Hindawi
Advances in Civil Engineering
Volume 2020, Article ID 8843943, 18 pages
https://doi.org/10.1155/2020/8843943

Research Article

Investigation on the Time Factor of CO-Based Emission Factors for Sustainable Development of Urban Tunnels in China

Weiwei Liu, Jianxun Chen, Yanbin Luo, Zhou Shi, Yunfei Wu, Zilong Xu, and Fangfang Dong

School of Highway, Chang'an University, Xi'an 710064, Shaanxi, China

Correspondence should be addressed to Jianxun Chen; chenjx1969@chd.edu.cn and Yanbin Luo; lyb@chd.edu.cn

Received 30 May 2020; Revised 2 August 2020; Accepted 7 August 2020; Published 31 August 2020

Academic Editor: Xuzhen He

Environmental pollution problems and energy-saving issues of urban tunnels have increasingly been attracting people's attention. The paper aims at investigating a reasonable time factor for CO-based emission factors in the ventilation design of urban road tunnels. The study results show that the prediction curve of CO-based emission factor for passenger cars consists of two stages. The average reduction rates of Stage I (2004–2010) and Stage II (2010–2030) are 38% and 14% per year, respectively. The CO emission factor series of passenger cars conforms to exponential function distribution. The time factors of CO-based emission back-calculated from the measured data range from 4.9% to 12.6%, which are 2.4–6.3 times the specified value in the Chinese ventilation specification but slightly smaller than predicted ones. Based on four aspects of predicted results, back analysis results, related references, and engineering applications, it is indicated that the time factor of CO-based emission factor (2%) in the current ventilation specification is conservative. And when defining 2000 and 2010 as base years, respectively, 4% and 3% can be used as the time factors of CO-based emission factors respectively for the ventilation design of urban tunnels. This study can provide a reference for ventilation design of urban tunnels in other regions.

1. Introduction

With the rapid growth of urban tunnels in the process of urbanization in China, the sustainable development of urban tunnels has attracted extensive attention of the society [1–3]. The urban tunnel is like a chimney to collect automobile exhaust in the city, which seriously affects the living environment of the residents around the tunnel. Due to the increasing attention to the urban tunnel pollution and the increasingly stringent standards for the environment inside and around tunnels, the economic burden of the society on tunnel ventilation cost is also increasing year by year. In addition, the unreasonable design parameters directly lead to the over design of the ventilation system, the huge energy consumption, and economic loss, which seriously restrict the sustainable development of Chinese society [4]. Urban tunnel ventilation is a community of economy, society, and environment. Therefore, it is urgent and necessary to explore a sustainable development road suitable for urban tunnels.

Vehicle emissions are often considered as the single largest contributor to atmospheric pollutants, which poses a threat to both living environment and human health [5–7]. The incomplete combustion of motor vehicle fuel in the engine cylinder will produce many harmful components and be discharged into the ambient air with the exhaust gas. These harmful components mainly include CO, NO_x, VOCs, SO_2, HC, and PM. Among them, CO, NO_x, and PM are observed as the pollutants with the highest concentration and the greatest impact in urban road tunnels [8, 9]. CO is recognized as the most harmful pollutant to the human body and is taken as health criteria to ensure the health of drivers and passengers by diluting the CO below the health threshold in urban tunnels [10]; NO_x is easy to produce photochemical smog by chemical reaction, and the presence of particulate matters leads to reduced visibility inside the tunnel. Moreover, CO emissions mainly come from gasoline vehicles, and about 70% of NO_x emissions and more than 90% PM emissions are emitted by diesel vehicles. However,

passenger cars and light-duty vehicles, mainly powered by gasoline engines, account for the majority of the total fleet in urban traffic, and diesel vehicles account for only about 10% of the total vehicle population [11, 12]. Therefore, the present study mainly focuses on the emission factors for CO in urban tunnels.

CO is often employed as the environmental health control index for mechanical ventilation in tunnels [10, 13]. CO concentration plays an important role to determine the fresh air demand in tunnel ventilation design [14]. An increasing body of evidence reveals that the CO concentration level in urban tunnels was considerably lower than the design threshold [11, 15–23]. However, the expected reduction in the ventilation system scale was not observed with the decrease of the CO emission level, which directly led to the great waste of energy and the overdesign of the tunnel ventilation system. A scientific and reasonable time factor (also named the annual reduction factor in China) for CO-based emission could effectively minimize overdesign of tunnel ventilation system and promote energy saving from the design source. The time factor is a key parameter to determine the base emission factors for automobile exhaust pollutants in future years. Whether the time factor is appropriate or not will directly affect the precalculation accuracy of pollutant emissions for future years and further affect the scale of the ventilation system, the operation safety, and the operation cost.

Urban road tunnels have no special ventilation specification available for reference; the ventilation design parameters and standards of urban tunnels are mainly guided by the Chinese guidelines for design of ventilation of highway tunnels in mountain areas [10]. For example, the current specification for ventilation design of highway tunnels provides that the base emission factors of main pollutants should reduce by 2% annually in China. However, an urban tunnel possesses different features in the aspects of large traffic flow, considerable proportion of light-duty vehicles, low vehicle speed, and rapid renewal of vehicles from general highway tunnels. Additionally, with the rapid progress of automobile industry, the increasingly stringent national regulations on automobile emissions, the continuous improvement of fuel quality, and the extensive application of new-energy green automobiles in China, the CO-based emission factor of automobiles has been decreasing year by year. Therefore, whether it is reasonable to take 2% referring to the current ventilation specification of highway tunnels as a time factor of CO-based emission factors for urban road tunnels is worth further studying.

There are differences between China and developed countries in terms of the base emission factor and the time factor. In PIARC, the base emission factor of a certain pollutant in automobile exhausted gas varies with vehicle type, fuel type, average vehicle speed, and road gradient [24], which quantifies the vehicle specific tailpipe emission and describes the level of motor vehicle emissions for a base year. In the current ventilation specification for highway tunnels in China, the base emission factor is defined as the specific tailpipe emission of a certain pollutant for an "average" passenger car that travels 1 km at a speed of 60 km/h on a road with 0% gradient in a specific base year [10]. Furthermore, the emissions for future years can be calculated by changeable time factors and base emission factors in PIARC; however, it can be calculated by the fixed time factor, also known as the annual reduction factor, and the base emission factor in China.

Ample research studies have been conducted on the time influencing factor of pollutants' base emission factors. The CO-based emission recommended by PIARC decreased by 44% between 1975 and 1987, with an average reduction of 4.7% per year. In 1987, PIARC estimated that the CO-based emission would drop by 50%–70% between 1987 and 2000 [25, 26]. Under the condition of 60 km/h and 0 gradient, the CO-based emission given by PIARC decreased by 85% from 68.2 g/h in 2010 to 18.2 g/h in 2018, with an average annual reduction of 15%. And PIARC recommended that, with 2010 and 2018 as the base years, the time factor of CO-based emission factor was 4.5% and 2.8% by 2030, respectively [13, 24]. The CO-based emission in Switzerland dropped sharply from 1.2 m^3/(h·pcu) in 1950 to 0.46 m^3/(h·pcu) in 1987, with an average annual reduction factor of 2.6%. The CO-based emission in Japan fell by 78% in the 20 years from 1960s to 1980s [27]. In China, abundant research studies in recent years have focused on vehicle emission factors and emission inventories of air pollutants [11, 28–31]. Wang et al. [32] pointed out that the CO-based emission for base year 1995, 0.01 m^3/(km·veh), specified in the previous specifications for design of ventilation and lighting of highway tunnel was a little bit higher through bench tests and road tests. Based on the analysis of automobile emission limits of EU standards, Guo et al. [33] found that the annual reduction factor of pollutant gases, between 1% and 2%, was on the conservative side. Liao and Guo [34] noted that the CO-based emission reduction factors of diesel and gasoline fuelled vehicles in three different periods of 2000–2015, 2000–2020, and 2000–2025 were 5.44% and 4.22%, 4.08% and 3.16%, and 3.26% and 2.53%, respectively, on the basis of the service life of cars and the implementation process of automobile emission standards. Based on the field measurement, a two-year on-road remote sensing measurement, conducted between 2014 and 2016 in Hong Kong, indicated that CO, HC, and NO showed an unexpected increasing trend during 1998–2004, and they all decreased steadily in the past decade (2005–2015), except for NO of >6001 cc vehicles during 2013–2015 [7]. Based on the prediction and analysis of vehicle pollutant emissions in a typical middle-sized city and two megacities in China, Sun et al. [9] found that, from 2011 to 2017, the total vehicle emissions in Langfang decreased for CO, but increased for VOCs, NO_x, and PM10, respectively. From 2018 to 2025, the emissions would increase more rapidly in Langfang than in Beijing and Tianjin, indicating the middle-sized cities might become a significant contributor to air pollution in China. Luo et al. [14] recommended 8% as the annual reduction factor of CO baseline emission for ventilation design of urban tunnels in Shenzhen. The reduction factors obtained from the above research results depending on the measured data or earlier studies actually reflected the past changes and were not completely identical to that of future year. And some studies

based on automobile emission regulations could not fully represent the actual vehicle emission reduction under road driving condition. Furthermore, some papers have presented that CO-based emission reduction factors of diesel- and gasoline-fuelled vehicles are separate, which may result in difficulty in parameter selection during tunnel ventilation design. Therefore, it is feasible to estimate the CO-based emission of motor vehicles by predicting CO emission factors in the future and provide a basis for choosing the annual reduction factor of CO-based emission.

A good many motor vehicle emission models have been developed by western developed countries, especially in the United States and Europe, such as MOBILE, COPERT, and IVE models in developed countries [23, 35–39]. Western developed countries have accumulated a substantial number of data and established a complete database. Therefore, the method is usually employed to calculate or make a short-term prediction on vehicle emission factors. In the late 1990s, the above vehicle emission models were successively introduced into China. However, as a result of late start-up, no complete database was established. And due to regional disparities, automotive technology gaps, and emission standard differences, the portability of models and the availability of parameters in China are poor [28, 40, 41]. Therefore, the vehicle emission models should not be used to predict the CO emission factors of motor vehicles in China in the coming decades. And most of all, the grey-forecasting model is a suitable and useful tool for prediction in view of the grey characteristics of poor data and information on CO-based emission factors from motor vehicles in China [42–44]. This paper can provide a reference for the ventilation design of urban tunnels in other regions and contribute to the energy conservation and sustainable development of Chinese cities.

2. Materials and Methods

2.1. Prediction Method. Grey prediction is one of the main methods of grey system theory that is a new approach for studying small samples, poor information, and uncertain systems [45]. Grey prediction, through the processing of original data and the establishment of grey model, discovers and masters the laws of system developments and makes a scientific quantitative prediction for the future states of systems [46]. The GM (1, 1) model has an advantage of making full use of "little data" to predict. And the metabolic GM (1, 1) model is an optimal form of the GM (1, 1) model. As new information is constantly added to the model, the metabolic GM (1, 1) model would eliminate the aging data. The updated sequence can better reflect the features of the current system and better reveal the trends of the system. The metabolic model can usually obtain higher prediction accuracy.

