

Research Article

Evaluating the Impacts of Bus Stop Design and Bus Dwelling on Operations of Multitype Road Users

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On urban streets with bus stops, bus arrivals can disrupt traffic flows in the neighboring areas. Different stop designs have distinct influences on the road users. This study aims to evaluate how different types of bus stops affect the operations of vehicles, bicycles, and buses that pass by. Four types of stops that differ in geometric layout are examined. They are termed the shared bike/bus (Type 1), separated shared bike/bus (Type 2), vehicle/bus with inboard bike lane (Type 3), and bus bay with inboard bike lane (Type 4). Data are collected from eight sites in two cities of China. Results of data analysis show that different bus stop designs have quite different impacts on the neighboring traffic flows. More specifically, Type 3 stops create the least bicycle delay but the largest vehicle delay. Type 4 stops have the least impact on bicycle and vehicle operations, but occupy the most road space. Traffic operations are less affected by Type 1 stops than by Type 2 stops. Policy suggestions are discussed regarding the optimal design of bus stops that minimizes the total vehicle delay of all modes.

1. Introduction

In recent years, as urban streets becoming more congested, many cities and countries have considered developing public transit systems within urban areas [1–8]. On urban streets with bus lines, bus stops are usually designed on roadsides to allow travelers to get on/off buses. Bus dwelling could disturb the continuing traffic flow in the neighboring areas posting excessive delays to road users. Evaluating the influence of bus stops on the operations of traffic flow can provide useful information to city planners for the design of bus stops.

Previous studies have evaluated traffic operations near bus stops. Some studies evaluated the traffic flow characteristics in the vicinity of stops [9–13]. For example, Sun and

Elefteriadou [13] analyzed the characteristics of vehicle lane-changing behaviors near the bus stops. Tirachini et al. [11] evaluated the impact of the passenger crowding at the bus stops on the operations and travel time of buses. Some other studies focused on evaluating the conflicts between different road users near the bus stop areas [14–18]. For example, Zhao et al. [16] evaluated the traffic interactions between the motorized and nonmotorized vehicles near a bus stop. However, the above studies did not distinguish the types of bus stop designs.

Until recently, only a few studies have compared the operation features between different types of bus stops [19–22]. For example, Koshy et al. [19] compared the influence of

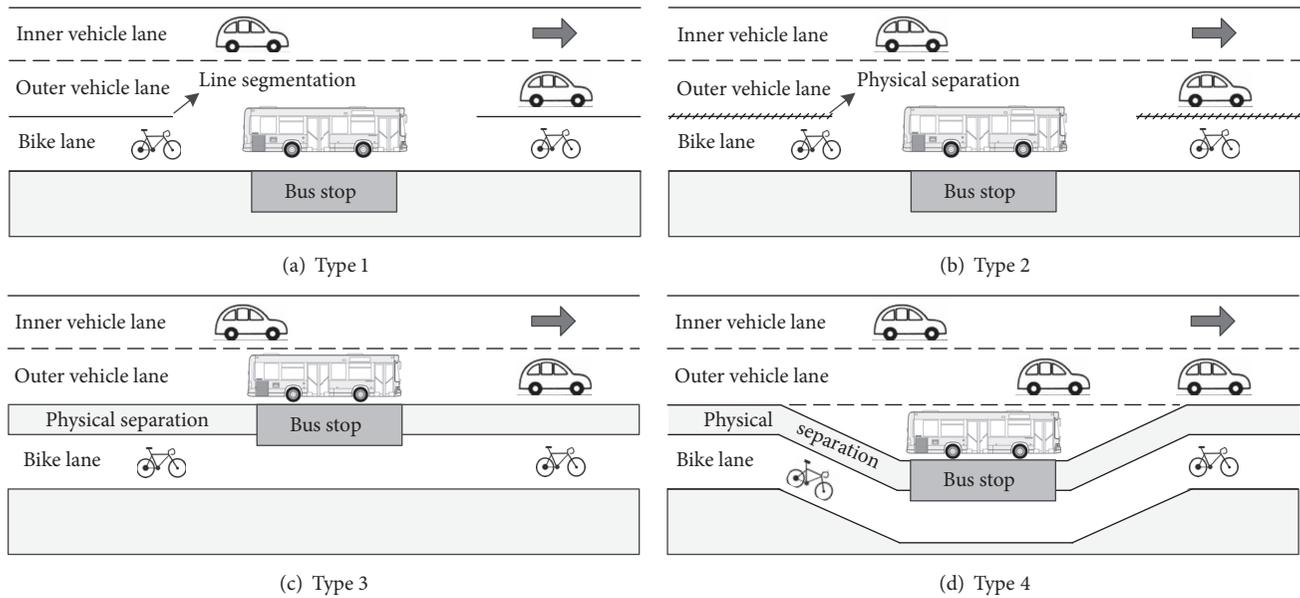


FIGURE 1: Illustration of four types of bus stops [21].

the curbside stops and bus bays on the operation of vehicles. Results showed that the average vehicle speed decreased rapidly at the curbside stops. However, the study was conducted in the simulation environment without validating the findings with actual data. Zhao et al. [20] evaluated the interactions between buses and bicycles at different stops. However, they only analyzed the impacts on bicycle speeds. The study did not evaluate how different bus stop designs impact the operations of vehicles and buses. As a result, it is still not quite clear to policy makers for what type of bus stop should be considered to minimize delay.

