

Research Article

Evaluating the Interference of Bicycle Traffic on Vehicle Operation on Urban Streets with Bike Lanes

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Many urban streets are designed with on-street bike lanes to provide right-of-way for bicycle traffic. However, when bicycle flow is large, extensive passing maneuvers could occupy vehicle lanes and thus cause interferences to vehicle traffic. The primary objective of this study is to evaluate how bicycle traffic affects vehicle operation on urban streets with bike lanes. Data were collected on six street segments in Nanjing, China. The cumulative curves were constructed to extract traffic flow information including individual bicycle and vehicle speeds and aggregated traffic parameters such as flow and density. The results showed that as bicycle density on bike lanes continuously increases faster bicycles may run into vehicle lanes causing considerable reductions in vehicle speeds. A generalized linear model was estimated to predict the vehicle delay. Results showed that vehicle delay increases as bicycle flow and vehicle flow increase. Number of vehicle lanes and width of bike lane also have significant impact on vehicle delay. Findings of the study are helpful to regions around the world in bike infrastructure design in order to improve operations of both bicycles and vehicles.

1. Introduction

In the past decade, there has been an increasing use of bicycles in many countries around the world [1–6]. Bicycle has been widely used in people's daily trips especially in some European countries [1, 2, 6]. In China, bicycle is still one of the most important travel modes in both commuting and recreational activities [7–10]. In urban areas, bike lanes are usually implemented on the streets to provide space for bicycle to operate [2, 11, 12]. The typical urban street section with bike lane is shown in Figure 1(a). Sometimes bike lanes are designed on the left side of vehicle parking, as shown in Figure 1(b). The purpose of the line segmentation is to separate the bicycle traffic from the vehicle traffic to reduce conflicts between different trip modes. The implementation

of bike lanes is considered useful in improving both safety and operations of traffic flow on urban streets.

As individual cycling speed is quite different, one of the most important features in bicycle traffic is that there are many overtaking behaviors between cyclers [13–15]. When overtaking happens, two bikes run adjacently which occupy more travel space. When bicycle traffic flow is small, it may not have significant impact on the vehicle traffic in adjacent lanes. In such situation, vehicle travel delay is mainly determined by the impact of intersections. However, when bicycle traffic flow is large such that existing bike lane may not accommodate the cycling demand, some bicycles could run closely to vehicles or even within vehicle lanes. In such situation, bicycle traffic could have an impact on the operation of vehicles and increase vehicle delays within road segment areas.

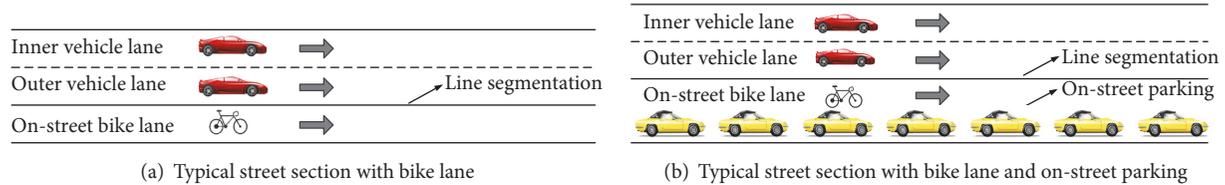


FIGURE 1: Illustration of a typical street section.

A review of the literature shows that most previous studies focused on evaluating the interactions between bicycles and vehicles within the intersections in urban areas [16–21]. However, such model cannot be directly used for the analysis of street sections. Some other studies evaluated the traffic operation and the level of service on the streets with bike lanes [11, 12, 22–24]. In recent years, the interactions between bicycle and vehicle traffic flow on streets have gained much attention from transportation professionals [25–29]. However, those previous studies did not aim to evaluate and predict the vehicle delay caused by bicycles under different traffic situations which is still a critical issue that has not been addressed properly.

An evaluation of bicycle traffic on the operation of vehicle traffic can help transport agencies estimate the conflicts between the two trip modes in the current situation or in the future when bicycle flow increases. The roads with severe conflicting issues can be identified to implement countermeasures. Besides, such evaluation can also help transport agencies to design the width of bicycle paths on urban streets to improve traffic operations. The primary objective of this study is to evaluate the impacts of bicycle traffic on the operations of vehicle traffic on the urban streets with bike lanes. More specifically, this study includes the following two tasks: (1) analyzing the features of bicycle traffic flow and vehicle speed under different traffic situations and (2) developing a model to predict the delay of vehicle caused by bicycle traffic.