Grey system is a differential equation created by discrete series, among which GM (1, 1) is a first order differential equation model. And the prediction model can be obtained by solving the first order differential equation [46], which can be expressed by

$$\hat{x}^{(1)}(k+1) = \left(x^{(0)}(1) - \frac{b}{a}\right)e^{-ak} + \frac{b}{a}, \quad k = 1, 2, \ldots, n, \tag{1}$$

where $x^{(0)}(k)$ is the value from original sequence; $\hat{x}^{(1)}(k+1)$ is the predicted value of the primary accumulating sequence; a is the development coefficient; and b is the grey action factor.

Predicted value can be obtained by

$$\hat{x}^{(0)}(k+1) = \hat{x}^{(1)}(k+1) - \hat{x}^{(1)}(k) = \left(1 - e^{a}\right)\left(x^{(0)}(1) - \frac{b}{a}\right)e^{-ak}, \tag{2}$$

where $\hat{x}^{(0)}(k+1)$ is the restored value of the model.

2.2. Model Checking. GM (1, 1) model needs to be checked from three aspects: residual test, correlation degree test, and posterior-variance test.

2.2.1. Residual Test. Residual test method is used to check the residual error between the predicted value and the actual value point by point. Absolute residual can be obtained by

$$\varepsilon^{(0)}(i) = \left|x^{(0)}(i) - \hat{x}^{(0)}(i)\right|, \quad i = 1, 2, \ldots, n. \tag{3}$$

And relative residual and average relative residual can be obtained using equations (4) and (5), respectively:

$$\Delta_i = \left|\frac{\varepsilon^{(0)}(i)}{x^{(0)}(i)}\right|\%, \quad i = 1, 2, \ldots, n, \tag{4}$$

$$\overline{\Delta} = \frac{1}{n}\sum_{i=1}^{n}\Delta_i, \quad i = 1, 2, \ldots, n. \tag{5}$$

For given constant α, only when both the average relative residual and the last relative residual are less than α, the model is described as a qualified residual model.

2.2.2. Correlation Degree Test. Correlation degree test method is used to check the similarity level between the predicted curve and the original curve. And the correlation degree test is usually expressed by grey absolute correlation degree, which is obtained by

$$\zeta = \frac{1 + |S| + |\hat{S}|}{1 + |S| + |\hat{S}| + |\hat{S} - S|}, \tag{6}$$

where $|S|, |\hat{S}|, |\hat{S} - S|$ can be calculated by using equations (7)–(9), respectively:

$$|S| = \left|\sum_{k=2}^{n-1}\left(x^{(0)}(k) - x^{(0)}(1)\right) + \frac{1}{2}\left(x^{(0)}(n) - x^{(0)}(1)\right)\right|, \tag{7}$$

$$|\widehat{S}| = \left|\sum_{k=2}^{n-1}\left(\widehat{x}^{(0)}(k) - \widehat{x}^{(0)}(1)\right) + \frac{1}{2}\left(\widehat{x}^{(0)}(n) - \widehat{x}^{(0)}(1)\right)\right|, \tag{8}$$

$$|\widehat{S} - S| = \left|\sum_{K=2}^{n-1}\left[\left(x^{(0)}(k) - x^{(0)}(1)\right) - \left(\widehat{x}^{(0)}(k) - \widehat{x}^{(0)}(1)\right)\right] + \frac{1}{2}\left[\left(x^{(0)}(n) - x^{(0)}(1)\right) - \left(\widehat{x}^{(0)}(n) - \widehat{x}^{(0)}(1)\right)\right]\right|. \tag{9}$$

For given constant ζ_0 that is greater than 0, when the grey absolute correlation degree is higher than ζ_0, the model is described as a qualified-correlation degree model.

2.2.3. Posterior-Variance Test. The posterior-variance test is used to check the statistical characteristics of residual distribution. The mean square ratio and the small residual probability can be calculated by using equations (10) and (11) below, respectively:

$$C = \frac{S_2}{S_1}, \tag{10}$$

$$P = P\left\{\left|\varepsilon^{(0)}(i) - \overline{\varepsilon}\right| < 0.6745S_1\right\}, \tag{11}$$

where S_1 is the mean square deviation of original sequence and S_2 is the mean square deviation of residual sequence.

For given constant C_0 that is greater than 0, when the posterior error ratio is less than ζ_0, the model is called as a qualified-mean square error model. And for given constant P_0 that is greater than 0, when the small error probability is higher than P_0, the model is called as a qualified small error probability model.

If the accuracies of the above three tests are all within the admissible ranges, the model can be used to predict. Otherwise, the residual correction should be carried out. And the reference levels of accuracy check for the GM (1, 1) model are listed in Table 1.

2.3. Back Analysis Method. The current ventilation specification gives two formulas for calculating CO emissions and air volume flow required for CO dilution in the whole tunnel, respectively. On the basis of these two formulas, CO-based emission and its reduction factor can be backcalculated by measured data and tunnel parameters. The calculation methods and procedures are detailed as follows.

The CO-based emission for design year is determined by

$$q_{\mathrm{CO}} = \frac{3.6 \cdot Q_{\mathrm{sup}} \cdot \delta_{\mathrm{CO}} \cdot P \cdot T_0}{P_0 \cdot T \cdot f_{\mathrm{a}} \cdot f_{\mathrm{d}} \cdot f_{\mathrm{h}} \cdot f_{\mathrm{iv}} \cdot L \cdot \sum_{m=1}^{n}\left(N_m \cdot f_m\right)}, \tag{12}$$

where q_{co} is the CO-based emission for design year in $\mathrm{m}^3/(\mathrm{km{\cdot}veh})$; Q_{sup} is the actual air volume flow in tunnel in m^3/s; δ_{CO} is the measured concentration of CO in ppm; P is the design atmospheric pressure in $\mathrm{kN/m}^2$; P_0 is the standard atmospheric pressure in $\mathrm{kN/m}^2$; T is the design temperature in summer in K; T_0 is the standard temperature in K; f_{a} is the road condition factor; f_{d} is the vehicle density factor; f_{h} is the altitude factor; f_{iv} is the velocity factors with different slopes; L is the length of tunnel in m; N_{m} is the number of vehicles for each type in tunnel; f_{m} is the vehicle type factor; and n is the number of vehicle types.

Then, the CO-based emission for the design year can be derived from the CO-based emission of the starting year, which can be expressed by

$$q_{\mathrm{CO}} = q_{\mathrm{CO}}^0 (1 - w)^a, \tag{13}$$

where q_{CO}^0 is the CO-based emission for base year in $\mathrm{m}^3/(\mathrm{km{\cdot}veh})$; w is the annual reduction factor in %; and a is the design service life in year.

When taking 2% as annual reduction factor in accordance with spec, CO-based emission of starting year can be obtained from equations (12) and (13), which can be described by

$$q_{\mathrm{CO}}^0 = \frac{3.6 \cdot Q_{\mathrm{sup}} \cdot \delta_{\mathrm{CO}} \cdot P \cdot T_0}{P_0 \cdot T \cdot f_{\mathrm{a}} \cdot f_{\mathrm{d}} \cdot f_{\mathrm{h}} \cdot f_{\mathrm{iv}} \cdot L \cdot (1 - 2\%)^a \cdot \sum_{m=1}^{n}\left(N_m \cdot f_m\right)}. \tag{14}$$

When taking 2000 as a base year and taking $0.007\,\mathrm{m}^3/(\mathrm{km{\cdot}veh})$ as CO-based emission based on current *spec*, the annual reduction factor can be calculated:

$$w = 1 - \left(\frac{3.6 \cdot Q_{\mathrm{sup}} \cdot \delta_{\mathrm{CO}} \cdot P \cdot T_0}{0.007 \cdot P_0 \cdot T \cdot f_{\mathrm{a}} \cdot f_{\mathrm{d}} \cdot f_{\mathrm{h}} \cdot f_{\mathrm{iv}} \cdot L \cdot \sum_{m=1}^{n}\left(N_m \cdot f_m\right)}\right)^{1/a}. \tag{15}$$

3. Grey Prediction of CO-Based Emission Factors

3.1. Establishment of Base GM (1, 1) Model. Through extensive literature research for collecting basic data, it was found that limited research results had been reported at this point concerning CO emission factor for mixed traffic in China, and the time series were incomplete and discontinuous, which was not suitable as the original data sequence for prediction. Therefore, the CO emission factors of passenger cars were employed instead. In order to avoid the influence of regional development imbalance and ensure the universality of the case study, the case data was collected from four regions with different degrees of economic development in China, as shown in Figure 1. Passenger cars account for an absolute proportion of motor vehicles in cities, which are between 60% and 90%.

Table 1: The accuracy check level of GM (1: 1) model.

Grades	Grey absolute correlation degree ζ	Relative residual error Δ	Mean square error ratio C	Small probability error P
Level I	0.90	0.01	$C \leq 0.35$	$P \geq 0.95$
Level II	0.80	0.05	$0.35 < C \leq 0.5$	$0.8 < P \leq 0.95$
Level III	0.70	0.10	$0.5 < C \leq 0.65$	$0.7 < P \leq 0.8$
Level IV	0.60	0.20	$C \geq 0.65$	$P < 0.7$

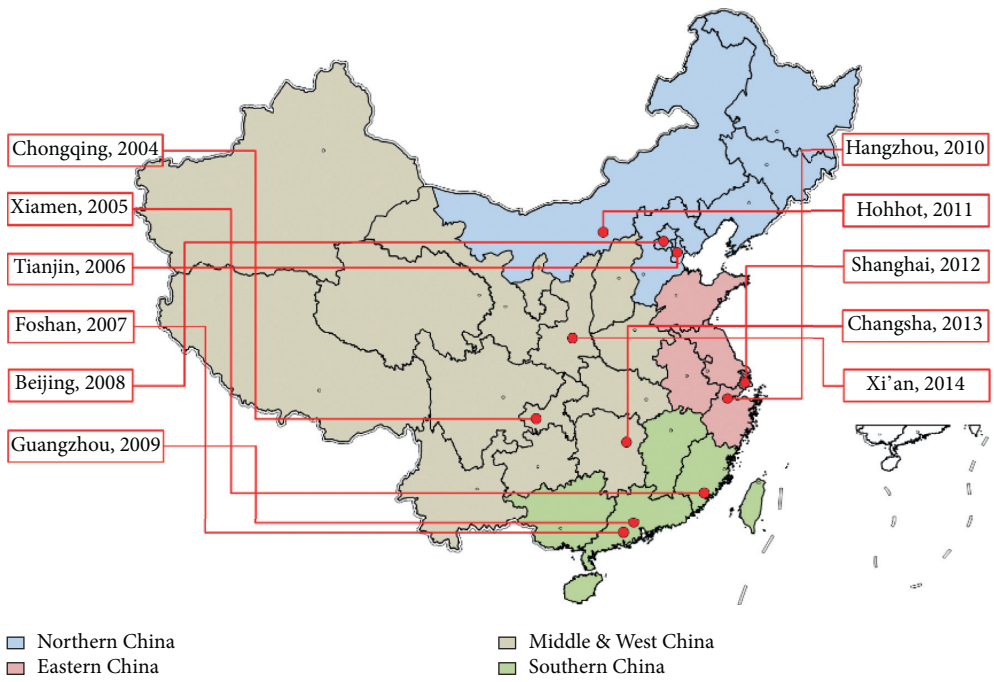


Figure 1: The collected cases of CO emission factors for GM (1, 1) model.