The primary objective of the study is to evaluate how different bus stop designs influence the operations of neighboring traffic. Four bus stops that differ in geometric layout were considered. With data collected in the field, the delay of vehicles, bicycles, and buses was evaluated for each stop. In the following section, data collection is presented. In Section 3, methodologies used in the study are introduced. Results of data analysis are shown in Section 4. The policy suggestions are given in Section 5. The paper ends with brief concluding remarks and future work in Section 6.

2. Data Collection

The research team carefully examined the current designs of bus stops on urban streets in several cities of China. Bus stops are usually implemented on the right side of urban streets. Bike lanes are usually provided to accommodate the large cycling demand. After a careful examination, four most common types of bus stops are identified, as illustrated in Figure 1.

Type 1 bus stop contains the shared bike/bus lane (see Figure 1(a)). Bike lane is designed on the right side of the vehicle lanes. Arriving bus occupies the space of bike lane. Bicycles go through the stop from either the right side or the left side of the bus.

Type 2 bus stop contains the separated shared bike/bus lane (see Figure 1(b)). Bike lane is physically separated from the vehicle lanes except for the short section near the bus stop. Arriving bus occupies the space of bike lane. Bicycles go through the stop from either the right side or the left side of the bus.

Type 3 bus stop contains the shared vehicle/bus lane with the separated inboard bike lane (see Figure 1(c)). Bike lane is separated from the vehicle lanes and the bus stop is a curbside design. Arriving bus occupies the space of the outer vehicle lane. Vehicles may shift to the inner lanes to pass the bus or wait after the bus in the outer lane.

Type 4 bus stop contains a bay design with the separated inboard bike lane (see Figure 1(d)). Arriving bus goes into the bay to drop off and pick up passengers. Bus does not occupy the space of vehicle lane or bike lane.

Field investigations were conducted to obtain the traffic flow data in the vicinity of the bus stops. The study sites selected for data collection should satisfy the following requirements: (1) the sites should have typical types of bus stops; (2) there should be no pedestrians in the bus lane and the bike lane; (3) the bus stop should be far away from the upstream and downstream intersections so that there is no spill back traffic; and (4) there are no junctions and taxi/truck loading areas nearby that might disrupt the traffic.

The flow of vehicles and bicycles may affect the delay of road users. For example, if vehicle flow is high, lane changes are more difficult and cars would not be able to avoid the bus by using the inner lane. Besides, with large traffic flow the travel delay may not only be because of the bus dwelling, but also the traffic flow itself. For such considerations, we selected the sites with low traffic demand so that traffic is in free flow condition during investigation. Though bus stops will create more serious problem in congested traffic, in most of the times traffic flow near bus stop is free flowing. Thus, this

TABLE 1: Information of study sites [21].

Number	Street name	Stop type	Bus arrival frequency	Vehicle flow (veh/h)	bicycle flow (bike/h)
Site 1	Hunan Rd, Nanjing	Type 1	1.9 min	653	1023
Site 2	Shanxi Rd, Nanjing	Type 2	1.1 min	726	1333
Site 3	Hongwu Rd, Nanjing	Type 3	1.42 min	707	874
Site 4	Houbiaoying Rd, Nanjing	Type 4	0.8 min	984	612
Site 5	Longsheng Rd, Shanghai	Type 1	1.7 min	1084	1179
Site 6	Renmin Rd, Shanghai	Type 2	1.5 min	953	980
Site 7	Wenchang Rd, Shanghai	Type 3	1.1 min	902	1209
Site 8	Wenhui Rd, Shanghai	Type 4	1.2 min	828	787

study only focused on the general free flow situation leaving the congested situation as a future research task.

Finally, eight streets in the urban areas in Nanjing and Shanghai, China, were selected for data collection. The information of study sites are shown in Table 1. Field data were collected on weekdays with the fine weather in May and June 2014. Video cameras were properly placed on the tall buildings near the investigated sites to capture the overall traffic operations (see Figure 2). Each site contained 1.5 hour video data during nonpeak period from 9:30 to 11:00 AM. The street segment includes three sections which are the upstream section, bus stop section, and downstream section. From the videos we observed that most of bus dwelling maneuvers are within 15 meters near the stop which is used to decide the length of upstream and downstream sections. The total length of each investigated segment is 50 meters.

3. Method

Two methods were considered in this study. The first method was to extract the traffic information from the video camera data. Student's *t*-test was then used to examine if the difference between groups was statistically significant. The methods are briefly introduced.

3.1. Extraction of Traffic Flow Information. Traffic flow information of bicycles, vehicles, and buses were extracted from the video camera data. As shown in Figure 3(a), the arriving location A and leaving location B are marked in the investigated street section. The distance between the two locations is $L=15$ meters. During the data processing procedure, the time that each bicycle/vehicle passed the locations A and B was recorded as t_A and t_B . Then the speed of bicycle/vehicle can be calculated as $v=L/(t_A-t_B)$. The type of bike (i.e., electric bike or conventional bike) was recorded by manually check the physical appearances of bikes as well as the motion characteristics of the riders. In addition, the position of bike (i.e., passing from the left side or the right side) was also recorded in the video processing. The position of each vehicle (i.e., inner lane or outer lane) was recorded simultaneously.