The remainder of this paper is organized as follows. A literature review is provided in the following section. In Section 3, data collection is introduced. In Section 4, the methodologies are briefly introduced. In Section 5, the results of data analysis are discussed. The paper ends with brief concluding remarks and future work in Section 6.

2. Literature Review

Previously, the focus of bicycle-vehicle interaction evaluation was on intersection areas. Bai et al. [16] evaluated the risk-taking behaviors of bicycles at signalized intersections using traffic conflicts technique. They found that about 77.7% of conflicts were caused by the risky behavior of the automobiles drivers that in particular did not yield right-of-way to electric-bikes/bicycles. Cherry et al. [17] examined some practical and low-cost measures to reduce the number of conflicts between bike lane occupants and right-turning vehicles at intersections. Changes including signal phase and

geometric design were proposed to achieve such goal. Sayed et al. [18] developed an automatic safety diagnosis approach for evaluating vehicle-bicycle conflicts at intersections using video analysis. Vehicle-bicycle conflicts as well as vehicle rear-end and merging conflicts were successfully identified and examined by their approach.

Klassen et al. [19] analyzed the factors that contribute to the severe bicycle-motor vehicle collisions at both intersections and mid-blocks. Results showed that significant factors affecting the intersection collision severity included the interaction between roadway and approach-control type, the existence of partial crosswalks and bike signs, and the cyclist's gender and age. Chen et al. [20] evaluated the impacts of bicycle-vehicle interactions on the capacity of left-turn vehicles at signalized intersections. A capacity-impact model was calibrated based on empirical data in Nanjing, China. Silvano et al. [21] developed a probabilistic approach to analyze vehicle-bicycle interactions at unsignalized crossings. The methodology is applied in a case study using observations at a typical Swedish roundabout.

The bicycle-vehicle interaction on street segment has been recognized as an important factor in estimating the level of service of bicycle facilities. For example, the bicycle level of service model for on-street bike lanes recommended in HCM [12] contains both bicycle flow rate and vehicle flow rate considering their interactions. Li et al. [22] reported that vehicle flow is an important factor affecting bicycle travellers' perception of comfort on on-street bike lanes and exclusive bike paths. Llorca et al. [23] investigated the behaviors of motor vehicles overtaking cyclists on two-lane rural roads. This research characterized 2928 overtaking maneuvers in the overtaking lateral clearance between motor vehicle and bicycle, as well as in the motor vehicle speed for detailed analysis.

Bella and Silvestri [24] estimated the interaction of driver and bicyclist on rural roads and evaluated the effects of cross-sections and road geometric elements. Beura et al. [25] proposed a model which is suitable for assessing the compatibility of roadways for bicycle use under complex interaction with various types of vehicles. Kassim et al. [26] examined the effects of variability in pedestrian volume on cyclist-vehicle interactions. The results showed that the pedestrian volume was found to be associated with a positive (desirable) impact on cyclist safety when vehicles yielded to the cyclists while making a right turn movement across the cyclist path. Chen et al. [27] evaluated the bicycle-vehicle conflicts on urban streets with bike lane and developed a

TABLE 1: Information about study sites.

Number	Street name	Number of vehicle lanes	Width of bike lane	On-street parking
Site 1	Houzaimen Street	1 lane	0.7 m	Yes
Site 2	Danfeng Street	2 lanes	0.7 m	Yes
Site 3	Yihe Road	1 lane	1 m	No
Site 4	Xuefu Road	1 lane	1 m	Yes
Site 5	Cigongsi Road	2 lanes	1.3 m	No
Site 6	Shengzhou Road	2 lanes	2.1 m	No

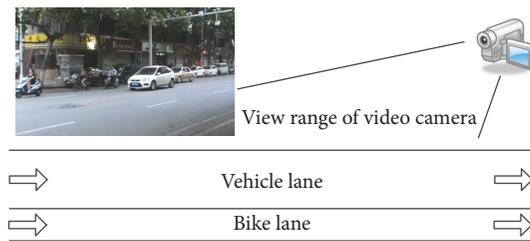


FIGURE 2: Data collection with video camera.

model to predict the vehicle delay. Two types of conflicts between bikes and vehicles, namely, the frictional conflicts and blocking conflicts, were identified from empirical data.