Table 2: The CO emission factors of passenger cars (g/(km·veh)).

Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Source	Chongqing road condition	Xiamen road condition	Tianjin road test	Foshan road condition	Beijing road condition	Guangzhou road condition	Hangzhou road condition	Hohhot road condition	East Yan'an road tunnel test	Changsha Yingpan road tunnel test	Xi'an road condition
EF_{CO}	31.93	19.6	13.67	9.82	5.528	3.26	1.80	1.75	2.51	1.72	1.04
Reference	[49]	[50]	[51]	[52]	[53]	[54]	[55]	[56]	[57]	[58]	[59]

And the passenger car is a main vehicle type for CO pollutant source not only in tunnels but also in urban areas, the emission contribution of which is within 60% to 90% [29, 47, 48]. Thus, it is feasible to adopt the CO emission factors of passenger cars as the original prediction sequence. The CO emission factors of passenger cars in different years are listed in Table 2.

In order to improve the accuracy of the GM (1, 1) model, the data scope should not be too big when choosing the original prediction sequence, and it would be better to be five or six dimensions [60]. The last CO emission factors of passenger cars from 2009 to 2014 were chosen to constitute the prediction sequence. And the time series are shown as follows:

$$X^{(0)} = (3.26, 1.80, 1.75, 2.51, 1.72, 1.04). \quad (16)$$

The prediction model can be obtained by least square estimation:

Table 3: The prediction and accuracy check results of passenger cars during 2015~2030 in China.

Year	EF_{CO} g/(km·veh)	Mean relative_residual error Δ	Absolute correlation degree ζ	Mean square errors ration C	Small probability error P	Accuracy grade
2015	0.93	0.0311	0.9990	0.0544	1	II
2016	0.75	0.0197	0.9985	0.0530	1	II
2017	0.66	0.0165	0.9978	0.0383	1	II
2018	0.57	0.0147	0.9987	0.0471	1	II
2019	0.49	0.0140	0.9995	0.0510	1	II
2020	0.41	0.0147	0.9992	0.0492	1	II
2021	0.36	0.0103	0.9982	0.0234	1	II
2022	0.31	0.0073	0.9996	0.0209	1	II
2023	0.26	0.0074	0.9992	0.0203	1	I
2024	0.23	0.0069	0.9989	0.0196	1	I
2025	0.19	0.0066	0.9991	0.0239	1	I
2026	0.17	0.0048	0.9995	0.0120	1	I
2027	0.14	0.0039	0.9991	0.0077	1	I
2028	0.12	0.0035	0.9993	0.0103	1	I
2029	0.10	0.0028	0.9995	0.0108	1	I
2030	0.09	0.0031	0.9995	0.0104	1	I

$$\hat{x}^{(1)}(k+1) = -14.2363e^{-0.14142617k} + 17.4963. \quad (17)$$

The error test results of the prediction model are listed in Table 3.

Compared with the accuracy check level of the GM (1, 1) model, the prediction model has level II qualified accuracy. Therefore, a medium-long term forecast on the developing trends of CO emission factors for passenger cars can be achieved by the model in China. And in 2015, the CO emission factor of passenger cars in China can be obtained by using equation (2), whose calculation result is 0.9257 g/(km·veh).

3.2. Establishment of Metabolic GM (1, 1) Model Groups. The prediction result showed that the CO emission factor of passenger cars in 2015 would drop to 0.9257 g/(km·veh) in China by using 6 dimensions GM (1, 1) model. The modeling data can be maintained in the same dimensions by adding new data to the original sequence and removing the old data of 2009 from the original sequence. And the first renewal of metabolic modeling data is expressed:

$$X_1^{(0)} = (1.80, 1.75, 2.51, 1.72, 1.04, 0.93). \quad (18)$$

The first renewal of the metabolic model can be obtained by using the same method, as in Section 3.1:

$$\hat{x}_1^{(1)}(k+1) == -11.2529e^{-0.16558304k} + 13.0529. \quad (19)$$

The error test results of the updated model are listed in Table 3.

According to the accuracy check level of the GM (1, 1) model, the first renewal metabolic model has level II qualified accuracy, which indicates that the updated model can be used for prediction. And in 2016, the CO emission factor of passenger cars in China will reduce to 0.7503 g/(km·veh). Original data series are updated by replacing the oldest data (in 2010) with the new data and then second metabolic projection is conducted. In the same way, the predicted values of CO emission factor for passenger cars before 2030, including 2030, will be obtained in turn, progressively.

3.3. Prediction Results and Analysis. The CO emission factors for passenger cars from 2015 to 2030 were obtained in turn after 16 metabolic prediction. And the predicted results are listed in Table 3.

As can be seen from Table 3, the predicted sequence meets the requirements of residual error test, correlation degree test, and posterior variance test. The prediction accuracies reach Level I and Level II precision. The metabolic prediction model group is available and shows good forecast effect. The CO emission factors of passenger cars declined gradually from 2015 to 2030, arriving at 0.09 g/(km·veh) in 2030. The relative residual, mean relative residual, mean square ratio, and small residual probability overall showed a reducing trend over the past 15 years. Under the influence of newly updated rounded CO emission factors, absolute correlation degrees fluctuated slightly, all above 0.99. Meanwhile, with continuous updating of forecast sequence, the prediction accuracy of CO emission factors raised up to Level I. With the rapid development of automobile engine and exhausted control technology, the continuous improvement of fuel quality, and the implement of growingly stringent standards, the CO emission factor has been effectively controlled, reducing to a low level. The space for further reduction of CO emission factors is becoming smaller and smaller. On the contrary, the difficulty for further improving vehicle emission level is increasing, resulting in a slower pace of decline in CO emission factors. At present, China has implemented the latest emission regulation (China VIa) in July 2020 and plans to implement the second phase emission regulation (China VIb) of China VI in July 2023. The CO emission limit of light-duty vehicles has been controlled to 0.7 g/km in the current emission

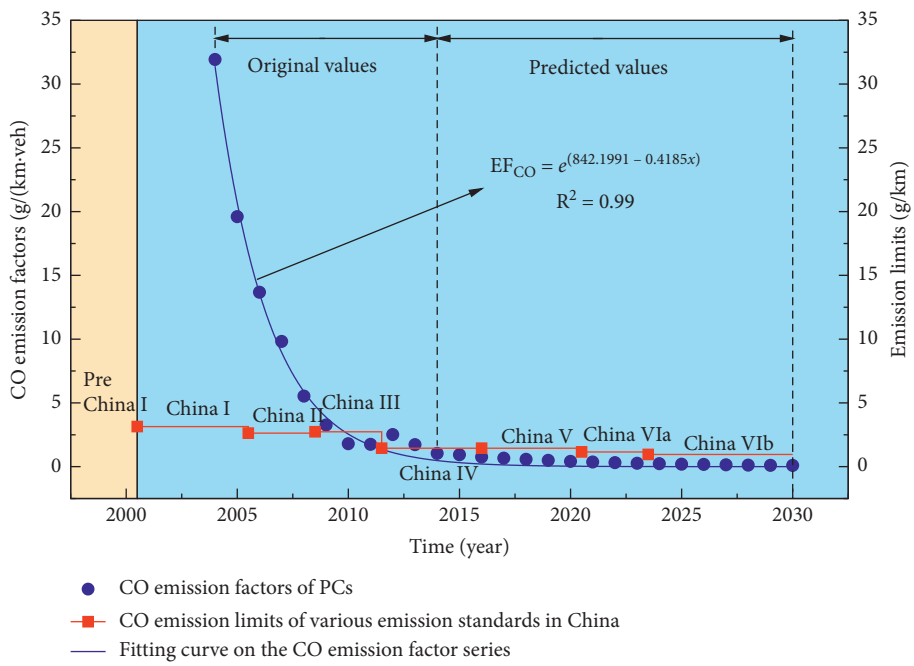


Figure 2: The developing changes of CO emission factors for passenger cars.

regulation of China VIa, which has reached a more stringent level. Compared with "China I" and "China V," it decreases by 74% and 30%, respectively. Due to the gradual narrowing of the space for reduction, the reduction range of CO emission limit is bound to be smaller and smaller, and it is bound to be more difficult to upgrade automobile engine and exhaust gas post-treatment technology. The type and composition of fuel may have an increasingly significant impact on CO emission limits in the coming years. Of course, it is worth mentioning that other pollutants emitted by motor vehicles are not necessarily similar to CO. For example, there is no change for CO emission limits of light-duty vehicles for China IV and China V, while the NO_x, HC, and PM mainly emitted by diesel-fuelled vehicles have been continuously tightened.

The CO emission factors for passenger cars in different periods and the CO emission factors for in-use passenger cars under different emission standards are shown in Figure 2.

As illustrated by Figure 2, the CO emission factor of the passenger car has been decreasing year by year. The descent process is divided into two stages with 2010 as the turning point. The first stage spanned from Pre-China I to 2010 in the implementation phase of China III standard for vehicle exhaust emissions. The CO emission factor of the passenger car was reduced by 94.36% during the six-year period from 2004 to 2010, with an average annual decrease of 38%, which demonstrated a significantly decreasing tendency. Emission standards, from Pre-China I to China III, have greatly promoted the development of automobile industry in China. A large number of new technologies and equipment have been continuously put into automobile manufacture, such as three-way catalyst (TWC) can significantly reduce CO, HC, and NO_X emissions from gasoline-fuelled vehicles by more than 95% [61]. At the same time, the improvements of fuel quality and the phase-out of "yellow label cars" (heavy-polluting vehicles) have significantly reduced the vehicle emissions for CO. All of these aspects make the CO emission factor of passenger cars under powerful control. The second stage was the implementation period of China III and more stringent emission standards for vehicle exhaust emission after 2010, and the descending rate of CO emission factor slowed down. From 2010 to 2030, the CO emission factor decreased by 95%, with an average annual decrease of 14%. After the implementation of China III standard, the number of vehicle meeting China I and higher emission standards accounts for the vast majority of urban vehicles. The high-emitting vehicles for Pre-China I are being phased out in China, the proportion of which in total in-use fleet has fallen to a relatively low level. Ministry of Environmental Protection of the People's Republic of China [62], on the basis of full research on the vehicle population throughout the country, indicated that the number of vehicles for Pre-China I reduced to 5 million 454 thousand in 2014, accounting for 3.8% of national vehicle number. With the deepening of environmental awareness and sustainable development, vehicle emission standards become increasingly stringent, the vehicle proportion of high emission standards has been gradually increasing, and the CO emission factor has been decreasing year by year. However, because China IV standard and higher emission standards have been tightened less than previous standards in terms of CO emission limits for vehicles, the tightening speed turned to slow down since the implementation of China IV standard. In all, the CO emission factors decreased by 99.72% during the period of 2004~2030, and the average annual reduction rate was about 20%. The result is similar to the annual reduction rate (10%) of major automobile pollutants and far higher than the

recommended value (2%) in the current ventilation specification for highway tunnels, which objectively reflects the actual change characteristics and trends of CO emission factors in the past decades and the following years [14].