With the time information, we can construct the cumulative count curves for the locations A and B separately, as shown in Figure 3(b). The x-axis is the time and the y-axis is the cumulative count of bicycle/vehicle that have passing

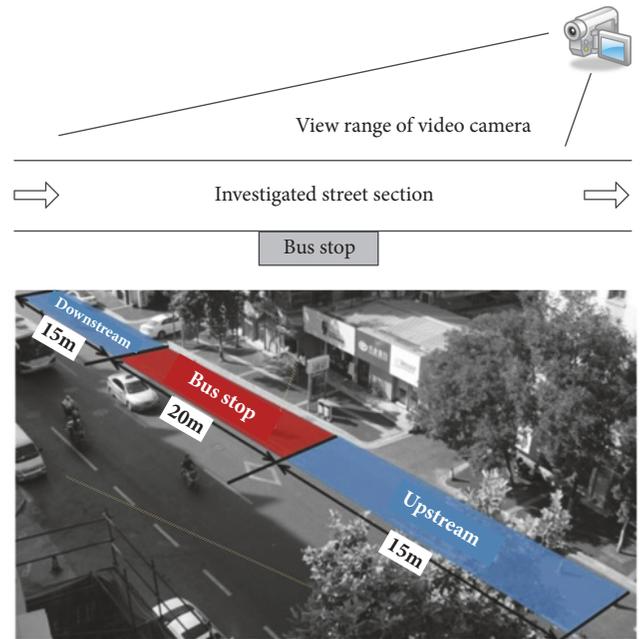


FIGURE 2: Data collection with video camera [21].

the corresponding location before the time point. The slope of the curve within any short period Δt is the number of bicycle/vehicles that passes the location within the period, which can be calculated for the traffic flow. The vertical difference between the two curves at time t can be calculated for the traffic density. The average speed can be calculated for each time period [23].

For each bus, four types of time information were recorded including the time that the bus passed the location A (t_A), the time that the bus completed the full stop (t_{STOP}), the time that the bus started leaving (t_{START}), and the time that the bus passed the location B (t_B). With the time information on locations A and B, the status of bus station, i.e., occupied by bus or no bus, was obtained for each time slice. The operation of buses at different stops was evaluated with the bus stopping and leaving time information.

3.2. Student's *t*-Test. Student's *t*-test has been extensively used to identify if the difference between two population

TABLE 2: Statistical tests for speed differences of all bicycles [21].

Speed	With bus at stop			Without bus at stop			ΔV_{Mean}^c (km/h)	p -value
	Sample size	V_{Mean}^a (km/h)	V_{Std}^b (km/h)	Sample size	V_{Mean} (km/h)	V_{Std} (km/h)		
Type 1	38	13.12	2.21	82	15.91	4.83	2.79	<0.001
Type 2	114	14.61	4.48	160	17.37	7.12	2.76	<0.001
Type 3	176	14.56	3.33	158	15.62	5.38	1.06	<0.001
Type 4	28	14.07	1.74	72	15.36	5.06	1.29	<0.005

^aMean bicycle speed including electric bicycles and conventional bicycles.

^bStandard deviation of bicycle speed including electric bicycles and conventional bicycles.

^cDifference between mean speed with bus at stop and without bus at stop.

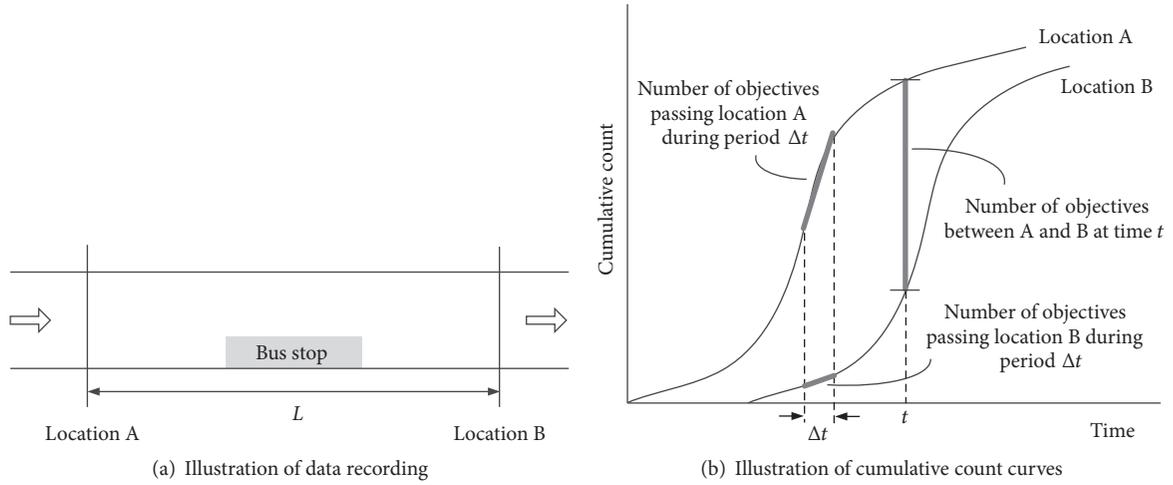


FIGURE 3: Illustration of data extraction from video camera.

means is statistically significant [24]. In this study, the t -test was conducted to identify if the difference of speeds was statistically significant. Let μ_1 be the mean of average bicycle/vehicle speed when no bus was at the stop station and μ_2 be the mean of average bicycle/vehicle speed when the stop was occupied by bus. The sample standard deviations s_1 and s_2 were obtained for the two groups with the sample size n_1 and n_2 , respectively.