3. Data Collection

Field investigation was conducted to obtain the traffic flow information for the data analysis in the study. The urban streets selected for data collection should satisfy the following requirements: (1) the streets should have bike lanes with line segmentation; (2) there should be no pedestrians in the vehicle and bike lanes; (3) the selected street sections should be far away from upstream and downstream intersections such that vehicle speed is not affected by downstream intersection queue; (4) there should be no bus stops within the sections; (5) vehicle traffic flow should be free flowing within the segment section; and (6) the bicycle traffic flow should vary largely to cover most traffic situations.

Finally, six typical urban streets in Nanjing, China, were selected for data collection. The information of study sites is shown in Table 1. The width of bike lanes varies from 0.7 m to 2.1 m. The number of vehicle lanes varies from 1 to 2. Three sites have on-street parking places on the right side of the bike lanes (see Figure 1(b)). Data was collected on three workdays in good weather conditions on May, 2014. The data collection period was two hours on each site, from 8 am to 10 am, covering both peak and nonpeak periods. This is to ensure the diversity of volume and traffic component during the investigation. In the field data collection, video cameras were placed near the investigated street sections to capture the overall traffic operations, as shown in Figure 2. Six graduate students were designated to install the equipment, shoot the video, and process the data. During the data processing, the spatiotemporal information of each bicycle or vehicle

was manually extracted by investigators from video tapes. The information includes the time that a bicycle or vehicle passes a defined location, the type of bike, and the lane that the bike or vehicle travels on. The investigators were well trained to ensure the quality of data collection and information extraction. The video processing is introduced in the following section.

4. Method

Two methods are used in this study including the cumulative curve method and the generalized linear model. The cumulative curve method is used to extract the traffic flow information from the video data. The generalized linear model is used to predict the vehicle delay caused by bicycle traffic and other variables. The methods are briefly introduced in this section.

4.1. Cumulative Curve Method. The cumulative curve method can extract most of the important traffic flow parameters from video data without loss of key information [30, 31]. As shown in Figure 3(a), the arriving location A and the leaving location B are marked in the selected street section. The distance between the two locations is L . The accurate time that each bicycle front wheel passes the location A and B was recorded, which is denoted as t_A and t_B . Then the speed of the bicycle can be calculated as $v = L/(t_A - t_B)$. The type of bike (i.e., electric bike or conventional bike) and the position of bike (i.e., on bike lane or on vehicle lane when riding in the study segment) were also recorded. Note that if a bike travels on both bike lane and vehicle lane, the position was designated as the lane that the bike spends the most time travelling on. Similarly, for each vehicle, the accurate time that the front bumper passes the location A and B was recorded. The lane information for the vehicle was also recorded.

With the arriving and leaving time information of each road user, we can construct the cumulative count curves for the location A and B separately, as shown in Figure 3(b). In the figure the x -axis is the time and the y -axis is the cumulative count of bicycles/vehicles that have passed the corresponding location before the time point. With the cumulative curves, as shown in Figure 3(b), the slope of the curve within any short period Δt is the number of bicycles/vehicles that pass the location within the period, which can be calculated as traffic flow. The vertical difference between the two curves

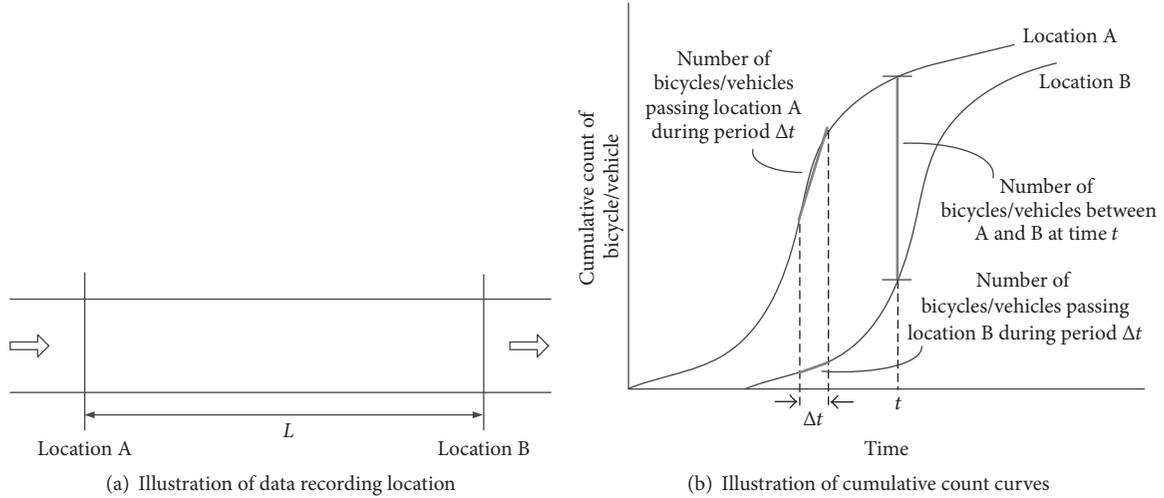


FIGURE 3: Traffic flow information extracted from cumulative curves.

at time t is the number of bicycles/vehicles within the study section at that time, which can be calculated for traffic density.