In addition, nonlinear curve fitting on the CO emission factor sequence of passenger cars has been conducted through OriginLab (Figure 2). Fitting curve conforms to exponential function distribution and the fitting function follows:

$$\mathrm{EF}_{\mathrm{CO}} = e^{(842.1991-0.4185x)}, \tag{20}$$

where x is the future design year differing from the base year. There is great fitting degree between the fitting function and the measured data, and the correlation coefficient reached 0.99. The fitting result indicates that CO emission factors of passenger cars are strongly correlated to the implementation schedule of emission standards and basically decrease in accordance with the exponential function.

On the basis of considering many constraints on automobile engine design and manufacturing technologies and significant regional gaps in vehicle working condition and maintenance condition, the current ventilation specification conservatively adopts 2% as the annual reduction factor of CO-based emission to ensure the reliability of the ventilation system in the case of the annual reduction factor of automobile major pollutants exceeding 10%; therefore, it means that ventilation facilities equipped for more than 8% of the reduction factor are used to serve as a safety reserve. The reliability of the ventilation system can be expressed by safety factor K, and the coefficient K can be defined as follows:

$$K = \left(1 - \frac{w_{\mathrm{d}}}{w_{\mathrm{a}}}\right) \times 100\%. \tag{21}$$

When $0 \le K < 1$, the ventilation system is reliable; when $K < 0$, the ventilation is unreliable. So, the safety factor of the ventilation system specified in the *"Guidelines for Design of Ventilation of Highway Tunnels"* is as follows:

$$K = \left(1 - \frac{w_{\mathrm{d}}}{w_{\mathrm{a}}}\right) \times 100\% = \left(1 - \frac{2\%}{10\%}\right) \times 100\% = 80\%. \tag{22}$$

Using the same safety factor as in the current specification by the analogy method, the revised value of the annual reduction factor can be obtained. Since the reduction process of automobile CO emission factors mainly consists of two distinct stages, therefore, when the CO-based emission takes 2000 as base year, the CO reduction factor for ventilation design in urban road tunnels is as follows:

$$20.2 \times (1 - 80\%) = 4.04\% \approx 4\%. \tag{23}$$

When taking 2010 as a base year, the CO reduction factor for the ventilation design in urban road tunnels is as follows:

$$13.9\% \times (1 - 80\%) = 2.8\% \approx 3\%. \tag{24}$$

4. Comparison with Field Measurements

4.1. Tunnel Description. There are many differences between urban tunnels and highway tunnels, especially in the aspect of traffic fleet. Gasoline-fuelled cars occupy a major part of urban traffic flows, and CO emitted by vehicles is a significant pollutant in urban tunnels. Therefore, in order to evaluate the operational environment and collect data on the traffic flow, traffic speed, air velocity, and CO concentration in the tunnel, detailed filed measurements were carried out in four typical urban tunnels with different with different positions, roles, and functions in Shenzhen, including Henglong Mountain Tunnel, Cejiexian Subway, Jiuweiling Tunnel, and Dameisha Tunnel (see Figure 3). The basic information of the four tunnels is summarized in Table 4. Each tunnel consists of two unidirectional bores, each bore has three lanes, and the northbound and southbound bores of Henglong Mountain Tunnel contain two exists and two entrances, respectively.

4.2. Measurement Schemes. The field measurement in the urban tunnels mainly consists of traffic flow, vehicle speed, air velocity, and CO concentration. The traffic flow and vehicle speed were continuously measured by photographic counting equipment. The air velocity was continuously monitored all day by using portable anemometer with sensitivity of 0.1 m/s and 3 min time resolution. The CO concentration was taken by the portable concentration detector with 1 ppm resolution and 3 min acquisition time. And both of air velocity and CO concentration were synchronously recorded every 3 minutes. All instruments were calibrated by professional institution prior to usage.

Sampling points of measured items are shown in Figure 4. Traffic flow and vehicle speed sampling points were set either side of the tunnel entrance or exit. However, for Henglong Mountain Tunnel, the meter was set at the south end of the tunnel without ramps. Air velocity sampling points were arranged along vehicle moving direction with 9 or 10 points in each bore. CO concentration sampling points were organized along the tunnel at equal intervals with 4 or 5 points in each bore at the beginning of measurement. However, the field monitoring results show that the CO concentration near tunnel entrance was essentially zero, so the CO concentration sampling points were adjusted to the position near tunnel exit. The air velocity and CO concentration sampling points were at the same location in longitudinal direction along the tunnel, and monitoring was performed 1.5 m above the cable trench.

4.3. Field Measurement Results and Analysis

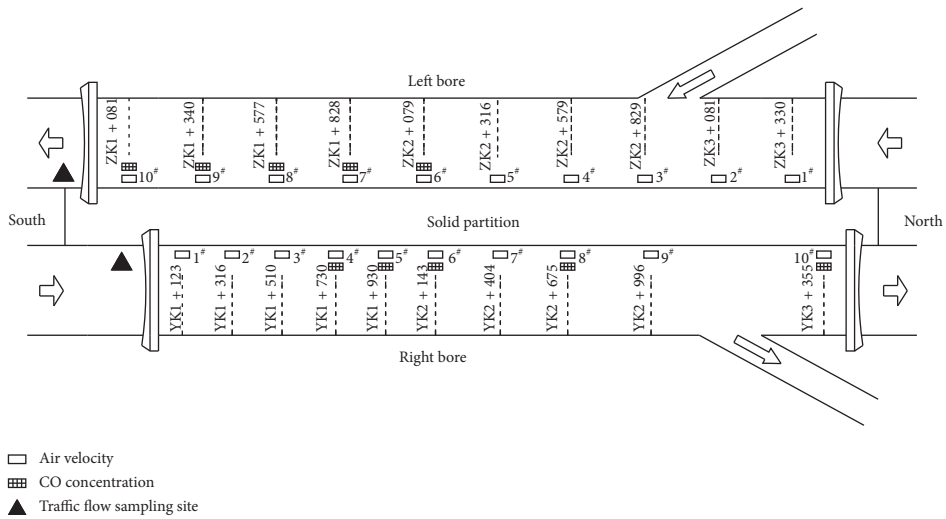
4.3.1. Traffic Characteristics. The traffic characteristics of the urban tunnel are mainly reflected in four aspects of traffic volume, traffic composition, the ratio of gasoline- and diesel-fuelled cars, and vehicle speed. Figure 5 illustrates the collected data on traffic volume and vehicle speed based on continuous investigation of the four urban tunnels in Shenzhen.

As shown in Figure 5, the average daily traffic volume of Henglong Mountain Tunnel exceeded designed value by more than 0.5 times, even nearly 1 times. During the Mid-Autumn Festival, the average daily traffic volume of

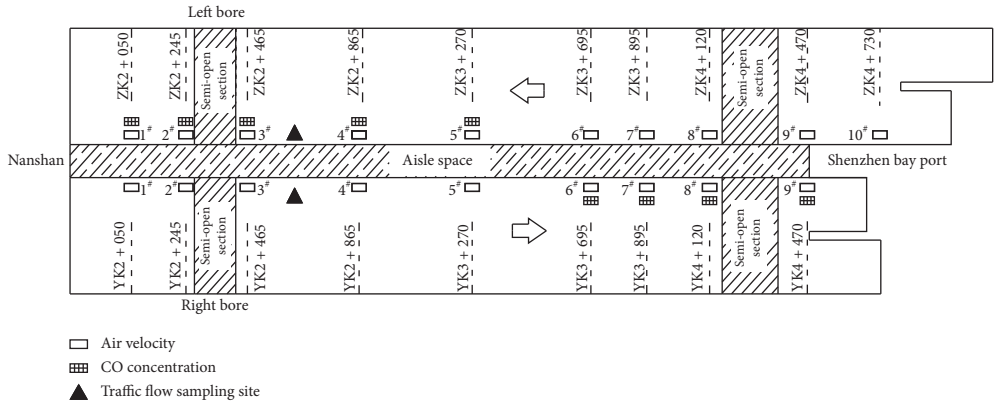
Figure 3: The study area and case tunnel locations.

Table 4: The general parameters of the four tunnels.

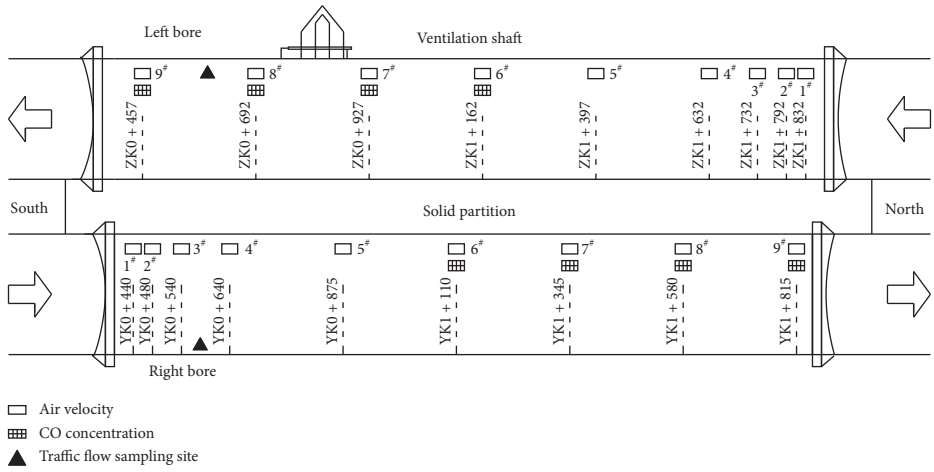
Tunnel		Road grade	Length (m)	Design speed (km/h)	Cross-sectional area (m^2)	Ventilation system
Henglong Mountain Tunnel	Left bore	Expressway (bidirectional six lanes)	2330	60	102.91	12 jet fans (main tunnel) 3 jet fans (ramp)
	Right bore		2275			12 jet fans (main tunnel) 3 jet fans (ramp)
Cejiexian Subway	Left bore	Highway (bidirectional six lanes)	Main bore: 4480	80	76.80	100 jet fans
	Right bore					66 jet fans
Jiuweiling Tunnel	Left bore	Expressway (bidirectional six lanes)	1472	80	91.45	1shaft + 6 jet fans
	Right bore		1447			22 jet fans
Dameisha Tunnel	Left bore	Highway (bidirectional six lanes)	1521	60	88.10	12 jet fans
	Right bore		1540			6 jet fans