The hypothesis states that

$$H_0: \mu_1 = \mu_2 \quad (1)$$

can be rejected if

$$t = \frac{|\mu_1 - \mu_2|}{\sqrt{s_1^2/n_1 + s_2^2/n_2}} \geq t_{\alpha/2} \quad (2)$$

where α is the level of significance and $t_{\alpha/2}$ is the 100(1- α)/2 % percentile of t distribution. The corresponding p -value of the test is given by

$$p = \Pr \left(|t| \geq \frac{|\mu_1 - \mu_2|}{\sqrt{s_1^2/n_1 + s_2^2/n_2}} \right) \quad (3)$$

4. Results of Data Analysis

The impact of bus stop on the bicycle traffic flow was first evaluated. Then the impact on the vehicle traffic was analyzed. We also evaluated the bus operation at different bus stops.

4.1. Impact of Bus Stop on Bicycle Traffic. Speed is an intuitional measure of how traffic flow operates. It reflects the travel time and delay status. Bicycle speed in the situation when bus stop is occupied or there is no bus was calculated. Electric bikes and conventional bikes were analyzed separately. Average bicycle speed at each bus stop is shown in Figure 4. At the Type 1 and Type 2 stops, the bicycle speed when the stop is occupied is obviously lower than that when there is no bus. The reduction of electric bike speed is larger than the conventional bike. At the Type 3 and Type 4 stops, the arrival of bus does not largely impact the speed of bicycles. The electric bicycle speed is reduced slightly.

Student's t -test was conducted to identify if the difference in bicycle speeds was statistically significant. The results are shown in Table 2. All the t -tests are significant at a 95% significance level. It indicates that bus dwelling has a significant impact on the speed of bicycle traffic. Type 1 and Type 2 stop reduce the average speed by 2.76 to 2.79 km/h, because the bus occupies the space of bike lane and blocks the maneuvers of bicyclists. Type 3 and Type 4 stop

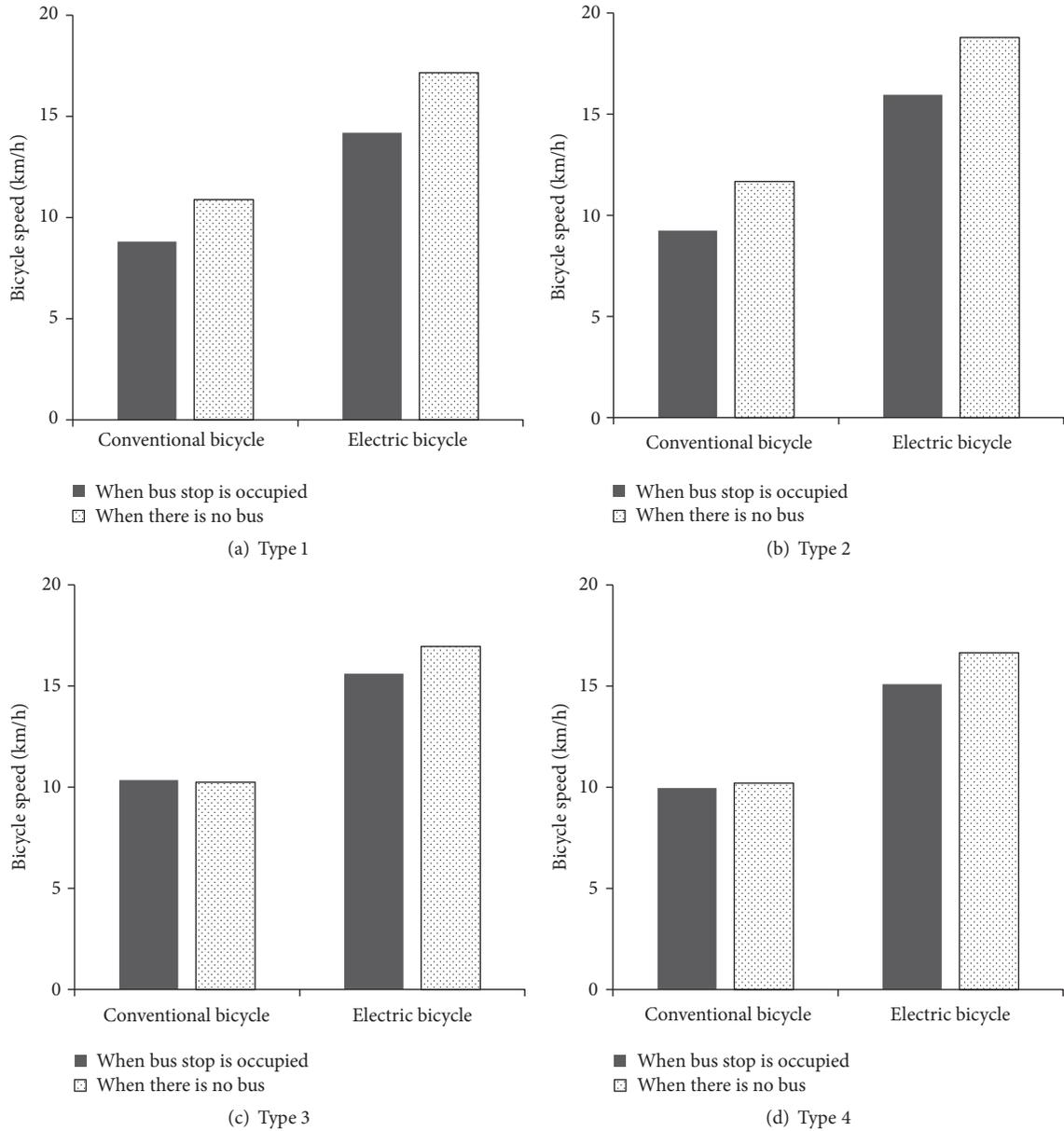


FIGURE 4: Bicycle speeds at different types of bus stops [21].