It should be noted that the density measure for bicycle traffic is different from that for vehicular traffic. The main reason is that more than one bike can occupy the same lane segment at a given instant. Some previous studies estimated bicycle density as the number of bicycles per kilometer per lane [11, 12, 32, 33]. The width for one bike lane should be around 1 meter. Thus, bike lane on sites 1 to 5 can be considered as 1 lane, while bike lane on site 5 is 2 lanes. However, in our case, bicycles ride on not only bike lane but also vehicle lanes, so that the measure of bike density in previous studies is not appropriate for our study purpose. As our study aims at evaluating the interactions between the number of bikes in study segment and the vehicle traffic operation and delay, the density of bicycle traffic was defined as the number of bikes per kilometer regardless of the width of bike lane.

Using the cumulative curve method, we can easily specify different aggregation periods for the data analysis to calculate the flow and density parameters. The individual vehicle speed can be matched with the aggregated flow and density according to the time information. The traffic flow information was then used for future analysis as presented in the following sections.

4.2. Generalized Linear Model. Generalized linear model has been widely used in many transportation studies [34]. The form of the regression model requires that the relationship between variables (or their transformations) is inherently linear. The basic model specification is

$$\mathbf{Y}_{n \times 1} = \mathbf{X}_{n \times p} \boldsymbol{\beta}_{p \times 1} + \boldsymbol{\varepsilon}_{n \times 1}, \quad (1)$$

where $\mathbf{Y}_{n \times 1}$ is the matrix of observed values of dependent variable, $\mathbf{X}_{n \times p}$ is the matrix of observed explanatory variables, $\boldsymbol{\beta}_{p \times 1}$ is the matrix of coefficients related to explanatory

variables, $\boldsymbol{\varepsilon}_{n \times 1}$ is the error term, n is the number of observations, and p is the number of predicting variables.

The expected value of dependent variable can be estimated by the explanatory variables using

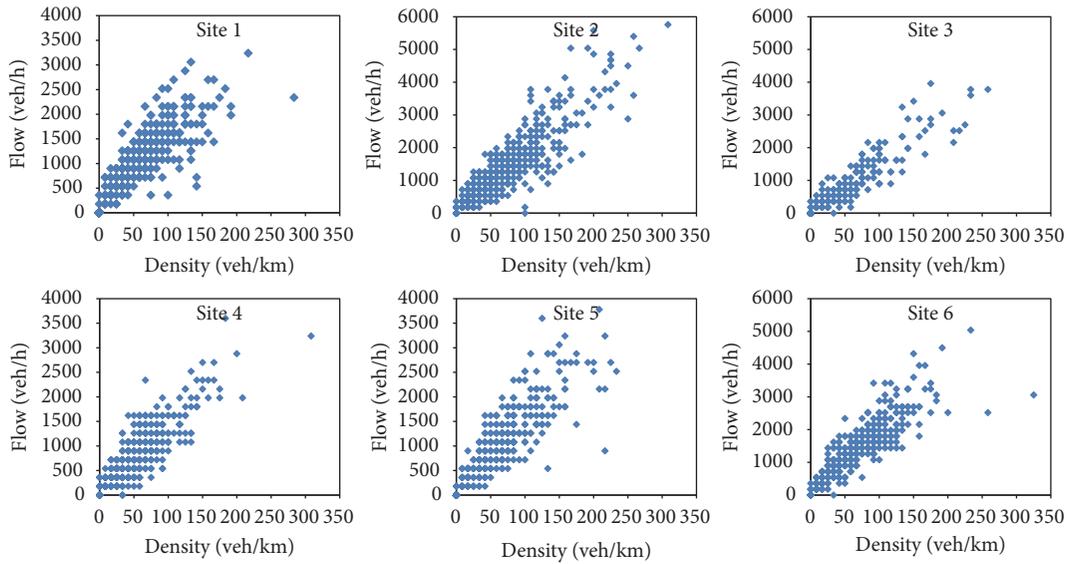
$$\hat{\mathbf{Y}} = \beta_0 + \beta_1 \mathbf{X}_1 + \beta_2 \mathbf{X}_2 + \cdots + \beta_p \mathbf{X}_p. \quad (2)$$

The parameters in the generalized linear model can be estimated by using the least squares estimation method. Readers can refer to [34] for details on the parameter estimates. In this study, the dependent variable is the delay in vehicle traffic, and the explanatory variables are the traffic flow parameters and other variables. The developed model can provide information to help understand how factors contribute to the vehicle delay on urban streets.

