Hindawi
Advances in Civil Engineering
Volume 2018, Article ID 7514612, 10 pages
https://doi.org/10.1155/2018/7514612

Research Article

Sustainable Highway Design: Disentangling the Effects of Geometric-Related and Traffic-Related Factors on Urban Highway Traffic Emissions

Xue Bing,[1] Quanlun Wei,[2] Jian Lu,[3] Chaoyang Li,[4,5] and Yi Zhang[4,5,6]

[1]*Shenyang Urban Planning Design & Research Institute, Shenyang 110004, China*
[2]*Shanghai Pudong Architectural Design & Research Institute Co., Ltd., Shanghai 201204, China*
[3]*Key Laboratory of Road and Traffic Engineering of Ministry of Education, Tongji University, Shanghai 200092, China*
[4]*School of Naval Architecture, Ocean & Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*
[5]*China Institute of Urban Governance, Shanghai Jiao Tong University, Shanghai 200240, China*
[6]*State Engineering Laboratory of Highway Maintenance Technology, Changsha University of Science & Technology, Changsha, Changsha 410004, China*

Correspondence should be addressed to Yi Zhang; darrenzhy@sjtu.edu.cn

Received 6 September 2017; Accepted 5 July 2018; Published 16 September 2018

Academic Editor: Mariano Angelo Zanini

Reducing highway traffic emissions, which is a major part of China's total transportation-related emissions, is a key to China's sustainable development. However, the effects of geometric-related and traffic-related factors on highway traffic emissions are rarely studied in China. Employing data collected from Cao'an Highway in Shanghai, China, and Traffic Software Integrated System (TSIS) as a simulation tool, this paper analyzed the effects of three geometric-related factors and one traffic-related factor on three traffic emissions (HC, CO, and NO_x). The geometric-related factors are lane width, number of vehicle lanes, and intersection lane configuration, and the traffic-related factor is free-flow speed. The results indicated that (1) widening the lane width may cause the increase of CO emissions, (2) increasing the number of vehicle lanes may result in the decrease of all three emissions, (3) intersection lane configuration has significant influence on traffic emissions, and (4) the average speed of 23-24 mph is associated with the lowest traffic emissions. The research findings will facilitate the understanding on effects of various factors on highway traffic emissions and provide insights for policy-makers, scholars, and engineers into the improvement of sustainable highway design and management.

1. Introduction and Background

During the past three decades, with important changes in its economy and social structure, China has experienced a major demographic transition of rapid and intense urbanization and motorization [1–3]. From 1978 to 2014, the level of motorization increased at 20% annually [4–6]. This situation has contributed to China's increasingly severe traffic and environmental problems [7–9]. Road traffic emissions, including traffic emissions from highways and urban streets [10–12], have covered over 85% of China's total transportation-related emissions [13] and become an issue of public concern. By the end of 2014, China's highway mileage reached 2.79 million miles, topping other countries in the world [14]. In the Copenhagen Accord of the 2009 United Nations Climate Change Conference, the Chinese government has committed to reduce the emissions per unit GDP by 40%–45% by 2020 as compared to 2005 [15]. In response to that goal, the Ministry of Transport of the People's Republic of China has committed to reduce highway traffic emissions by 11% in 2015 as compared to in 2005 [16]. How does one maintain the momentum of highway system development while controlling the traffic emissions? This question is rarely studied from the perspective of highway design and management in China. It has become one of the most important and urgent problems for policy-makers and scholars in China.