reduce the average speed only by 1.06 to 1.29 km/h. Because of the physical separation between buses and bicycles, the interactions between them are reduced. The slight reduction of speed is probably due to the passengers' getting on/off behaviors.

4.2. Impact of Bus Stop on Vehicle Traffic. We first validated that vehicle traffic is in free flow condition. The reduction of vehicle speed in the inner lane and outer lane was calculated, as shown in Figure 5. Bus dwelling has a large impact on the vehicle speed in the outer lane, but has a minor impact in the inner lane. The quantitative influences of bus stops were calculated as shown in Table 3. Students' t-test results show that the differences in vehicle speeds are all statistically significant at a 95% significance level.

The results in Table 3 show that Type 3 stop has the largest impact on vehicle speed, followed by the Type 2 stop. The average vehicle speed is reduced by 6.82 and 6.06 km/h, respectively. Type 4 stop only decreases the vehicle speed by 2.19 km/h which is much smaller as compared to other stops. Especially on the outer vehicle lane, the Type 4 bus stop reduces average vehicle speed by 14.3%, which is much lower than that for the Type 1 (28.4%), Type 2 (24.3%), and Type 3 (33.2%). It suggests that the bus bay design in Type 4 stop can remarkably reduce the conflicts between the buses and the vehicle traffic. Type 1 stop has slightly smaller impact on the vehicle speed as compared to Type 2 stop. This would be because that driver near the Type 1 stop observes the overall traffic situation better than near the Type 2 stop and would take proactive action to avoid potential travel delay. Type 3 stop