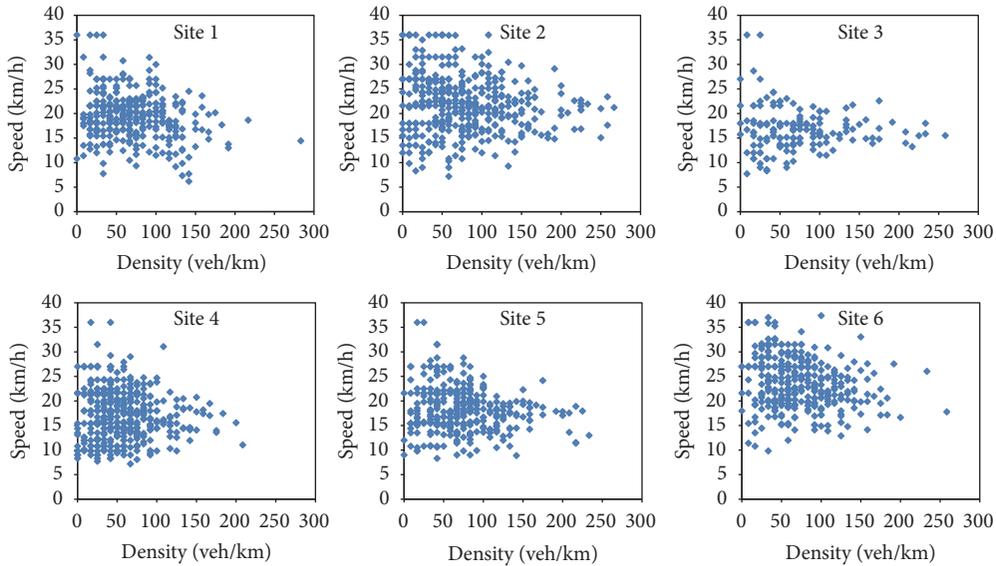
5. Results

5.1. Analysis of Traffic Flow Features. The relationships between bicycle traffic flow parameters are shown in Figure 4. Figure 4(a) shows the relationship between bicycle flow and density in each 10-second period. The flow increases linearly with the density indicating that the bicycle traffic within the street section is not congested. Figure 4(b) shows the relationship between bicycle speed and density. Two important features are identified: (1) the average bicycle speed decreases slightly as the density increases (but the flow is still increasing) and (2) when density becomes large the variation of bicycle speed decreases remarkably. This is because faster travellers are forced to ride at the average speed when there are many bicycles in the road segment. As shown in Figure 4, consistent findings are found on different urban street sections.

Figure 5(a) shows the number of bicycles that travel into vehicle lanes. It is quite clear that more bicycles travel into vehicle lanes as the bicycle density increases. Figure 5(b) shows the speeds of bicycles travelling on bike lanes and vehicle lanes. The average bicycle speed on vehicle lanes is