Traffic simulation is an effective way to study highway traffic emissions. The most significant benefit of traffic simulation models is to simulate the spatial and temporal variation characteristics of traffic flow in highway networks and avoid the limitation of collecting real-world data. Microtraffic simulation models, such as VISSIM, PARAMICS, and TSIS (Traffic Software Integrated System), are most popularly employed in the traffic emissions-related research. With VISSIM, Noland and Quddus evaluated the influence of the road capacity on emissions [17], and Chen and Yu estimated the impact of two different traffic control and management strategies on traffic emissions [18]. Stevanovic et al. linked VISSIM, Comprehensive Modal Emission Model (CMEM), and VisSim-based genetic algorithm optimization of signal timings (VISGAOST) to optimize signal timings and minimize fuel consumption and CO_2 emissions [19]. Liu et al. developed a microsimulation platform based on VISSIM and PERE models to investigate the relationship between vehicle speed, energy consumption, and emissions [20]. By employing PARAMICS, Servin et al. and Boriboonsomsin analyzed road traffic emissions in various traffic conditions [21, 22]. Bartin et al. integrated MOBILE6.2 into PARAMICS and evaluated the effect of electronic toll collection (ETC) on air pollution levels [23]. Chamberlin et al. compared the emissions estimates from Motor Vehicle Emission Simulator (MOVES) with those generated by CMEM by using PARAMICS [24]. Employing the simulation tool TSIS, Xia simulated the target area and took travel delay to assist evaluating flow condition of the intersection [25]. Sha simulated the traffic flows of typical intersections and found that the signal optimization based on emissions was a useful way to reduce traffic emissions [26].

Although some scholars have preliminary studies traffic emissions with data collected in China, they rarely focused on highway emissions [27–32]. From the literature review above, we could find out that the relationship between geometric-related and traffic-related factors on highway traffic emissions have been widely examined using traffic simulation in the western countries [33–39]. However, due to the differences between vehicle emissions standard, highway design methods, traffic flow characteristics, etc., the findings in the western context may not be transferable and applicable in China. Reducing highway traffic emissions, which is a major part of China's total transportation-related emissions, is a key to China's sustainable development. Currently, studies focusing on the relationships between geometric-related and traffic-related factors on highway traffic emissions in China remain generally weak, providing insufficient support for strategies and guidelines from the perspective of improving highway design and traffic management. Therefore, it is imperative for policy-makers, scholars, and practitioners in China to investigate the factors significantly associated with highway emissions to draw up strategies and guidelines to achieve the goal of designing sustainable highways, reducing highway emissions, and developing sustainable transportation.

In this paper, we employed the microtraffic simulation software, TSIS, to study the effects of four factors on three highway traffic emissions, hydrocarbon (HC), carbon monoxide (CO), and nitric oxide (NO_x), in the Chinese context. Three geometry-related factors were studied including lane width, number of vehicle lanes, and intersection lane configuration, and one traffic-related factor, free-flow speed, was also studied. The intersection lane configuration stands for the setting of vehicle lanes for specific turning, e.g., right turn, left turn, and u turn [22]. First, we built the study area in TSIS with geometry-related and traffic-related data we had collected for the study. Then, we changed the geometry-related and traffic-related factors of the study area in TSIS and obtained the traffic emissions in different scenarios. Thirdly, we employed linear regression models to quantify the relationships between selected factors and traffic emissions. Finally, we proposed policy recommendations on reduction of highway traffic emissions relative to the four factors. The research findings of the present paper will provide insights for policy-makers and scholars into the improvement of highway design and traffic management oriented towards traffic emission reduction.

2. Data and Methods

2.1. Study Area and Data Collection. The study case is a highway section of Cao'an Highway in the northwestern outskirts in Shanghai, China. Cao'an Highway is a part of China National Highway 312, which is a key east-west route beginning in Shanghai and ending at Khorgas, Xinjiang in the Ili River valley, on the border with Kazakhstan. In total, China National Highway 312 spans 3,086 miles and its segment in Shanghai (Cao'an Highway) spans 22.5 miles. Cao'an Highway used to be one of the major routes that connect the urban core of Shanghai with Suzhou City, another economically developed big city in China. However, in the past decade, the lands along the Cao'an Highway have been developed into urban areas with increasing population and jobs. At the same time, new express highways and high-speed rails have been built to accommodate increasing demand of passenger and good transportation between Shanghai and Suzhou. With a high volume of traffic in Cao'an Highway, the traffic emissions have raised concerns related to environmental protection and public health. Therefore, it is imperative to look into the relationship of various factors to traffic emissions of Cao'an Highway. The study area was between Miquan Road and Yutian Road, with a length of 3521 ft between the Cao'an-Miquan and the Cao'an-Yutian intersections (Figure 1).