(a)

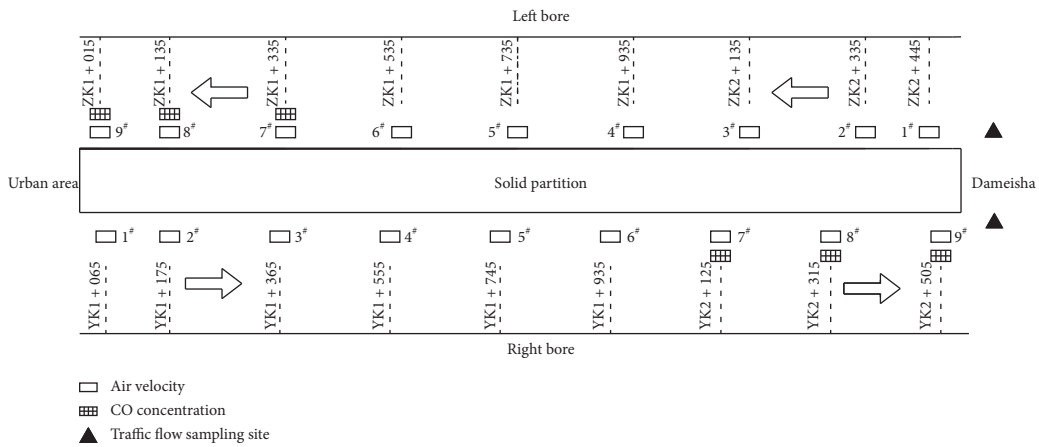


(b)



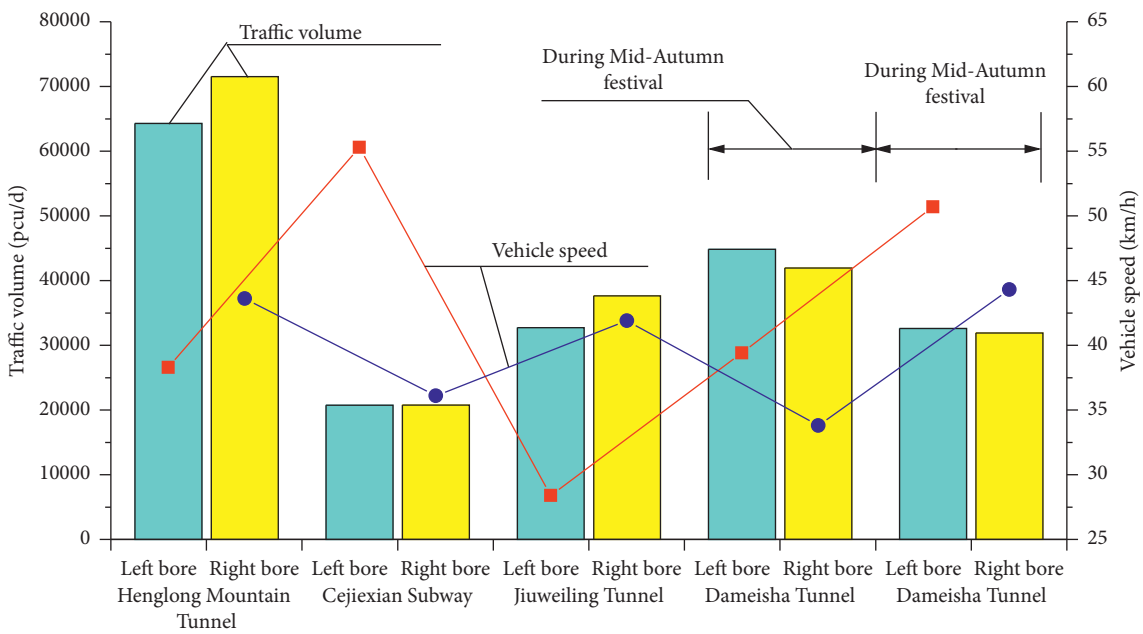
(c)

Figure 4: Continued.



(d)

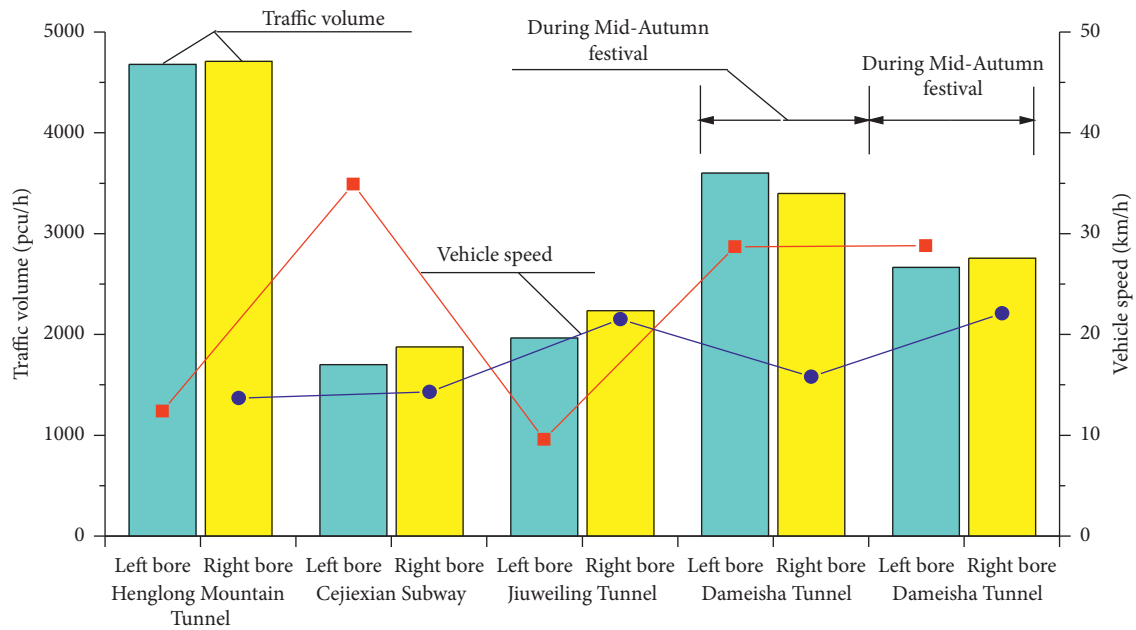
Figure 4: The sampling points distribution in the four urban tunnels. (a) Henglong Mountain Tunnel. (b) Cejiexian Subway. (c) Jiuweiling Tunnel. (d) Dameisha Tunnel.



Traffic volume	Dv	41000	41000	39000	39000	—	—	44405	44405	44405	44405
	Mv	64314	71535	20776	20780	32753	37641	44868	41948	32626	31884
Vehicle speed	Dv	60	60	80	80	80	80	60	60	60	60
	Mv	38.3	43.6	55.3	36.1	28.4	41.9	39.4	33.8	50.7	44.3

(a)

Figure 5: Continued.



		Henglong Mountain Tunnel		Cejiexian Subway		Jiuweiling Tunnel		Dameisha Tunnel		Dameisha Tunnel	
		Left bore	Right bore	Left bore	Right bore	Left bore	Right bore	Left bore	Right bore	Left bore	Right bore
Traffic volume	Dv	5000	5000	4757	4757	—	—	5400	5400	5400	5400
	Mv	4679	4708	1701	1877	1967	2237	3602	3398	2667	2756
Vehicle speed	Dv	60	60	80	80	80	80	60	60	60	60
	Mv	12.4	13.7	34.9	14.3	9.6	21.5	28.7	15.8	28.8	22.1

(b)

Figure 5: The investigation results of traffic flow. (a) The average daily traffic volume and vehicle speed. (b) The average peak hourly traffic volume and vehicle speed. *Note*. Dv: designed value; Mv: measured value.

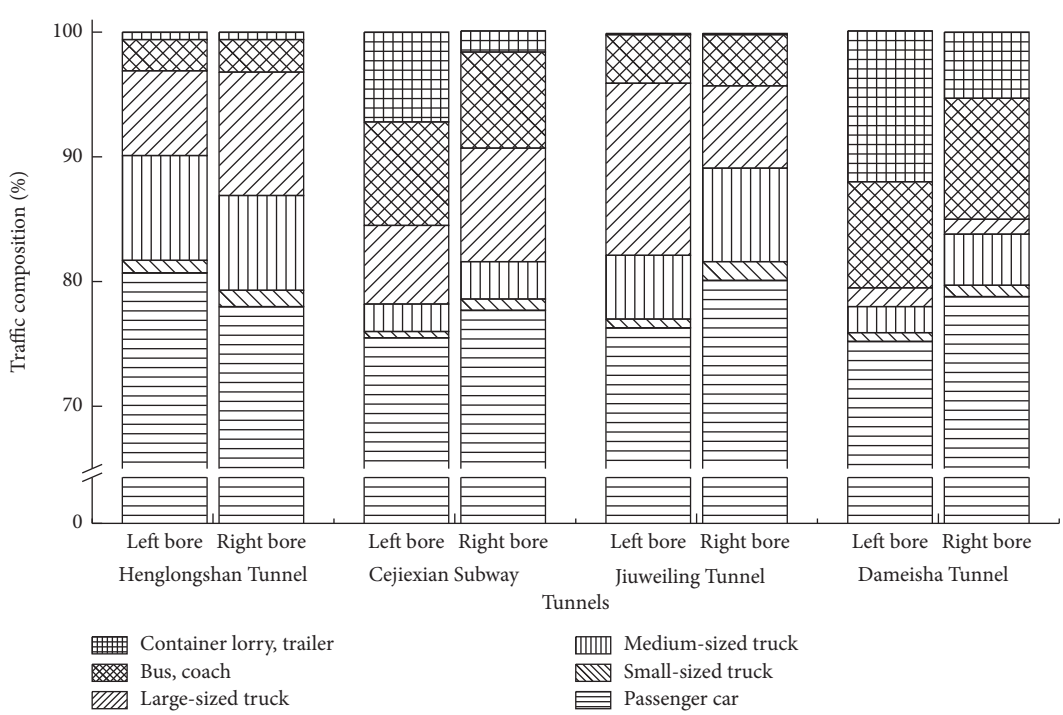


Figure 6: Traffic composition of the four urban tunnels.

