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Research Article

Improving Pedestrian Hybrid Beacon Crosswalk by Using Upstream Detection Strategy

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Walking, as a healthy and environmentally friendly mode of travel, has been revived in many cities around the world. The mid-block crosswalk (MBC) is a common type of pedestrian facility, and the pedestrian hybrid beacon (PHB) is one of most commonly used signalized MBCs, having a wide range of applications. This study applied an upstream detection (UD) strategy to PHB to reduce the pedestrian waiting time at the crossing. Data were collected through video recordings at two crosswalks at two different periods of the day in the city of Nanjing. First, basic simulation models were developed in VISSIM according to the current layout and the signal control methods of the two crosswalks. Second, signal control logic was adjusted to develop simulation models of PHB. Third, upstream detectors were added to develop simulation models of PHB with a UD strategy. Models for PHB were simulated with 10 different random seeds, and a paired t-test was conducted to evaluate the performance of the UD strategy statistically. The results show that the UD strategy for PHB reduces pedestrian waiting time and increases vehicle delay. However, the reduction in pedestrian waiting time is greater than the increase in vehicle delay. The UD strategy has also been found to be more effective for crosswalks, with relatively short crossing lengths and low pedestrian volume. Finally, a discussion about factors concerned with the application of UD strategies in practice is carried out.

1. Introduction

With the accelerated process of urbanization and the overuse of personal cars, traffic congestion has become a serious problem that negatively affects daily life. Meanwhile, as a healthy and environment-friendly mode of travel, walking has been revived in many countries around the world [1] and is considered a potential solution to traffic congestion. When compared to other road users (such as cars, buses, and trucks), pedestrians are the most vulnerable, especially the elderly and children. Therefore, creating a safe, comfortable, and efficient travel environment for pedestrians is important when the objective is to attract more people into the streets.

Many traffic structures are designed for pedestrian safety and convenience, such as sidewalks, crossings, and walking streets. Among these structures, mid-block crosswalks (MBCs) are installed at locations away from intersections. The main purpose of the MBC is to promote a safe and easy route for pedestrians to cross roadways. Common treatments of MBC include traffic signals, flashing beacons, in-roadway warning lights, driver warning signs, and pavement markings [2]. Traffic mitigation measures such as curb extensions and raised crosswalks are also options for traffic engineers to improve pedestrian safety. The rectangular rapid-flashing beacon (RRFB), which is an increasingly used traffic control device, is effective at increasing driver yielding behavior, as drivers can see the beacon from a long distance away [3, 4]. Traffic signal treatment orients pedestrians and vehicles temporally. Most MBC signals operate in a pedestrian-actuated mode to reduce unnecessary delays for vehicles, with installed push buttons to activate pedestrian crossing phase [5].

The most commonly used signalized MBCs are the conventional pedestrian-actuated crossings (PA), pedestrian light-controlled crossings (PELICAN), pedestrian user-friendly intelligent crossings (PUFFIN), and pedestrian hybrid beacons (PHB) [5, 6]. Among these signalized MBCs, PHB

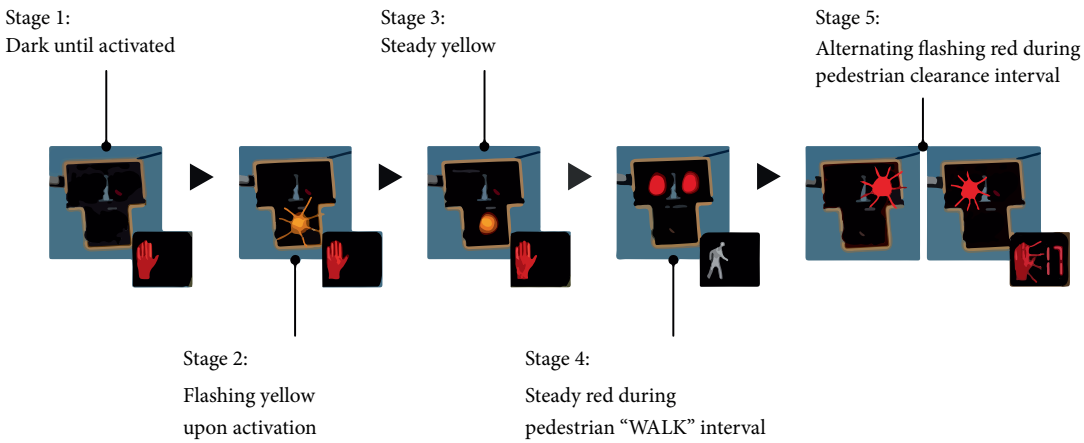

Figure 1: The operation of pedestrian hybrid beacon (PHB).

was first utilized in Tucson, Arizona, with its previous name being high-intensity activated crosswalk (HAWK) [7]. It was officially included in the 2009 Manual on Uniform Traffic Control Devices (MUTCD) [8] and designated as the pedestrian hybrid beacon (PHB). PHB has a wide range of applications, and can be adapted for many roadway and traffic circumstances. According to MUTCD, it can be installed in locations that do not warrant a traffic signal, or in locations that may warrant a traffic signal but, for some reason, a decision has been made not to install one [8]. They are strongly considered for all mid-block and intersection crossings where roadway speed limits are 40 mph or higher [9].

The face of PHB consists of two circular red indicators above a circular yellow indicator. The operation of PHB, as shown in Figure 1, can be divided into five stages [10, 11]:

(i) *Stage 1*. PHB remains dark when there is no pedestrian actuation, and the pedestrian signal head shows a steady "DON'T WALK."

(ii) *Stage 2*. PHB displays a flashing yellow indicator for vehicles after being activated by a pedestrian. The duration of flashing yellow indicator should be determined by engineering judgment [8].