The study area included two signalized intersections. For each approach in either intersection, at least 1500 ft was covered in the simulation. The traffic volume data was collected at weekday morning peak hour from 8 am to 9 am for five consecutive days in September, 2013. At each intersection, we recorded the signal scenarios and manually counted the number of light vehicles and heavy duty vehicles

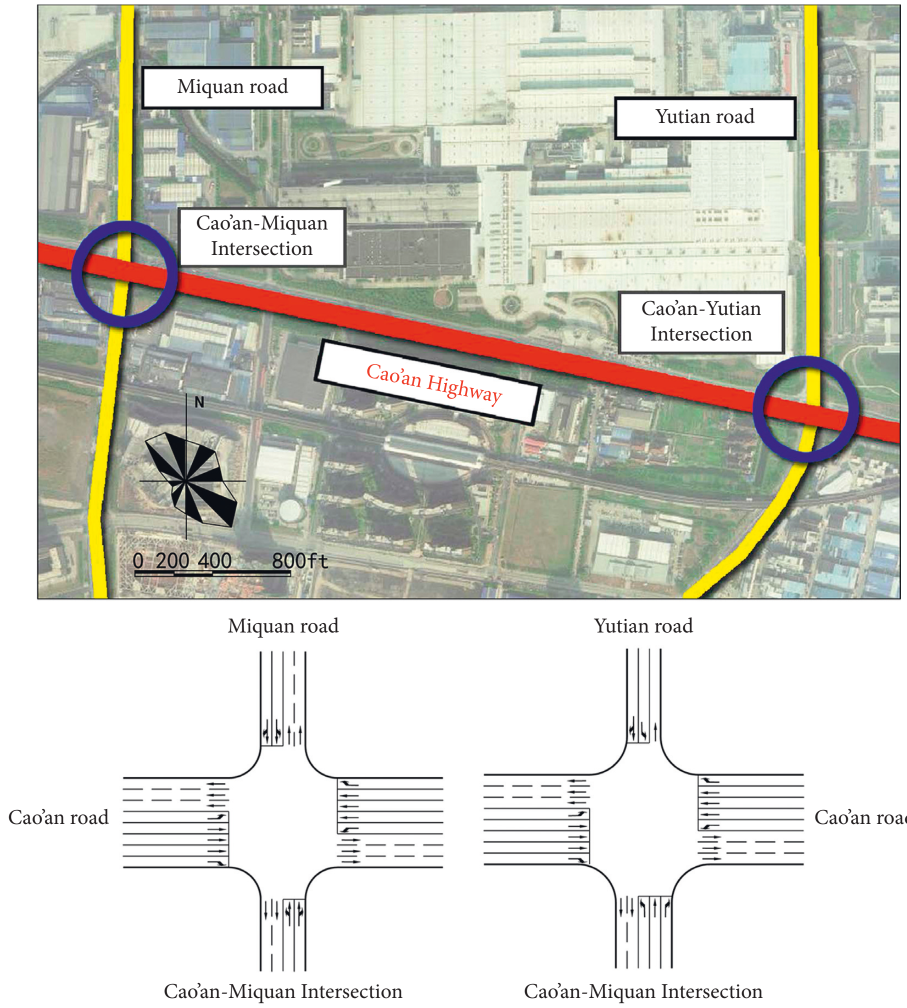

Figure 1: Study area and intersection lane configuration (courtesy of Baidu Maps).

for each traffic movement. We also obtained the data of lane width, number of vehicle lanes, and intersection lane configuration by field survey. The specific information of traffic volume, traffic distribution, and signal control plan is shown in Table 1.

2.2. Selection of the Influencing Factors. As suggested by Guensler [40], factors that influence highway traffic emissions can be divided into four categories (Table 2). Different types of vehicles display different characteristics with regard to the amount of total emissions and emissions rates of specific compound [27–29, 41]. In general, heavy duty vehicles have higher emissions than light vehicles. Older vehicles with greater mileage usually lead to higher emissions. More advanced and emission control technology generally result in lower emissions [17, 42]. Also, ambient temperature impacts traffic emissions: as temperatures drop, HC and CO emission rates are typically higher compared to warmer temperatures [43–46]. Moisture is another environmental factor as higher relative humidity leads to lower NO_x emissions [47].