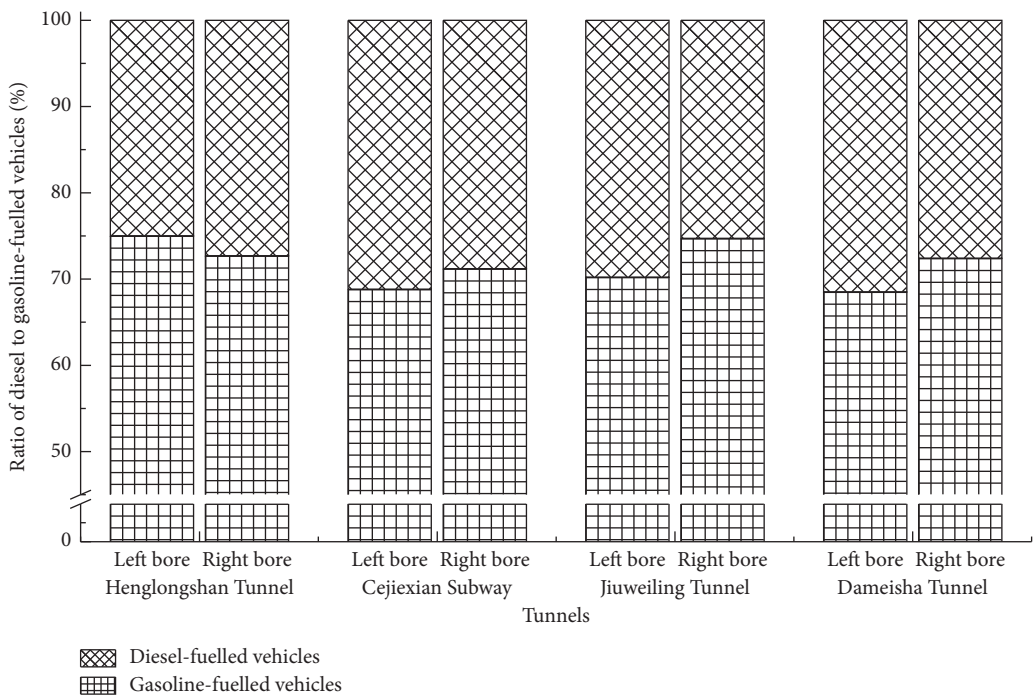


Figure 7: The proportions of diesel to gasoline-fuelled vehicles in the four urban tunnels.

Dameisha Tunnel had reached the designed level, which is much higher than that of nonholidays. The average peak hourly traffic volumes in the four tunnels, especially in Henglong Mountain Tunnel, were approaching the design limit. The daily traffic speeds in the four tunnels were basically more than 30 km/h and less than the design speed, and speeding rarely appeared. However, due to the influence of various factors, such as considerable traffic volume for Henglong Mountain Tunnel, the customs port for Cejiexian Subway, the traffic lights for Jiuweiling Tunnel, and the toll gate for Dameisha Tunnel, the peak hourly traffic speed in the four tunnels, except for the left bore of Cejiexian Subway, were less than 30 km/h, which could be considered as a block condition in the highway tunnel.

As illustrated in Figure 6, the traffic fleet in the four tunnels is mainly composed of passenger cars, the percentage of which is between 75% and 81%. And at rush hour, the passenger cars account for a higher proportion than that all day, between 76% and 89%. Next is large-sized buses and large-sized trucks. Figure 7 demonstrated that gasoline-fuelled vehicles account for the vast majority of the total number of vehicles. The proportion of gasoline-fuelled vehicles in traffic flow reached about 70% throughout a full day, and it increased by about 3%–5% at rush hour. What needs to be mentioned is that electric vehicles, mainly including electric buses and electric taxies, occupy a small percentage, so there is no special identification and statistics for electric vehicles.

4.3.2. Air Velocity. The air velocity directly affects pollutant concentration and driving comfort in the tunnel. And the air velocity in the tunnel is influenced by many factors, such as traffic volume, vehicle speed, mechanical wind, air pressure, and temperature. Based on continuous monitoring of air velocity in the four tunnels, the statistical results are shown in Figure 8.

During the sampling period, the prevailing wind directions in the four tunnels are consistent with the moving directions of motor vehicles. As can be seen from Figure 8, the air velocities in the four tunnels, except for the left bore of Jiuweiling Tunnel, fluctuated greatly with time. The average air velocities in the four tunnels, especially in the left bore of Jiuweiling Tunnel, were all below 5 m/s, which suggested that the air velocities were at a low level in urban tunnels and might not meet the requirement of air exchanging frequency. However, the maximum air velocity in the four tunnels, particularly in the right bores of Henglong Mountain Tunnel, Connection Subway, and Dameisha Tunnel, exceeded the upper limit value of 10 m/s stipulated for unidirectional bore in the current ventilation specification in China. And the maximum air velocity usually occurred when traffic flow moved smoothly and freely. The piston effect resulted from motor vehicle movement played a significant role in pushing forward the air flow. The air velocity in urban tunnels is the result of the interaction of natural wind, piston wind, and mechanical wind.

4.3.3. CO Concentration. CO, produced by incomplete combustion of fuel in automobile engines, is considered to be a pollutant which has the highest content and the greatest influence on the human health in urban tunnels. Therefore, CO is an important item of ventilation design and operation monitoring for urban tunnels. The statistics results of measured CO concentration in the four tunnels are shown in Figure 9.

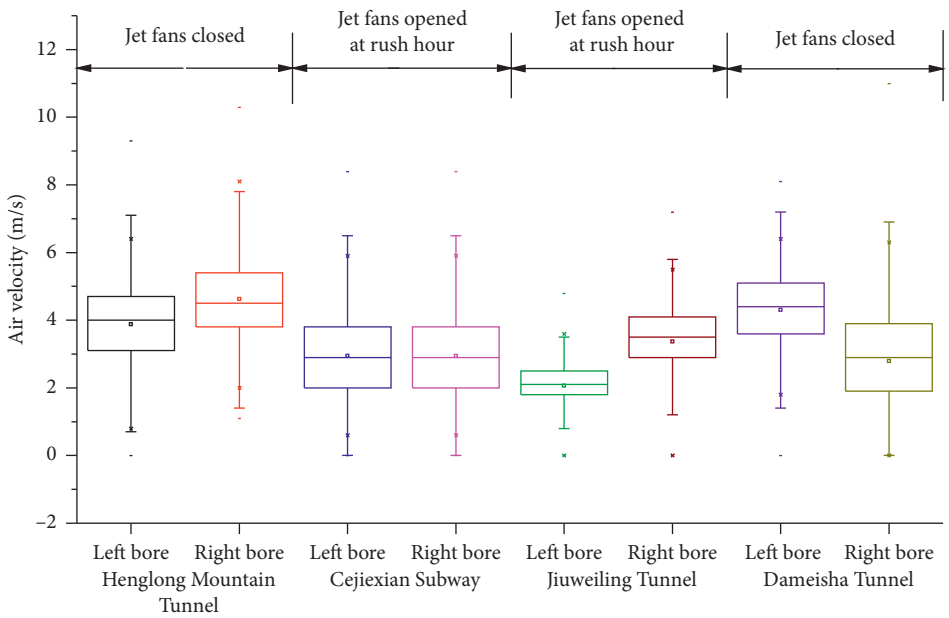


Figure 8: The statistics results of air velocity in the four urban tunnels.

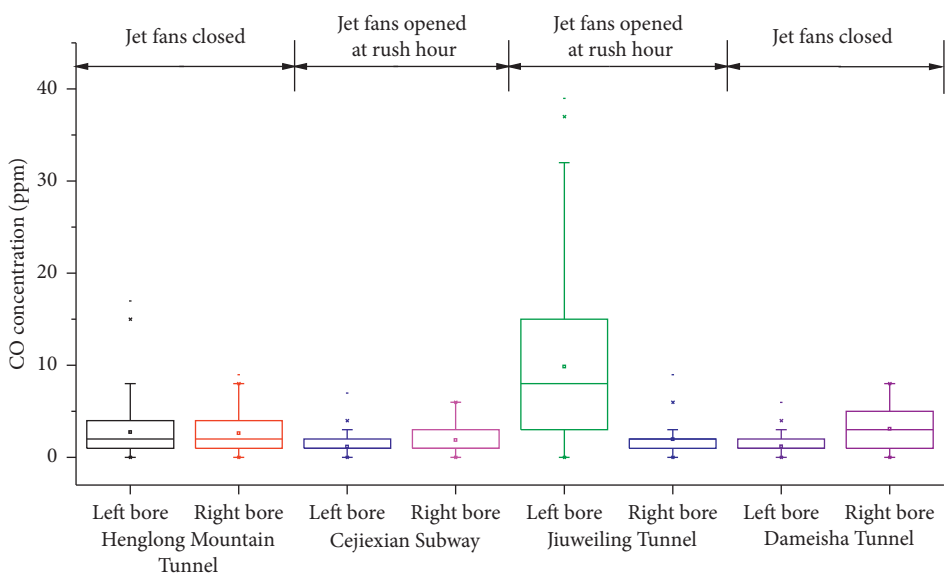


Figure 9: The statistics results of CO concentration in the four urban tunnels.

It is one of the most important purposes of tunnel ventilation to ensure in-tunnel CO concentration below a safety threshold during tunnel operation. Figure 9 revealed that CO concentrations, basically below 10 ppm except for the left bores of Henglong Mountain Tunnel and Jiuweiling Tunnel, stayed at a lower level in the four tunnels. And the maximum CO concentration reached 39 ppm, which rose sharply because of a closed lane in the left bore and the influence of traffic lights and vehicle merge about 300 m away from the south portal of Jiuweiling Tunnel under the condition of opening fans. For the ventilation environment of urban tunnel operation, more attention should be paid to the maximum pollutant concentration rather than the average value, and the maximum concentration can directly reflect the pollution status of vehicle exhaust emissions. Compared with the design threshold (100 ppm) of CO concentration, the CO concentrations in the four tunnels were all below the 40% of design threshold and within the safety limit. Therefore, based on the prediction results of CO emission factors, the field measurement results in the four urban tunnels reveal that, with the continuous reduction of CO emission level of light-duty vehicles, particularly passenger cars, the expected low CO concentrations have been observed in many tunnels worldwide. While the CO design concentration in urban road tunnels lacks timely correction and improvement, which has seriously lagged behind and

Table 5: The backcalculated CO-based emission factors for different base years (60 km/h).

Tunnel	Specified value of 2000	Left bore			Right bore		
		2014	2000	Ratio of backcalculated value to specified value in 2000 (%)	2014	2000	Ratio of backcalculated value to specified value in 2000 (%)
Henglong Mountain Tunnel	0.007	0.0020	0.0027	39	0.0013	0.0017	25
Cejiexian Subway	0.007	0.0011	0.0014	20	0.0012	0.0016	23
Jiuweiling Tunnel	0.007	0.0034	0.0046	65	0.0030	0.0039	56
Dameisha Tunnel	0.007	0.0023	0.0031	44	0.0022	0.0030	42

Table 6: The backcalculated reduction rates of CO-based emission factors (60 km/h).