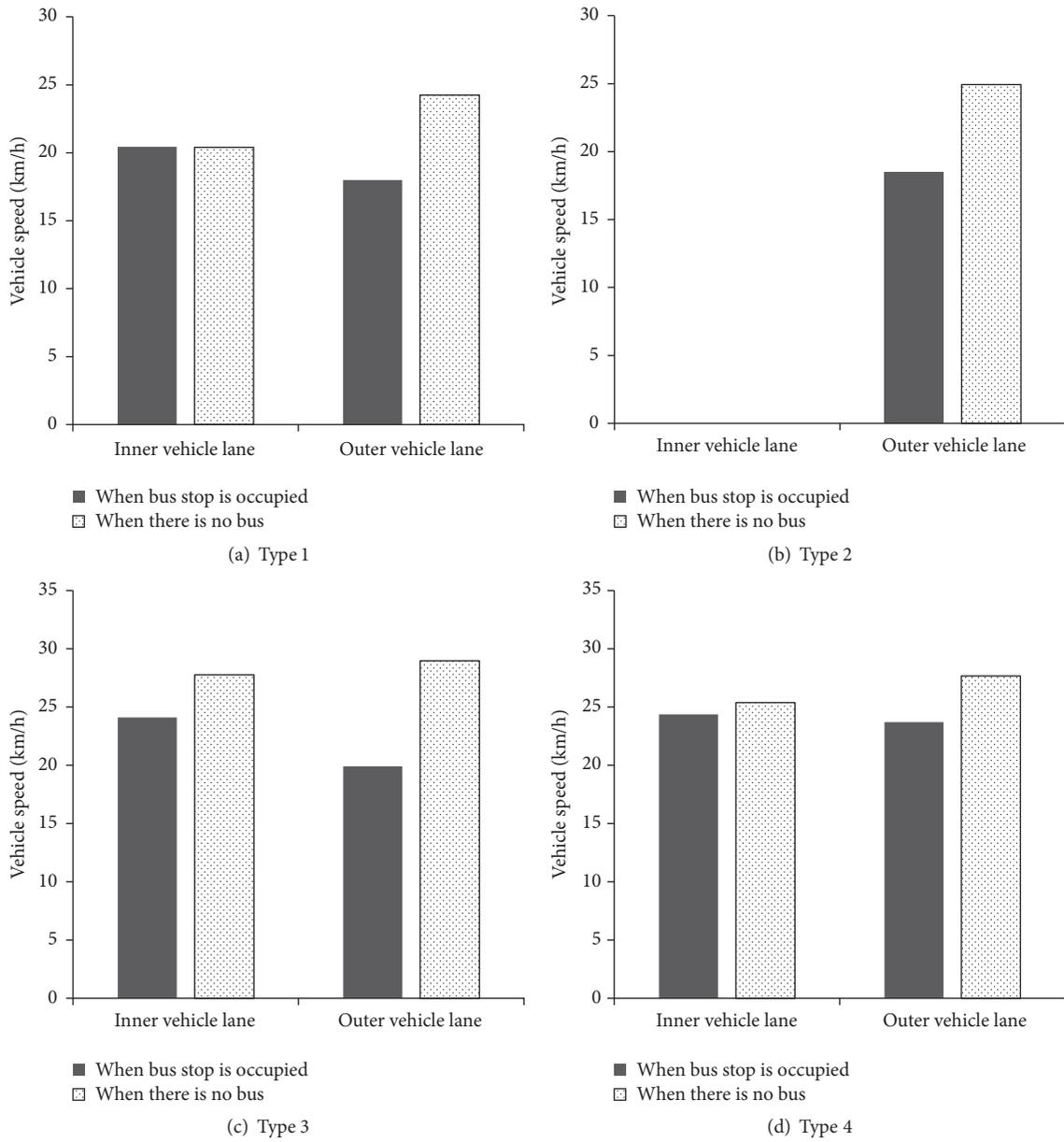


FIGURE 5: Vehicle speeds at different types of bus stop areas [21].

TABLE 3: Statistical tests for speed differences of all vehicles [21].

Speed	With bus at stop			Without bus at stop			ΔV_{Mean}^c (km/h)	<i>p</i> -value
	Sample size	V_{Mean}^a (km/h)	V_{Std}^b (km/h)	Sample size	V_{Mean} (km/h)	V_{Std} (km/h)		
Type 1	26	18.22	3.82	156	22.32	4.94	4.10	<0.001
Type 2	76	18.87	4.66	170	24.93	6.17	6.06	<0.001
Type 3	144	21.43	6.32	178	28.24	7.87	6.82	<0.001
Type 4	102	24.10	7.24	156	26.29	8.29	2.19	<0.001

^aMean vehicle speed on the two travel lanes.^bStandard deviation of vehicle speed on the two travel lanes.^cDifference between mean speed with bus at stop and without bus at stop.

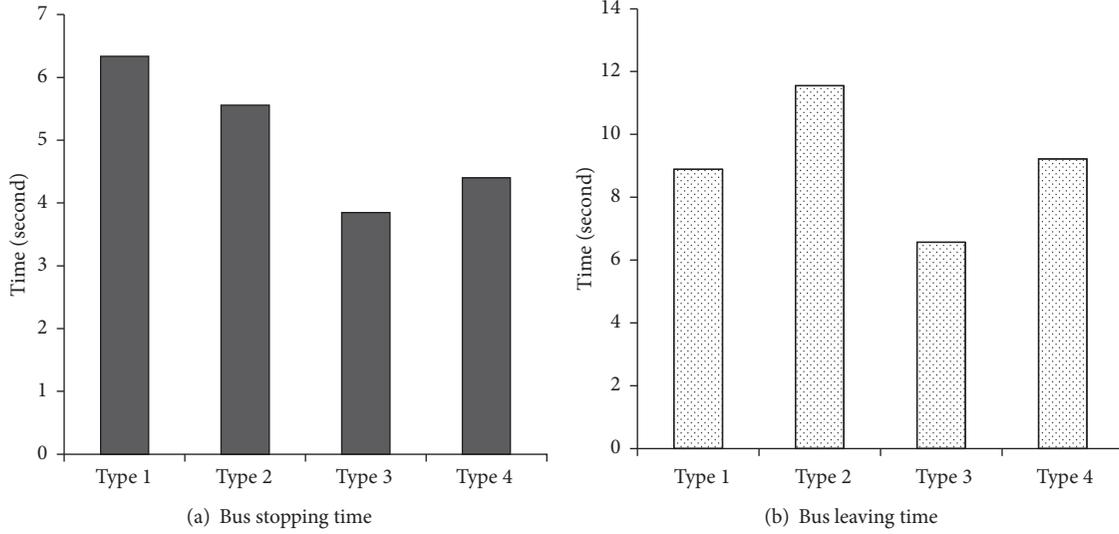


FIGURE 6: Bus operations at different types of bus stop areas [21].

has the largest impact on vehicle speed, because the arrival of bus occupies the vehicle travel lane and blocks the continuing vehicle traffic.

4.3. Impact of Bus Stop on Bus Operation. The study calculated two measures to present the operations of buses. The bus stopping time was calculated as the difference between the time that a bus reaches upstream section (t_A) and the time that the bus fully stops before passengers getting off (t_{STOP}). The measure indicates if a bus can complete the stopping action easily. The bus leaving time was calculated as the difference between the time that a bus starts to run after passengers getting on (t_{START}) and the time that the bus leaves downstream section (t_B). It indicates the easiness of merging into the street mainline. To ensure there is no spillover from stops, the research team excluded the data that contains two or more buses at the same time. The bus stopping time and leaving time at each stop are shown in Figure 6.

The results show that Type 3 stop has the shorted bus stopping and leaving time. It suggests a bus could complete the stopping and merging actions quickly, and the bus operation is less impacted by other road users. A bus also completes the stopping action easily at the Type 4 stop, but has difficulties in merging into the street mainline due to the bay design. Type 1 and Type 2 bus stop have a relatively longer time in the stopping and leaving process than Type 4 stop. This result is a little counterintuitive since people expect that it would be more difficult for a bus to reenter traffic from a taper. The possible reason would be that a bus driver could drive really cautiously to avoid the potential conflicts with bicycles nearby. It takes longer time than avoiding conflicts with vehicles. Type 2 stop has a longer bus leaving time than Type 1 stop, probably because a bus driver needs to avoid the physical separation barrier in the ahead street.