Driving behavior and operating environment are hard to change in order to reduce traffic emissions. Meanwhile, some geometry-related and traffic-related factors, which are related to the highway design and traffic management, are potentially practical and feasible for emission reduction. Choosing more traffic-related factors will deepen the study as the influencing factors of traffic emissions are diverse and complicated. However, due to the limited available data sources, software capability, and simulation accuracy, at this stage in this study, we were only able to present four factors, which are lane width, number of vehicle lanes, exclusive lane set, and free-flow speed. Therefore, we selected four geometry-related and traffic-related factors to build simulation scenarios: lane width, number of lanes, intersection lane configuration, and free-flow speed.

2.3. Simulation and Statistical Analysis Methods. The simulation model employed in the study is TSIS (version 6.1). TSIS is developed in the US and is an integrated development environment that enables users to conduct traffic operations analysis. Built using component architecture, TSIS is a toolbox that contains tools that allow the user to

Table 1: Traffic distribution and signal control of the two intersections.

Category	Intersection		Cao'an-Miquan				Cao'an-Yutian			
	Direction		Total (pcu/h)	LT (%)	TH (%)	RT (%)	Total (pcu/h)	LT (%)	TH (%)	RT (%)
Traffic distribution	EB		728	15	81	4	723	6	89	5
	WB		737	7	73	20	838	5	85	10
	NB		171	18	62	20	146	29	50	21
	SB		345	53	31	16	232	46	27	27
	Phase	Maneuver	Green(s)	Yellow(s)		All-red (s)	Green (s)	Yellow (s)		All-red (s)
Signal control	I	EB and WB	30	3		0	35	3		0
	II	NB and SB	27	3		0	27	3		0

Note. pcu/h: Passenger Car Unit per hour (a Passenger Car Unit is essentially the impact that a mode of transport has on traffic variables, such as headway, speed, and density, compared to a single car), EB: east bound, WB: west bound, NB: north bound, SB: south bound, LT: left turn, TH: through, and RT: right turn.

Table 2: The influencing factors of traffic emissions.

Category	Type of factors
Vehicle characteristics	Vehicle type, year of manufacture, mileage, fuel supply system, emission control systems
Fuel parameters	Fuel type, oxygen content, sulfur content, volatility, density
Operating conditions	Startup mode, speed, acceleration, excess air ratio, load, road geometry, type of signal control, driving behavior
Operating environment	Ambient temperature, relative humidity

define and manage traffic analysis projects, define traffic networks, and create inputs for traffic simulation analysis, execute traffic simulation models, and interpret the results of those models. TSIS was used for managing, working, and controlling a microscopic traffic simulation model CORridor SIMulation (CORSIM) and its associated tools. CORSIM consists of an integrated set of two microscopic simulation models that represent the entire traffic environment. CORSIM models the movements of individual vehicles, which include the influences of geometric conditions, control conditions, and driver behavior. CORSIM also contains an emission calculation module. The selected highway section was established in TSIS, and different scenarios regarding the four factors were simulated, respectively. The main input data have been listed in Sections 2.1 and 2.2.

All the factors not mentioned in this paper were controlled for the default values in TSIS. In this paper, we employed the software's own emission calculation module to obtain simulated traffic flow and emissions data. The output data for further analysis included the average traffic delay, the average speed, and the total traffic emissions of HC, CO, and NO_x. The statistical analysis software SPSS 17.0 was used to conduct linear regression and analyze the relationship of selected factors and traffic emissions.

3. Results

This section presents the simulation results, as well as the regression analyses. In Table 3, we summarize the simulation results across the four factors.

3.1. Lane Width. We changed the lane width from 10 ft to 13 ft by one feet at a time on Cao'an Highway. The results in Table 3 indicated that HC and NO_x emissions did not change significantly as lane width was increased; however, a large increase of CO emissions appeared when the lane width was changed from 12 ft to 13 ft. On a highway with narrow lanes, the driving behavior will be improved with lower driving speeds and less speed variations, which is probably leading to less traffic emissions, consistent with previous studies [48, 49]. However, it is unclearly why HC and NO_x emissions remained the same when the lane widths changed from 12 ft to 13 ft. The standard lane width is 12 ft in highway geometric design and TSIS [50]. It is most likely the capability of TSIS in relation to the driving behavior and traffic flow characteristics limits the results of HC and NO_x emissions in some scenarios. Although it is not appropriate to compare the results generated by different software directly in this paper, we will look into the comparison of results from different software in further studies to further examine the relationship of lane width on HC and NO_x emissions.