Tunnel	The specified value of q_{co} in 2000 (m^3/(km·veh))	Left bore		Right bore	
		The backcalculated value of q_{co} in 2014 (m^3/(km·veh))	Annual reduction factor (%)	The backcalculated value of q_{co} in 2014 (m^3/(km·veh))	Annual reduction factor (%)
Henglong Mountain Tunnel	0.007	0.0020	8.4	0.0013	11.3
Cejiexian Subway	0.007	0.0011	12.6	0.0012	11.6
Jiuweiling Tunnel	0.007	0.0034	4.9	0.0030	6.0
Dameisha Tunnel	0.007	0.0023	7.6	0.0022	7.9

separated from the actual situations in China. Considering the unbalanced development of different tier cities in China, the difference of vehicle renewal, and the delay in the implementation of emission regulations, 70 ppm is recommended as the design threshold for urban tunnels in China under the free flowing peak traffic, daily congested condition, or standstill on all lanes, which is consistent with the latest research results of PIARC in 2019 [13].

4.4. Back Analysis of CO-Based Emission and Time Factor. The CO-based emission factors for the measurement year (2014) and the base year (2000) in the current traffic of four urban road tunnels in Shenzhen can be calculated by using equations (12) and (14). And the calculation results are listed in Table 5.

As can be seen from Table 5, the CO-based emission factors for the base year (2000) calculated from measured data are only 20%–65% of the specified value, which suggests that the base emission factor given in the current specification for the base year (2000) is either too large, or the annual reduction factor is too small, or perhaps both. Due to the overall consideration of current ventilation specification in determining the base emission factor, such as the implementation phase of emission standards, complex condition of in-use vehicles, vehicle population in China, and impacts of energy conservation and emission reduction, it can be considered that the base emission factor for the base year (2000) is rational and the reduction factor is too small. Therefore, on the basis of the back analysis results of base emission factors for CO, the revised values of annual reduction factors are obtained by equation (15). And the revised results are listed in Table 6.

As can be seen from Table 6, the annual reduction factors of base emission factors for CO calculated from measured data range from 4.9% to 12.6%, which is 2.4–6.3 times the specified value in the current ventilation specification. And compared with the predicted results, the calculated annual reduction factors are slightly smaller. The difference could be explained from the following aspects. The predicted results based on major cities in China are more extensive and more representative than back analysis results of Shenzhen city. And the vehicle population of Shenzhen ranked the 4th among major cities in China, after Beijing, Chongqing, and Chengdu by the end of 2014. More pollutants are emitted by motor vehicles at lower working speed under typical urban road conditions, which results in relatively small calculated results. The predicted results are basically consistent with the calculated results, which verifies the rationality and forward looking of the projection.

As can be seen in Table 7, from four aspects of predicted results, calculated results, related references, and engineering application, it is indicated that the annual reduction factor (2%) of base emission factor for CO in the current ventilation specification is conservative. Meanwhile, engineering practices showed that ventilation equipment was greatly reduced and the early-stage investments of projects were effectively saved by adopting 3% as the annual reduction factor during tunnel ventilation design. And during the period of operation, the tunnel environment is good and the air quality meets standard. The problems of overdesign and long-term (or even permanent) idleness of ventilation equipment have been improved, and the ventilation costs are greatly saved. These improvements effectively achieve the goal of energy saving.

Table 7: The summary of time factors of CO-based emission factors in China.

No.	Annual reduction rate (%)	Time span	Source	Reference
1	2	2000–2030	Current spec.	[10]
2	3.6	2010–2030	PIARC	[24]
3	2.4	2018–2035	PIARC	[13]
4	4.22	2000–2015 (gasoline-fuelled vehicle)	Manual for design	[34]
5	5.44	2000–2015 (diesel-fuelled vehicle)	Manual for design	[34]
6	3	1995-	Engineering application (such as Qingdao Jiaozhou bay subsea tunnel and connection subway)	[63]
7	34	2004–2011		
8	14.5	2011–2030	Predicted results	This study
9	20.2	2004–2030		
10	4.9–12.6	2000–2014	Backcalculated results	This study

Therefore, it is recommended that the annual reduction factor of base emission factors for CO be greater than 2%. On the basis of considering the tunnel geographical location, traffic environment, traffic volume, and traffic composition, determining a reasonable annual reduction factor is of great significance to calculate fresh air demand. Under the premise of ensuring the safety of tunnel operation, the optimization of annual reduction factor can achieve the goal of energy saving and environmental protection and contribute to the sustainable development of urban tunnels.

5. Conclusions

Based on the extensive investigations into CO emission factors for passenger cars, a representative set of CO emission factors for typical urban tunnels was selected as the original sequence. The CO emission factors for future years were projected by using the GM (1, 1) model, and through the attenuation analysis of CO emission factors, the annual reduction factors of CO-based emissions were determined approximately. Furthermore, a reasonable annual reduction rate was obtained and the validity of grey forecasting model was proven by comparing the predicted results with the back analysis results of measured data, engineering application, and related studies. The main conclusions are as follows:

(1) The prediction curve of CO emission factors consists of two stages. The CO emission factors of passenger cars in Stage I (2004–2010) and Stage II (2010–2030) were reduced by 94.36% and 95%, respectively, with an average annual decrease of 38% and 14%, respectively. In all, the CO emission factors decreased by 99.72% during the period from 2004 to 2030, and the average annual reduction factor was about 20%.

(2) The nonlinear fitting on the CO emission factor series of passenger cars conforms to exponential function distribution and the fitting function follows $EF_{CO} = e^{(842.1991-0.4185x)}$.

(3) The annual reduction factors of CO-based emission factors backcalculated from measurement data, between 4.9% and 12.6%, are 2.4–6.3 times over the specified value in the current ventilation specification. And compared with predicted results, the backcalculated annual reduction factors are slightly smaller.

(4) From four aspects of predicted results, backcalculated results, related references, and engineering application, it is indicated that the annual reduction factor (2%) of CO-based emission factors in the current specification is conservative. And when defining 2000 and 2010 as base year, respectively, it could employ 4% and 3% as the reduction factors for urban road tunnels.

Urban tunnel construction is one of the major ways to alleviate traffic pressure and provide smooth transportation for citizens. However, with the explosive growth of urban vehicle ownership in the process of urbanization in China, the issues of urban tunnel pollution, high ventilation cost, environmental protection, and energy saving that affect the sustainable development of cities are increasingly becoming the research focus of urban tunnels. The study results can provide theoretical reference for ventilation design and further help support sustainable development of urban tunnels.

Data Availability

The data used to support the findings of this study are presented in the tables and figures.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to acknowledge the financial support provided by the National Key R&D Program of China (Grant No. 2018YFB1600100), the National Natural Science Foundation of China (Grant Nos. 51978065 and 51678063), the China Postdoctoral Science Foundation (Grant No.

2016M602738), and the Chang Jiang Scholars Program (Grant No. Q2018209). The authors also thank the "Transport and Management Bureau of Shenzhen Municipality" for assistance with the experiments.

References

[1] L. Cui, X. L. Wang, K. F. Ho et al., "Decrease of VOC emissions from vehicular emissions in Hong Kong from 2003 to 2015: results from a tunnel study," *Atmospheric Environment*, vol. 177, pp. 64–74, 2018.

[2] S. K. Jin, J. L. Jin, and Y. F. Gong, "Natural ventilation of urban shallowly-buried road tunnels with roof openings," *Tunnelling and Underground Space Technology*, vol. 63, pp. 217–227, 2017.

[3] P.-g. Zhu, X.-n. Tong, L. Chen, C.-w. Wang, H. Song, and X.-y. Li, "Influence of opening area ratio on natural ventilation in city tunnel under block transportation," *Sustainable Cities and Society*, vol. 19, pp. 144–150, 2015.

[4] C. Guo, M. Wang, L. Yang, Z. Sun, Y. Zhang, and J. Xu, "A review of energy consumption and saving in extra-long tunnel operation ventilation in China," *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 1558–1569, 2016.

[5] V. Franco, M. Kousoulidou, M. Muntean, L. Ntziachristos, S. Hausberger, and P. Dilara, "Road vehicle emission factors development: a review," *Atmospheric Environment*, vol. 70, pp. 84–97, 2013.

[6] Y.-H. Liu, W.-Y. Liao, L. Li, Y.-T. Huang, and W.-J. Xu, "Vehicle emission trends in China's Guangdong province from 1994 to 2014," *Science of The Total Environment*, vol. 586, pp. 512–521, 2017.

[7] Y. Huang, B. Organ, J. L. Zhou et al., "Emission measurement of diesel vehicles in Hong Kong through on-road remote sensing: performance review and identification of high-emitters," *Environmental Pollution*, vol. 237, pp. 133–142, 2018.

[8] B. Degraeuwe and M. Weiss, "Does the new European driving cycle (NEDC) really fail to capture the NO_X emissions of diesel cars in Europe?" *Environmental Pollution*, vol. 222, pp. 234–241, 2017.

[9] S. D. Sun, J. X. Jin, and M. Xia, "Vehicle emissions in a middle-sized city of China: urrent status and future trends," *Environment International*, vol. 137, Article ID 105514, 2020.

[10] Ministry of Transport of the People's Republic of China, Guidelines for Design of Ventilation of Highway Tunnels, China Communications Press. Beijing, China, 2014, in Chinese.

[11] C. Huang, S. Tao, S. Lou et al., "Evaluation of emission factors for light-duty gasoline vehicles based on chassis dynamometer and tunnel studies in Shanghai, China," *Atmospheric Environment*, vol. 169, pp. 193–203, 2017.

[12] H. Liu, J. Ma, F. Dong et al., "Experimental investigation of the effects of diesel fuel properties on combustion and emissions on a multi-cylinder heavy-duty diesel engine," *Energy Conversion and Management*, vol. 171, pp. 1787–1800, 2018.

[13] PIARC-World Road Association, *PIARC Technical Committee on Road Tunnels Operation (D5). Road Tunnels: Vehicle Emissions and Air Demand for Ventilation*, PIARC-World Road Association, Paris, France, 2019.

[14] Y. B. Luo, J. X. Chen, W. W. Liu et al., "The energy-saving of urban tunnel ventilation based on the investigation of the annual discount rate of CO baseline emission in city of Shenzhen," *Journal of Testing and Evaluation*, vol. 47, no. 4, pp. 3041–3058, 2019.

[15] W. K. Chow and M. Y. Chan, "Field measurement on transient carbon monoxide levels in vehicular tunnels," *Building and Environment*, vol. 38, no. 2, pp. 227–236, 2003.