(a) Relationship between bicycle flow and bicycle density



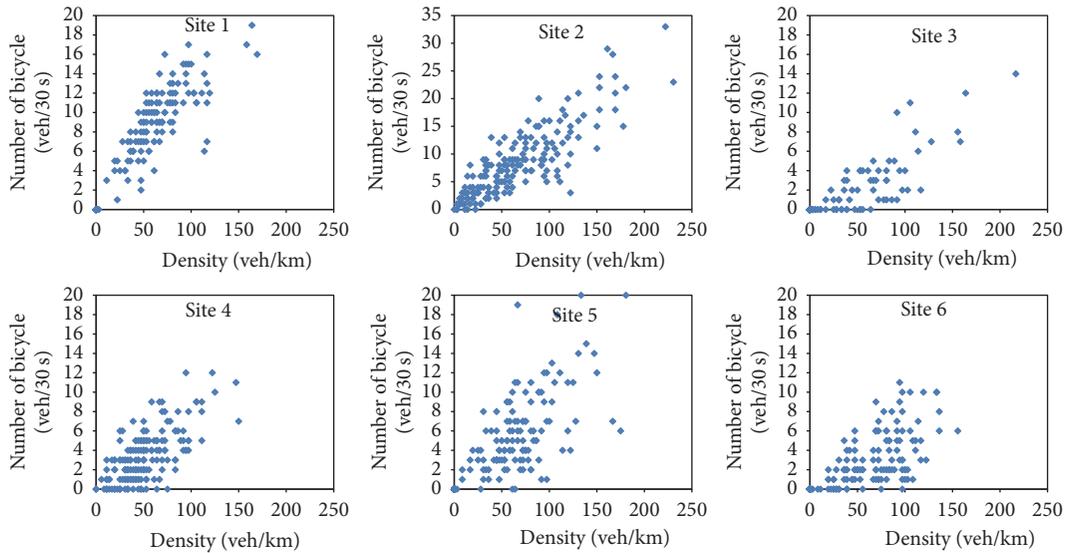
(b) Relationship between bicycle speed and bicycle density

FIGURE 4: Relationship between bicycle traffic flow parameters.

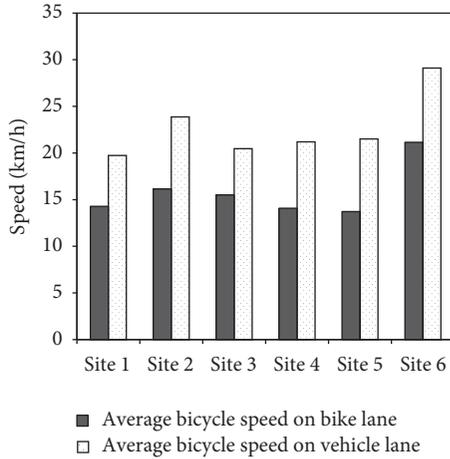
22.64 km/h, which is much higher than that on bike lanes which is 15.81 km/h. It suggests that when there are slow bicycles on bike lanes, a considerable number of cyclists tend to ride on vehicle lanes to overtake the slow cyclists to avoid travel delays. The proportion of electric bicycle on bike lanes and vehicle lanes is shown in Figure 5(c). The result shows that more than 80% of the cyclists travelling on vehicle lanes are riding electric bicycles. Most of the cyclists on bike lanes are riding conventional bicycles. It suggests that electric bicycles are more likely to be involved in collisions with motorized vehicles.

5.2. Impacts of Bicycle Traffic on Vehicle Operation. To evaluate the impacts on vehicle operation, vehicles are classified

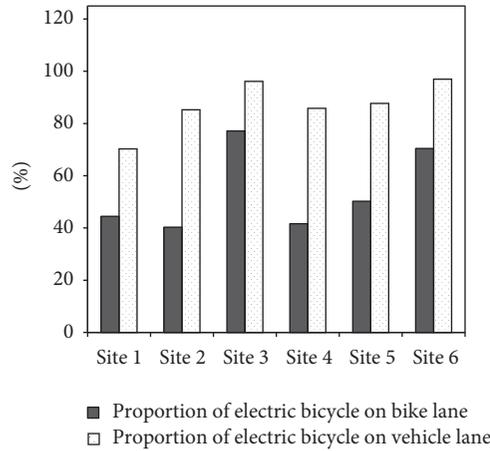
into two groups according to the travel lanes, which are the vehicles on the inner lane and the vehicles on the outer lane (see Figure 1(a)). Note that the vehicle traffic was free flowing within the study period, which means vehicle speed is not affected by vehicle flow or downstream intersection queue spillover. The vehicle speeds under different bicycle densities on the outer lane are shown in Figure 6(a). It is identified that the speeds are greatly impacted by the bicycle density. The average vehicle speed decreases as the bicycle density increases. Besides, the variation of vehicle speeds also decreases significantly because drivers are afraid of driving fast if there are many nearby bicycles. The vehicle speeds on the inner lane are shown in Figure 6(b). The speeds are less impacted by the bicycle density as compared to those on the



(a) Number of bicycles travelling on vehicle lanes



(b) Bicycle speeds on bike lane and vehicle lane



(c) Proportion of electric bicycle on bike lane and vehicle lane

FIGURE 5: Traffic flow features on bike lanes and vehicle lanes.

outer lane. The average speed and speed variation decrease slightly as bicycle density increases.