3.2. Number of Vehicle Lanes. The number of vehicle lanes was changed from 4 to 8 on Cao'an Highway in the simulation. The results indicate that the HC, NO_x, and CO emissions all decreased along with the increase in the number of vehicle lanes. We employed linear regression in this study to reveal the relationship between various factors and traffic emissions. With an R^2 of 0.964, 0.978, and 0.923, the relationship of number of vehicle lanes and HC, CO, and NO_x emissions satisfy the linear relationship. The linear

Table 3: Simulation results of different factors.

Number	Influencing factors		HC (g/mile)	CO (g/mile)	NO_x (g/mile)	Delay (s)	Average speed (mph)
1	Lane width (ft)	10	0.16	13.01	0.69	48.37	23.04
		11	0.16	12.97	0.69	47.72	23.11
		12	0.16	13.03	0.69	48.00	23.08
		13	0.16	13.05	0.69	46.54	23.24
2	Number of vehicle lanes	4	0.17	13.51	0.75	57.42	22.09
		6	0.16	13.03	0.69	48.00	23.08
		8	0.15	12.74	0.67	43.09	23.63
3	Exclusive lane set	Original	0.16	13.03	0.69	48.00	23.08
		Remove left turn pocket	0.17	13.52	0.73	57.48	22.06
		Remove right turn pocket	0.16	12.98	0.69	49.39	22.93
		Remove both pockets	0.17	13.59	0.73	62.11	21.61
4	Free-flow speed (mph)	30	0.16	13.03	0.69	48.00	23.08
		35	0.20	16.25	0.82	45.29	25.57
		40	0.25	19.64	1.01	45.67	27.74
		45	0.30	23.30	1.19	45.06	29.58
		50	0.36	27.93	1.39	49.52	30.28

relationship between the number of vehicle lanes and the three emissions are

$$\begin{aligned} Y_{\text{HC-NVL}} &= -0.006X_{\text{NVL}} + 0.180, \\ Y_{\text{CO-NVL}} &= -0.193X_{\text{NVL}} + 14.253, \\ Y_{\text{NO}_x\text{-NVL}} &= -0.04X_{\text{NVL}} + 0.783, \end{aligned} \tag{1}$$

where $Y_{\text{HC-NVL}}$, $Y_{\text{CO-NVL}}$, and $Y_{\text{NO}_x\text{-NVL}}$ are the HC, CO, and NO_x emissions per unit distance (g/mile), respectively, X_{NVL} is the number of vehicle lanes, and X is 4, 6, or 8. We did not consider the scenario when the number of vehicle lanes is over 8 as it is very rare in China.

Among the three emissions, the CO emissions have the highest goodness of fitting (Figure 2, upper left). This is very possibly due to higher fuel efficiency as higher rates of conversion to CO_2 could in part explain the lower CO emissions rates with increasing the number of vehicle lanes [29, 41, 51, 52].

3.3. Intersection Lane Configuration. The two intersections had the same original lane set at each approach on Cao'an Highway, which included one left turn pocket, three through lanes, and one right turn pocket. We changed the intersection lane configuration on Cao'an Highway by removing left turn pocket, right turn pocket, or both pocket signs, respectively, and ran the simulation model to obtain the emission results as shown in Table 3. When the exclusive left turn lanes were removed, HC, CO, and NO_x emissions all increased. On the contrary, the three emissions all reduced when the exclusive right turn lanes were removed. In this study case, the proportion of left-turn vehicles was high. Therefore, the exclusive left turn lanes are effective to reduce the average delay and number of stops, which attributed to the reduction of traffic emissions. Compared to the left-turn vehicles, the proportion of right-turn vehicles was relatively lower. Exclusive right turn lane set may increase the possibility of vehicle's unnecessary lane changing and result in the increase of vehicle emissions.