[16] X. C. Cong, J. H. Qu, and G. S. Yang, "On-road measurements of pollutant concentration profiles inside Yangkou tunnel, Qingdao, China," *Environmental Geochemistry and Health*, vol. 39, no. 5, pp. 1179–1190, 2017.

[17] C. M. Ma, G. B. Hong, and C. T. Chang, "Influence of traffic flow patterns on air quality inside the longest tunnel in Asia," *Aerosol Air Qual, Res.*vol. 11, pp. 22–50, 2011.

[18] J. C. Witte, M. R. Schoeberl, A. R. Douglass et al., "Satellite observations of changes in air quality during the 2008 Beijing olympics and paralympics," *Geophysical Research Letters*, vol. 36, no. 17, pp. 37–44, 2009.

[19] M. Weiss, P. Bonnel, R. Hummel, A. Provenza, and U. Manfredi, "On-road emissions of light-duty vehicles in Europe," *Environmental Science & Technology*, vol. 45, no. 19, pp. 8575–8581, 2011.

[20] H. M. Worden, Y. F. Cheng, G. Pfister et al., "Satellite-based estimates of reduced CO and CO_2 emissions due to traffic restrictions during the 2008 Beijing Olympics," *Geophysical Research Letters*, vol. 39, no. 14, pp. 259–281, 2012.

[21] M. Kousoulidou, G. Fontaras, L. Ntziachristos, P. Bonnel, Z. Samaras, and P. Dilara, "Use of portable emissions measurement system (PEMS) for the development and validation of passenger car emission factors," *Atmospheric Environment*, vol. 64, pp. 329–338, 2013.

[22] D. T. Zhao, H. Chen, H. P. Shao, and X. K. Sun, "Vehicle emission factors for particulate and gaseous pollutants in an urban tunnel in Xi'an, China," *Journal of Chemistry*, vol. 2018, Article ID 8964852, 11 pages, 2018.

[23] S. H. Kota, H. Zhang, G. Chen, G. W. Schade, and Q. Ying, "Evaluation of on-road vehicle CO and NO_x National Emission Inventories using an urban-scale source-oriented air quality model," *Atmospheric Environment*, vol. 85, no. 1, pp. 99–108, 2014.

[24] PIARC-World Road Association, "PIARC technical committee on road tunnels operation (C5)," *Road Tunnels: Vehicle Emissions and Air Demand for Ventilation*, PIARC-World Road Association, Paris, France, 2012.

[25] PIARC-World Road Association, "PIARC technical committee report on road tunnels," *XV world road congress, Mexico*, J. B. Shears & Sons Ltd, London, UK, 1975.

[26] PIARC-World Road Association, "PIARC technical committee report on road tunnels," *PIARC-World Road Association*, XVIIIth World Road Congress, Brussels, Belgium, 1987.

[27] Ministry of transport of the people's republic of China, *Specifications for Design of Ventilation and Lighting of Highway Tunnel*, China Communications Press, Beijing, China, 1999, in Chinese.

[28] X. Shen, Z. Yao, Q. Zhang et al., "Development of database of real-world diesel vehicle emission factors for China," *Journal of Environmental Sciences*, vol. 31, pp. 209–220, 2015.

[29] H. Wang, C. Chen, C. Huang, and L. Fu, "On-road vehicle emission inventory and its uncertainty analysis for Shanghai, China," *Science of The Total Environment*, vol. 398, no. 1-3, pp. 60–67, 2008.

[30] Y. Wang, Z. H. Huang, Y. J. Liu et al., "Back-calculation of traffic-related PM10 emission factors based on roadside concentration measurements," *Atmosphere*, vol. 8, no. 12, p. 99, 2017.

[31] X. Yan, G. Song, J. Yan et al., "Emission characteristics of gas-fired boilers in beijing city, China: category-specific emission

factor, emission inventory, and spatial characteristics," *Aerosol and Air Quality Research*, vol. 17, no. 7, pp. 1825–1836, 2017.

[32] S. C. Wang, H. X. Liu, and H. W. Wang, "Experiment study based on vehicle CO criterion emission amount in highway tunnel," *Journal of Highway and Transportation Research and Development*, vol. 21, no. 9, pp. 153–157, 2004, in Chinese.

[33] C. Guo, M. N. Wang, Y. W. Li et al., "Research on discount rate of CO and smoke baseline emission in road tunnel ventilation," *Journal of Highway and Transportation Research and Development*, vol. 25, no. 10, pp. 105–109, 2008, in Chinese.

[34] C. H. Liao and X. H. Guo, *Manual for Design of Highway Tunnel. Modern Tunnelling Technology*, China Communications Press, Beijing, China, 2012, in Chinese.

[35] US Environmental Protection Agency, "Using MOVES in project-level carbon monoxide analyses," U.S. Environmental Protection Agency, Washington, DC, USA, EPA-420-B-10-041, 2010.

[36] E. M. Fujita, D. E. Campbell, B. Zielinska et al., "Comparison of the MOVES2010a, MOBILE6.2, and EMFAC2007 mobile source emission models with on-road traffic tunnel and remote sensing measurements," *Journal of the Air & Waste Management Association*, vol. 62, no. 10, pp. 1134–1149, 2012.

[37] L. Ntziachristos, D. Gkatzoflias, C. Kouridis et al., "COPERT: a European road transport emission inventory model," in *Proceedings of the 4th International ICSC Symposium on Information Technologies in Environmental Engineering*, pp. 491–504, Thessaloniki, Greece, May 2009.

[38] M. Shafie-Pour and A. Tavakoli, "On-road vehicle emissions forecast using IVE simulation model," *International Journal of Environmental Research*, vol. 7, no. 2, pp. 367–376, 2013.

[39] T. Saatcioglu, K. Alp, A. Hanedar et al., "Effect of the Marmaray project on air pollution in Istanbul: an IVE model application," *Fresenius Environmental Bulletin*, vol. 20, no. 9A, pp. 2340–2349, 2011.

[40] Y. T. Ma, Q. H. Liu, G. Q. Lei et al., "Application of vehicular emission models and comparison of their adaptability," *Acta Scientiarum Naturalium Universitatis Pekinensis*, vol. 2, no. 3, pp. 1–10, 2007, in Chinese.

[41] X. Liu, "A more accurate method using MOVES (Motor Vehicle Emission Simulator) to estimate emission burden for regional-level analysis," *Journal of the Air & Waste Management Association*, vol. 65, no. 7, pp. 837–843, 2015.

[42] A. M. Andrew, "Why the world is grey," *Grey Systems: Theory and Application*, vol. 1, no. 2, pp. 112–116, 2011.

[43] K. W. Hipel, "Grey Systems: Theory and application," *Grey Systems: Theory and Application*, vol. 1, no. 3, pp. 274-275, 2011.

[44] R. Vallee, "Grey information: theory and practical applications," *Kybernetes*, vol. 37, no. 1, p. 89, 2008.

[45] S. S. Rao and X. T. Liu, "Universal grey system theory for analysis of uncertain structural systems," *AIAA Journal*, vol. 55, no. 11, pp. 3966–3979, 2017.

[46] J. L. Deng, "Introduction to grey system theory," *Journal of Grey Systems*, vol. 1, no. 1, pp. 1–24, 1989.

[47] K. Li, Y. J. Wang, T. Wang et al., "Vehicle pollution emission inventory research in Urumqi city," *Research of Environmental Sciences*, vol. 23, no. 4, pp. 407–412, 2010, in Chinese.

[48] Q. L. Yang, G. C. Chen, N. Ma et al., "Study on the motor vehicle share ration in the downtown of Chongqing," *Journal of Southwest China Normal University (Natural Science Edition)*, vol. 34, no. 4, pp. 173–177, 2009, in Chinese.

[49] P. Guo, N. Ma, G. C. Chen et al., "A study on the vehicle emission factors in Chongqing," *Journal of Southwest University (Natural Science Edition)*, vol. 31, no. 11, pp. 108–113, 2009, in Chinese.

[50] J. Wang, "Research on the discharging factor of vehicles in Xiamen," *Modern Scientific Instruments*, vol. 6, pp. 1–64, 2005, in Chinese.

[51] J. C. Xu, Research and application of real-world vehicle emission characteristic, Wuhan University of Technology, Wuhan, China, Master's thesis, 2006, in Chinese.

[52] N. Zhang, Study on emission characteristics of traffic pollutant in Foshan City, Beijing Technology and Business University, Beijing, China, Master's thesis, 2010, in Chinese.

[53] K. K. Liu, The study on the characteristics of CO pollution of motor vehicle emissions in typical urban road tunnel, Beijing Forestry University, Beijing, China, Master's thesis, 2010, in Chinese.

[54] Q. R. Zhu, Y. H. Liu, W. L. Zeng et al., "Research on distribution characteristics of motor vehicle exhaust emissions based on GPS floating car method," *Research of Environmental Sciences*, vol. 24, no. 10, pp. 1097–1103, 2011, in Chinese.

[55] X. X. Li, Research on characteristics of vehicle exhaust pollution and its abatement control measures in Hangzhou, Zhejiang University, Hangzhou, China, Master's thesis, 2013, in Chinese.

[56] K. Wang, Vehicle exhaust pollution estimates and analysis in Hohhot, Inner Mongolia University of Technology, Hohhot, China, Master's thesis, 2014, in Chinese.

[57] Y. Deng, C. Chen, Q. Li et al., "Measurements of real-world vehicle CO and NO x fleet average emissions in urban tunnels of two cities in China," *Atmospheric Environment*, vol. 122, pp. 417–426, 2015.

[58] Q. Li, C. Chen, Y. Deng et al., "Influence of traffic force on pollutant dispersion of CO, NO and particle matter (PM2.5) measured in an urban tunnel in Changsha, China," *Tunnelling and Underground Space Technology*, vol. 49, pp. 400–407, 2015.

[59] K. Q. Yang, The study of Xi'an motor vehicle exhaust emission quantitative simulation, Chang'an University, Xi'an, China, Master's Thesis, 2015, in Chinese.

[60] C. M. Lu, Y. H. Hao, and X. M. Wang, "China's population projections based on GM (1, 1) metabolic model," *Kybernetes*, vol. 38, no. 3-4, pp. 417–425, 2009.

[61] C. H. He, "Automobile emission limits and fuel quality improvements," in *Proceedings of the 4th Guangdong Forum on Oil and Gas Development: Energy-Saving, Consumption-Reducing and Emission Reducing*, Guangdong, China2008, in Chinese.

[62] Ministry of Environmental Protection of the People's Republic of China, "China vehicle emission control annual report," *Technical report, Ministry of Environmental Protection of the People's Republic of China*, in Chinese, 2015.

[63] Z. L. Zhu and F. Tian, "Study on pollutant base emission of Qingdao Jiaozhou bay subsea tunnel," *Energy and Environment*, vol. 1, pp. 24-25, 2012, in Chinese.