We also evaluated the relationship between vehicle speeds and the number of bicycles on vehicle lanes. Similarly to those in Figure 6, the average vehicle speed and speed variation decrease when more bicycles travel on vehicle lanes, which is consistent with intuition. The disturbance of bicycle traffic on vehicle operation is more severe on the outer lane as compared that on the inner lane. It suggests that, for those streets with only one vehicle lane, the interaction between vehicle and bicycle is more severe since vehicles do not have other lane choices. Attention with priority should be paid to those kinds of streets to implement countermeasures in order to improve the traffic operations. Vehicle traffic on the streets with more travel lanes is less impacted by the bicycle traffic.

5.3. Modeling Results of Vehicle Delay. A generalized linear model was developed to evaluate the relationship between

vehicle delay and explanatory variables. Delay was calculated as the difference in the time when each vehicle travels through the road section in the reduced speed and in the free flow speed. Considering the fact that several variables such as bicycle density and the number of bicycles travelling on vehicle lanes are hard to measure in practice, those variables were not included in the model. Only those variables that can be measured in practice were included in the model development, which include the vehicle flow, bicycle flow, number of vehicle lanes, width of bike lane, proportion of electric bicycles, and presence of on-street parking.

The modeling results are shown in Table 2. It is identified that four explanatory variables are significantly related to the average vehicle delay on urban streets. The modeling results also show how these variables affect the delay of vehicle traffic. The vehicle delay increases as the bicycle flow increases; a thousand unit of increase in bicycle flow will increase the delay per vehicle by 32.67 second/km. A thousand unit of

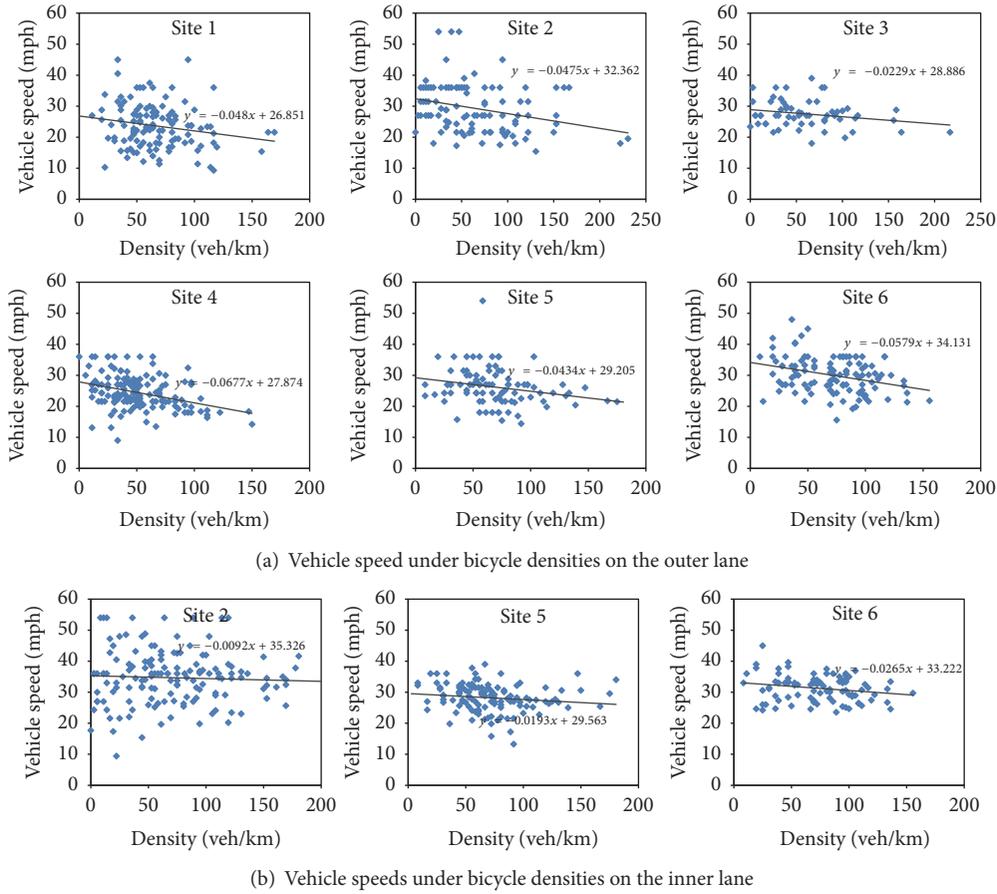


FIGURE 6: Vehicle speeds under different density conditions.

TABLE 2: Modeling results of vehicle delay.