3.4. Free-Flow Speed. The value of free-flow speed is mainly determined by the road conditions, vehicle performance, characteristics of driving behavior, etc. In this paper, we changed the free-flow speed from 30 to 50 mph by 5 mph each time on Cao'an Highway. The HC, NO_x, and CO emissions were increasing with the increase of the free-flow speed. The findings are consistent with the previous literature [53, 54]. However, the reason to this situation requires further investigation. The curve fit demonstrated the variation trends of the three emissions based on the free-flow speed (Figure 3).

We further built linear regression models, as follows, to quantify the relationships between HC, CO, NO_x emissions, and free-flow speed:

$$\begin{aligned} Y_{\text{HC-FFS}} &= 0.01X_{\text{FFS}} - 0.135, \\ Y_{\text{CO-FFS}} &= 0.035X_{\text{FFS}} - 0.394, \\ Y_{\text{NO}_x\text{-FFS}} &= 0.737X_{\text{FFS}} - 9.46, \end{aligned} \tag{2}$$

where $Y_{\text{HC-FFS}}$, $Y_{\text{CO-FFS}}$, and $Y_{\text{NO}_x\text{-FFS}}$ are the emissions of HC, CO, and NO_x per unit distance (g/mile), respectively, and X_{FFS} is the free-flow speed. The R^2 of the three models are 0.994, 0.995, and 0.995, respectively, indicating high goodness of fitting.

3.5. Average Speed and Highway Traffic Emissions. Literatures have suggested that the average speed is an important indicator for the traffic emissions [55–57]. In this section, the relationship between average speed and traffic emissions was revealed, using the data from the simulations across different scenarios regarding different factors. However, in order to keep traffic flow in the same composition, we kept the heavy duty vehicle factor to zero as the effects of heavy duty vehicles were too significant. The curve fit of the three emissions based on the average speed is shown in Figure 4.

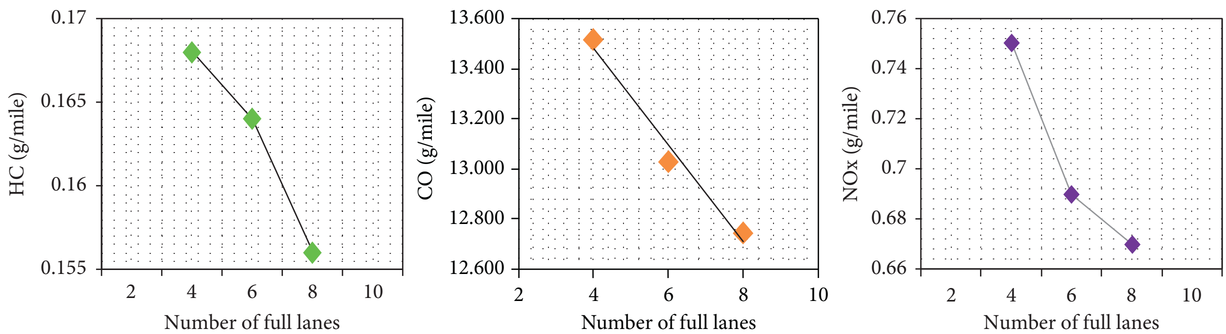

FIGURE 2: Curve fit of number of vehicle lanes with HC, CO, and NO_x emissions.

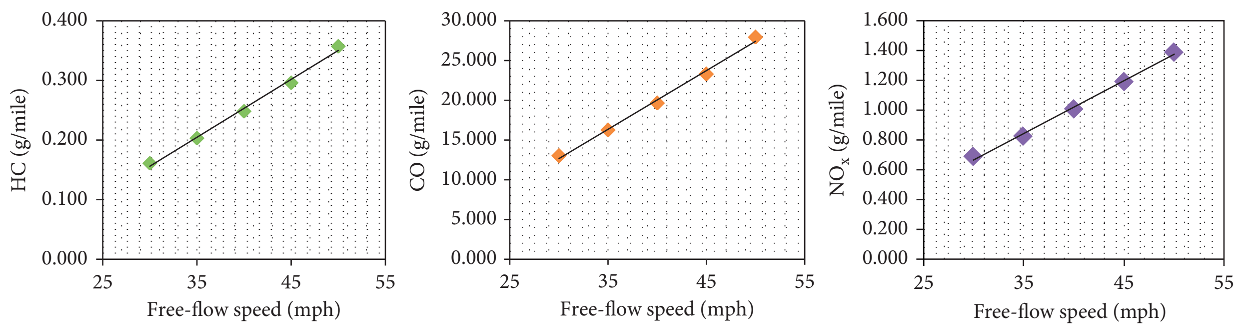

FIGURE 3: Curve fit of free-flow speed with HC, CO, and NO_x emissions.