5. Policy Suggestions

Analyses in the above sections suggest that traffic operations are quite different at different types of bus stops, resulting

in different influences on the delay of bicycles, vehicles, and buses. The advantages and disadvantages of the four stops are summarized in Figure 7. Four measurements are considered which are the decrease in bicycle speed, decrease in vehicle speed, bus stopping plus leaving time, and number of occupied lanes. It is quite clear that Type 1 and Type 2 bus stops have a large impact on the bicycle speed and a moderate impact on the vehicle speed. The two stops have a large impact on the bus operation, and require the moderate road space. Type 3 bus stop has the least impact on the bicycle traffic but has the largest impact on the vehicle traffic. Type 4 bus stop has the smallest impact on both the bicycle and the vehicle traffic. It requires the most travel lanes and occupies the largest road resource.

Findings of this study can help city planners to decide which bus stop design should be considered under different situations. More specifically, if city planners would like to reduce the bicycle and vehicle delay, Type 4 stop is recommended for application if urban street has enough space for the bay design. Otherwise, if the road resource is limited and city planners would reduce the vehicle delay, Type 1 stop is recommended. Type 3 stop is recommended if the bus operation is the primary consideration.

A quantitative procedure is proposed to help select bus stops to minimize the total person delay by all modes for the study segment. The utility function u_i for a stop type i is defined as

$$u_i = - \left(D_i^{BIC} + D_i^{VEH} + D_i^{BUS} \right) \cdot (S_i)^k \quad (4)$$

$$D_i^{BIC} = F_i^{E-BIC} \cdot \left(\frac{L}{\bar{V}_i^{E-BIC}} - \frac{L}{\bar{V}_i^{E-BIC}} \right) + F_i^{C-BIC} \cdot \left(\frac{L}{\bar{V}_i^{C-BIC}} - \frac{L}{\bar{V}_i^{C-BIC}} \right) \quad (5)$$

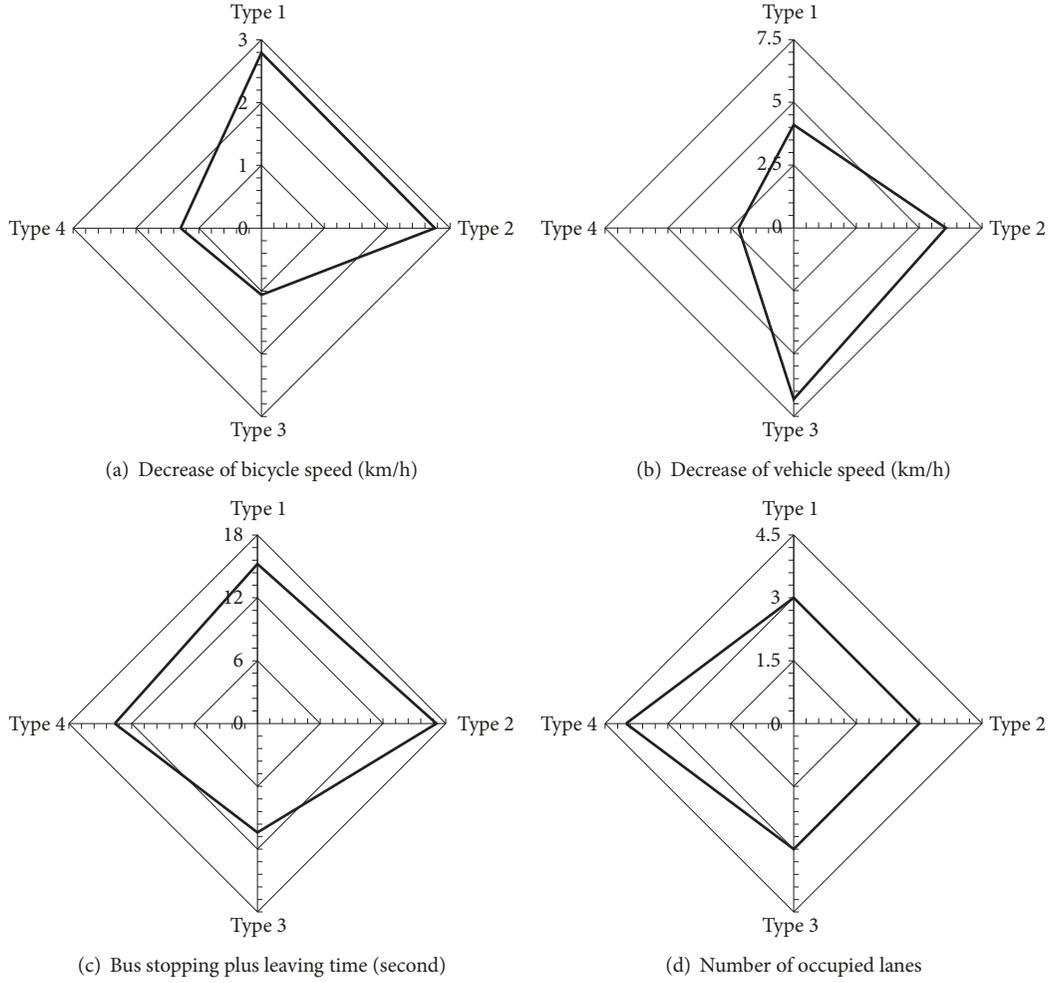


FIGURE 7: Summary of impacts of different bus stops [21].