Variable	Coef.	Std. err.	z	P > z	[95% conf. interval]
Bicycle flow (thousand)	32.67	7.67	4.29	<0.001	[17.33, 48.00]
Vehicle flow (thousand)	38.00	8.67	4.35	<0.001	[20.67, 55.33]
Number of vehicle lanes	-30.87	3.03	-10.12	<0.001	[-36.93, -24.80]
Width of bike lane	-5.83	3.10	-1.88	0.061	[-12.03, 0.367]
Constant	80.43	5.07	15.85	<0.001	[70.30, 90.57]

Statistics. log likelihood = -1077.782; Prob = <0.001; AIC = 3.063.

increase in vehicle flow will increase the delay per vehicle by 38.00 second/km. There is less vehicle delay on the streets with more vehicle lanes since the variable coefficient is negative. For the same traffic situation, increasing vehicle lane from 1 to 2 will decrease the vehicle delay by 30.87 second/km. Moreover, the width of bike lanes on street is negatively related to the vehicle delay, indicating that there is less delay on the streets with wider bike lanes.

The proportion of electric bicycles is not found to be significantly related to the delay of vehicles on urban streets. The result is a little counterintuitive since this study has shown that electric bicycles are more likely to run into vehicle lanes. The possible reason for the result would be that the need of overtaking due to the speed differences in bicycle

traffic is the primary cause for a cyclist to run into vehicle lanes. If most of the cyclists are electric bicycle users, the speed difference between cyclists is actually quite small. As a consequence, they may run within the bike lanes without disturbing adjacent vehicle traffic. Besides, the presence of on-street parking is not found to have significant impact on the vehicle delay.

6. Conclusions and Discussion

This study evaluated the impacts of bicycle traffic on the operation of vehicle traffic on urban streets with on-street bike lanes. Video data was collected on six street sections

in Nanjing, China. The cumulative curve method was considered to extract the individual bicycle/vehicle speeds and aggregated traffic parameters including the flow and density. The traffic flow features and the impacts of bicycle traffic on vehicle speeds were first analyzed. Then a generalized linear model was developed to predict the vehicle delay using various explanatory variables.

The results of the study showed that the average bicycle speed as well as the speed variation decrease as the bicycle density increases. More bicycles travel into vehicle lanes as the bicycle density increases. The average speed of those bicycles is much higher than that on bicycle lanes. And electric bicycles are more likely to run into vehicle lanes. The average vehicle speed as well as the speed variation decrease as the bicycle density or the number of bicycles in vehicle lanes increase. The modeling results showed that four variables significantly affect the delay in vehicle traffic on urban streets, which are the bicycle flow, vehicle flow, number of vehicle lanes, and width of bike lanes. The impacts of those variables can be quantified according to the parameter coefficients.

Though data were collected under the environment in China, findings of the study can also provide information for bicycle infrastructure design in other regions. Bicycle traffic flow is increasing in many countries in the past, resulting in needs of design of bike lanes on many streets in urban areas. Though some driving behaviors may be different between China and other countries, the interferences between bicycles and vehicles on public roads remain.

The findings of this study can provide useful information for policy making. The delay contour can be constructed using the model estimated in our study. The delay contour shows how the delay changes with respect to the bicycle and vehicle flow. For a local street, if the estimated delay falls into the unacceptable delay zone (e.g., exceeds tolerable delay threshold), countermeasures are required to improve the operation of traffic on the street. Besides, the proposed model can be used to predict the traffic operational features in the future with increased bicycle flow. Furthermore, the model can also be used to evaluate the impacts of some polices, such as expanding/reducing bike lane width, on the operations of vehicle traffic and bicycle traffic.

On many streets within urban areas, there is no on-street bike lane such that bicycles and vehicles are forced to run on the same travel lane. Under such condition the impact of bicycle traffic on vehicle operation could be different from what is presented in our study. The models developed in this study cannot be directly used to evaluate vehicle delay on those bicycle-vehicle shared-use paths. In the future, study effects could be put on evaluating the interactions between bicycles and vehicles in mixed traffic flow on shared-use paths. The results can be compared with those in the present study to give some instructions on the on-street bike lane designs. In addition, this study only collected traffic data from six roadway segments in one Chinese city. More data could be collected from multiple streets in more cities or countries to validate the findings in the study and calibrate the delay model. The authors recommend that future studies could focus on resolving those issues.

Disclosure

This paper is a revised version of an original one which was presented at the 95th Annual Meeting of Transportation Research Board.

Conflicts of Interest

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

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