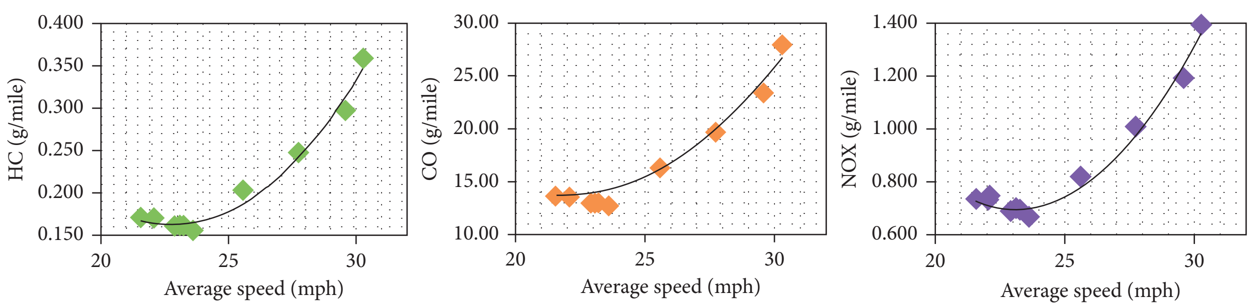

FIGURE 4: Curve fit of average speeds with HC, CO, and NO_x emissions.

The emissions and the average speed satisfy the relationships as follows:

$$\begin{aligned}
Y_{\text{HC-AS}} &= 0.003X_{\text{AS}}^2 - 0.158X_{\text{AS}} + 1.974,\\
Y_{\text{CO-AS}} &= 0.213X_{\text{AS}}^2 - 9.504X_{\text{AS}} + 119.145,\\
Y_{\text{NO-AS}} &= 0.013X_{\text{AS}} - 0.624X_{\text{AS}} + 7.929,
\end{aligned} \tag{3}$$

where $Y_{\text{HC-AS}}$, $Y_{\text{CO-AS}}$, and $Y_{\text{NO-AS}}$ are the emissions of HC, CO, and NO_x per unit distance (g/mile), respectively, and X_{AS} is the average speed. The R^2 of the three models are 0.983, 0.758, and 0.984 respectively.

The regression models demonstrated the significant relationships between the emissions and average speed of traffic flow. The results also indicated when the average speed is between 23 and 24 mph, the total traffic emissions are lowest. When the average speed is greater than 23-24 mph, the total traffic emissions will increase significantly.

4. Discussion and Policy Implications

The analysis in this paper has demonstrated the geometry-related and traffic-related factors have significant effects on highway traffic emissions. The results are similar to the previous literature [35, 39, 58–61] in other locations in and outside China. Policies regarding the changing of those factors may potentially reduce the traffic emissions.

4.1. Lane Width. China's National Standard for the design of highway lane width is 11.5 ft to 12.5 ft. As suggested by the results in this study, there would be an increase of CO emissions when the lane width changed from 12 ft to 13 ft. As we have explained in Section 3.1, drivers would drive more carefully if the vehicle lanes are narrower, resulting in lower driving speeds, less speed variations, and less traffic emissions [48, 49]. Yet, it is important to note that narrower lane means lower traffic efficiency, so considering efficiency and emissions, we recommend it is better to keep the lane width between 11.5 ft and 12 ft. The idea of lane narrowing has been proposed recently in China in the newest revision of the National Highway Design Standard, which is in line with the demand of emission reduction.

4.2. Number of Vehicle Lanes. More vehicle lanes would lead to less emissions. As the land resources are limited for highway system, the combination of narrowing lane width and increasing number of vehicle lanes may enhance not only the highway capacity but also the possibility of reducing traffic emissions. This design method may be beneficial to the future highway design oriented towards traffic demand management and emission reduction.