$$D_i^{VEH} = F_i^{I-VEH} \cdot \left(\frac{L}{\bar{V}_i^{I-VEH}} - \frac{L}{\bar{V}_i^{I-VEH}} \right) + F_i^{O-VEH} \cdot \left(\frac{L}{\bar{V}_i^{O-VEH}} - \frac{L}{\bar{V}_i^{I-VEH}} \right) \quad (6)$$

$$D_i^{BUS} = F_i^{BUS} \cdot \bar{P}_i^{BUS} \cdot (\bar{T}_i^{STOP} + \bar{T}_i^{LEAV} - \bar{T}_i) \quad (7)$$

where D_i^{BIC} is the bicycle delay at stop i , D_i^{VEH} is the vehicle delay at stop i , D_i^{BUS} is the bus delay at stop i , S_i is the space requirement at stop i , κ is the parameter which decides the importance of road resource, F_i^{E-BIC} and F_i^{C-BIC} are the flow rate of electric and conventional bicycle, \bar{V}_i^{E-BIC} and \bar{V}_i^{C-BIC} are the average bicycle speed when stop is occupied by bus, $\bar{V}_i^{I-E-BIC}$ and $\bar{V}_i^{I-C-BIC}$ are the average bicycle speed without a bus at stop, L is the street segment length, F_i^{I-VEH} and F_i^{O-VEH} are the vehicle flow rate on the inner and outer lane, \bar{V}_i^{I-VEH} and \bar{V}_i^{O-VEH} are the average vehicle speed when stop is occupied by bus, \bar{V}_i^{I-VEH} and \bar{V}_i^{O-VEH} are the average vehicle

speed without a bus at stop, F_i^{BUS} is the bus frequency, \bar{P}_i^{BUS} is the average passenger number per bus, \bar{T}_i^{STOP} is the average bus stopping time, \bar{T}_i^{LEAV} is the average bus leaving time, and \bar{T}_i is the average bus traveling time without dwelling.

In the practical application, the utility value for each bus stop can be calculated using (4) to (7) given the traffic flow information in the street segment of interest. The bus stop with the largest utility value is selected the optimum to minimize the total delay. An example of bus stop selection is given in this section. The geometric and traffic parameters for a street segment in Nanjing are shown in Table 4. The parameter κ is set to be 1. The utility value of each stop is calculated in the table. According to the results, Type 3 stop is considered the best design for the delay minimization. The same procedure can be followed to decide how existing bus stops can be redesigned to improve the traffic operations.

6. Conclusions and Recommendations

This study evaluated the influences of the bus stop designs on the operations of bicycles, vehicles, and buses. Four common stop types were considered. Field investigations

TABLE 4: Procedure for bus stop selection.

Parameters	Value			
Length of street segment (m)	50			
Flow of electric bicycle (bic/h)	600			
Flow of conventional bicycle (bic/h)	400			
Flow of vehicle in inner lane (veh/h)	550			
Flow of vehicle in outer lane (veh/h)	450			
Frequency of bus (bus/h)	12			
Average passenger number per bus (person)	20			
Average bus traveling time without dwelling (sec)	6			
κ	1			
Results	Type 1	Type 2	Type 3	Type 4
Total bicycle delay (h)	0.798	0.734	0.134	0.234
Total vehicle delay (h)	0.319	0.386	0.504	0.181
Total bus delay (h)	0.615	0.741	0.295	0.508
Utility in the delay model	-5.196	-5.583	-2.798	-3.690

were conducted to collect traffic information such as flow and speed. Results of data analysis showed that the bus dwelling process had impacts on the operations of different road users. The average bicycle speed was reduced by 1.06 to 2.79 km/h when the bus stop was occupied as compared to the no bus case. The average vehicle speed was reduced by 2.19 to 6.82 km/h. The bus stopping time and leaving time were also evaluated.

The results in the study showed that different bus stop designs had quite different impacts on traffic flow. Type 3 stop had the least impact on bicycle speed and delay, but had the largest impact on vehicle speed and delay. Type 4 stop did not disturb bicycle and vehicle traffic, but occupied the most road space and also limited the number of buses able to stop. The advantages and disadvantages of each stop design were summarized in the study. A quantitative procedure was proposed to help city planners to decide which bus stop to consider for minimizing the total delay of all modes. The same procedure can be followed to decide how to redesign current bus stops to improve the traffic operations.

The study also has several limitations. First, the study only considered the street segments with free flow traffic conditions and low bus volumes. Traffic operations could be very different in the congested traffic situation or with bus spillover from stops. The delay model needs to be modified to accommodate busy traffic conditions. In addition, due to the availability of data, the vehicle and bicycle traffic flow are not controlled when analyzing the bus delay at different stops. More data needs to be collected to estimate the bus delay near stops. Furthermore, the focus of the study is only on delay, but safety is another factor that needs to be considered in the bus stop design. Conflicts between road users and how buses, vehicles, and bicyclists make responses to conflicts could be investigated. Authors recommend that future studies could focus on those issues.

Data Availability

The data supporting the study analysis are publicly available at <https://pan.baidu.com/s/1xQ3N8oM0hhZCuvtr3NeccQ>.

Disclosure

The earlier version of the paper has been presented in the 94th Annual Meeting of Transportation Research Board.

Conflicts of Interest

The authors declare that there are no conflicts of interest for the paper.

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