFs in the Xianyue Mountain Tunnel [37] and Zhujiang Tunnel [38] were much higher because of terrain and gradient factors as well as old emission standards in China. In general, the EFs in the present study were lower than those of most other studies. It was found that the limitation of GVs is an effective policy in reducing vehicle emissions.

4. Conclusions

On-road traffic conditions, meteorological parameters, and emissions of $PM_{2.5}$, CO, NO_X, HC, and VOCs were measured in the Wenchang Gate-Peace Gate Tunnel in Xi'an from July 17 to July 27, 2015. The EFs of the different pollutants for the total fleet during distinct sampling periods were derived using the mass balance model. Moreover, linear regression analysis was adopted to calculate the EFs for the cars (80% of the total vehicles) and the taxis (16%). For mixed traffic, a weekday-weekend pattern in which the values during the weekdays were higher than those during weekends was found in the pollutant emissions. Similarly, the evening transit had higher emissions than during other times, which was observed in the diurnal variations. $PM_{2.5}$ emissions correlated well with NO_X, while HC emissions had a high correlation with CO. The EFs during the night were the highest because of the GVs, and the average EFs for the five pollutants in this study were lower than those of most of the other literature studies. This is probably the result of stricter emission standards and the new emission-reduced technology of vehicles. In addition, the EFs for the taxis were significantly higher than those of the cars, showing a reasonable agreement with other studies. This study not only presents the latest vehicle emission levels in Xi'an but also provides a sound reference for traffic pollutant assessments and policymaking for the government. Further study can focus on sampling more periods in which diesel trucks are allowed in the tunnel such that light-duty and heavy-duty emission factors can be determined, and one can consider the impact of trucks on the EFs of cars and taxis at night.

Table 4: A comparison of the EFs ($g \cdot veh^{-1} \cdot km^{-1}$) among this study and other studies.

Tunnel	City/Country	Test year	Average vehicle speed ($km \cdot h^{-1}$)	Vehicle type	$PM_{2.5}$	CO	NO_X	HC	VOCs	References
Clem Jones Tunnel	Brisbane, Australia	2014	80	Light-duty	0.015 ± 0.002	1.370 ± 0.079	0.519 ± 0.036			[35]
Zhujiang Tunnel	Guangzhou, China	2014	20–47	Total fleet		3.096 ± 0.680	1.286 ± 0.204	0.448 ± 0.038		[32]
Yingpan Road Tunnel	Changsha, China	2013	30	97.3% gasoline		0.745 ± 0.561~6.050 ± 5.940	0.121 ± 0.022~0.818 ± 0.755			[33]
Van Nuys Tunnel	Nuys, California	2010	42.4	97% gasoline		21.300 ± 3.700	3.000 ± 0.600	2.300 ± 0.300		[39]
Loma Larga Tunnel	Monterrey, Mexico	2009	42–76	97% gasoline	Uphill: 0.013 ± 0.006	11.800 ± 3.880	0.130 ± 0.100	1.540 ± 0.080		[29]
Xianyue Mountain Tunnel	Xiamen, China	2005	47.45	Car		14.200	2.210	0.670		[37]
				Taxi		19.700	4.150	0.960		
Shing Mun Tunnel	Hong Kong, China	2004	65	50% gasoline	0.131 ± 0.037	1.845 ± 0.434	0.878 ± 0.308	0.115 ± 0.030	0.115	[31, 40]
Taipei Tunnel	Taipei, Taiwan	2002		Total fleet		3.640 ± 0.260	0.900 ± 0.180	0.440 ± 0.060	0.240	[36]
Zhujiang Tunnel	Guangzhou, China	1999	49	Total fleet		15.400 ± 6.630	1.380 ± 0.480	1.860 ± 1.760	0.520 ± 0.070	[34, 38]
				Car		12.510	0.420	4.700		
				Taxi		16.640	2.000	0.540		
North Ring Road Tunnel	Xi'an, China	1996	42.2	66.7% gasoline		33.279 ± 12.158	4.061 ± 1.981	3.577 ± 1.820		[27]
Caldecott Tunnel	San Francisco, USA	1997		Light-duty	0.006					[41]
				Heavy-duty	0.430 ± 0.079					
Wenchang Gate-Peace Gate Tunnel (this study)	Xi'an, China	2015	33.18	Total fleet	0.006 ± 0.005	1.097 ± 0.398	0.159 ± 0.092	0.179 ± 0.089	0.317 ± 0.172	
				Car	0.004	1.085	0.078	0.123	0.060	
				Taxi	0.038	1.167	0.582	0.442	1.650	

Data Availability

The data in this study were tested and provided by the Xi'an Institute of Environmental Science, only for use by the collaborators, and they are not allowed to be disseminated to the public.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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