4.3. Intersection Lane Configuration. Intersections are important links of road network. However, due to the fact that traffic flow of all directions packing in, the intersections have usually become the bottlenecks in the road network. According to the findings in this paper, one advice for the study case is to improve intersection lane configuration based on traffic flow distribution. The result from previous studies showed that the existence of exclusive lane set is generally beneficial to emissions reduction at intersections [22, 61]. Furthermore, it is important to set an exclusive signal phase or waiting area for left turn exclusive lane, and a right turn exclusive lane is always useful.

4.4. Speed. In this paper, free-flow speed and the average speed were adopted to reveal the relationships between the two types of speeds and traffic emissions. The free-flow speed is the speed at which vehicle runs without the impact of intersection delay or other vehicles, which is partly determined by the speed limit of the highway. The average speed displayed the how vehicle runs under the influences of intersection delay or other vehicles, which is closer to real conditions. For the study case, the emissions increased simultaneously with the free-flow speed increasing from 30 to 50 mph. The average speed of 23-24 mph corresponded to the lowest emission, implying the potential of traffic management measure of maintaining a certain average speed. This finding is consistent with previous studies as the average speed is highly correlated to traffic emissions [55–57]. Therefore, in order to reduce traffic emissions, we may suggest that besides appropriate speed limit, it is also important to achieve a reasonable average speed in accordance with different highway design and characteristics of traffic flow through traffic management measures.

5. Strengths and Limitations

This study has a number of strengths and limitations. In terms of the limitations, firstly, the study was restricted to a single-highway section of Cao'an Highway in the outskirts of Shanghai, China. The results, therefore, may not be fully generalizable to other highways with characteristics that are different from the study case. Secondly, we used three geometry-related and one traffic-related factors in the study. The full evaluation of factors influencing highway traffic emissions will require us to introduce more factors, e.g., highway grade and speed limit [58], in future studies. In terms of the strengths, the study focused on highway traffic emissions, which are one of the major sources of transport emissions in China. Secondly, the study investigated the relationship between four factors and highway traffic emissions with a quantitative approach. That would facilitate the emerging research on traffic emissions in China. Finally, the findings are able to provide informative policy implications for policy-makers, scholars, and engineers.

6. Conclusion

This paper established a TSIS simulation model of a highway section in Shanghai, China, to study the effects of geometry-related and traffic-related factors on highway traffic emissions. Four factors, lane width, number of vehicle lanes, heavy duty vehicle factor, free-flow speed, and intersection lane configuration, were selected to build different scenarios in the simulation to obtain the traffic emissions. The study found out that (1) widening the lane width may lead to the increase of CO emissions; (2) increasing the number of vehicle lanes may result in the decrease of HC, CO, and NO_x emissions; and (3) intersection lane configuration has significant influence on traffic emissions. Emissions and average speed of traffic flow have significant statistical relationships as the average speed of 23-24 mph is associated with the lowest traffic emissions. Policy recommendations on reduction of highway traffic emissions regarding to the four factors were put forward, which included (1) the combination of narrowing lane width and increasing number of vehicle lanes; (2) keeping appropriate average speed of traffic flow, and (3) designing exclusive lanes at intersections when needed. The research findings will provide insights for policy-makers, scholars, and engineers into the improvement of highway design and traffic management oriented towards traffic emission reduction.

Disclosure

This work represents the authors' personal opinion.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

Xue Bing and Quanlun Wei contributed equally to this work.

Acknowledgments

The authors acknowledge the financial support of 12N11 by the Department of Transportation of Jiangsu Province, National Social Science Foundation of China (Project nos. 14BSH032 and 18BSH143), National Natural Science Foundation of China (Project nos. 51308336, 51408065, 7167010212, and 61773077), the Fundamental Research Funds for the Central Universities of Shanghai Jiao Tong University (Project nos. 15JCZZ05 and 16JXYB08), the Open Fund of the State Engineering Laboratory of Highway Maintenance Technology (Changsha University of Science & Technology, Project no. KFJ160106), the 2017-2018 Annual Research Fund of Peking University-Lincoln Institute Center for Urban Development and Land Policy, and the Urban China Initiative (UCI) Grant Project.

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