(iii) *Stage 3*. PHB switches to a steady yellow indicator for vehicles. The duration of the steady yellow indicator is between 3 and 6 s, depending on the speed limit of vehicles on the roadway.

(iv) *Stage 4*. PHB displays two solid red indicators to vehicles, and the pedestrian signal head displays a "WALK" signal, allowing pedestrians to cross the crosswalk from the curbside.

(v) *Stage 5*. PHB switches to an alternating flashing red indicator for vehicles, and the pedestrian signal head displays a flashing "DON'T WALK" signal with a countdown timer. In this stage, drivers are allowed to proceed after stopping if pedestrians have cleared their half of the roadway. This treatment is implemented to reduce unnecessary vehicle delay.

Previous studies have demonstrated that PHB has improved the driver compliance rate [3, 12–14], reduced pedestrian accidents [15, 16], and decreased unnecessary vehicle delay [17]. However, other studies indicate a low pedestrian compliance rate with PHB. According to Marisamynathan and Vedagiri [18], the pedestrian compliance rate is defined as the percentage of pedestrians crossing the road during the pedestrian green phase or "WALK" signal. This definition is equivalent to the percentage of pedestrians crossing the road according to the signal rule. Godavarthy and Russell [19] investigated two PHB locations and found that the pedestrian compliance rates were 46.0% and 68.0%, respectively. Arhin and Noel [20] found low pedestrian compliance (50–66%) with a PHB signal at the intersection of Georgia Avenue and Hemlock Street in Washington, D.C.

The operation of PHB is effective at reducing unnecessary vehicle delays, as shown in Figure 1. However, pedestrians who need to cross the roadway must wait at the curbside until the vehicle clearance time (Stages 2 and 3) is terminated. The waiting time between pressing the button and receiving the "WALK" signal is long when there is a high pedestrian volume or the PHB is coordinated with adjacent traffic signals. Moreover, gap-crossing behavior is easily executed by those who are not willing to wait for the "WALK" signal. This behavior violates the signal rule, causing potential conflicts with vehicles. Previous studies have also found that pedestrian compliance is highly associated with pedestrian waiting time. The 2010 Highway Capacity Manual (HCM) [21] states that there is a high likelihood for noncompliant pedestrians with the signal indicator if they experience longer than 30 s waiting time. In contrast, pedestrians are inclined to comply with the signal indicator if the expected waiting time is less than 10 s. Van Houten et al. [22] found that pedestrian compliance decreases as the minimum green time for vehicles increases. This is evident at locations with lower average daily traffic and one-way traffic. Yang and Sun [23] also found that the duration of the red signal time has the greatest influence on pedestrian red-time crossing. Therefore, the pedestrian waiting time at crosswalks should also be optimized to improve pedestrian compliance and provide equal treatment of pedestrians and vehicles.

To reduce pedestrian waiting time at MBCs, Hassan et al. [24–26] proposed a strategy termed upstream detection (UD) for pedestrians. The main idea of this strategy is to provide earlier

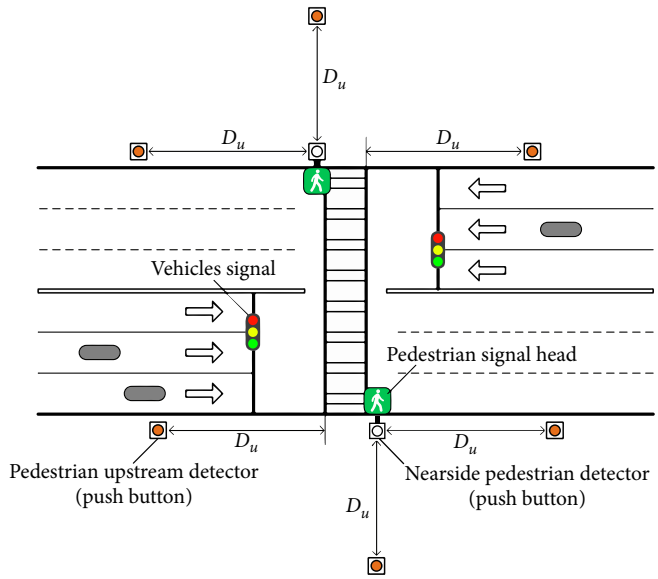

Figure 2: Pedestrian upstream detection (UD) strategy for mid-block crossings.

activation of the pedestrian stage. To achieve this aim, upstream detectors are installed at upstream MBC positions, as shown in Figure 2. To detect the pedestrian and communicate with the signal controller, each upstream detector contains a push button and a means of communication such as communication cables, Wi-Fi, Bluetooth, or Zigbee. There are three optional positions for upstream detectors on each side of the crosswalk. These positions cover possible pedestrian crossing paths and can be used selectively. The distance between each upstream detector and the crosswalk is denoted as D_u (m) in Figure 2.

The UD strategy does not remove the original push button of MBC, which is shown as a nearside push button in Figure 2. This means that MBC with upstream detectors can still be used in how it is currently used. Each upstream detector has the same function as the nearside detector (except for their different positions). Hence, when pedestrians press the upstream push button, the signal controller responds similar to a nearside push button. In practice, each upstream detector should be mounted on a separate pole of minimum specification, because it is only used for mounting the detector.

Hassan et al. [24–26] applied the UD strategy to the PUFFIN crossing, widely used in the United Kingdom. The optimal locations (D_u) of upstream detectors for PUFFIN were obtained. Simulations were conducted under different combinations of pedestrian and vehicle volume, revealing pedestrian waiting time is reduced without severely affecting the vehicles. The UD strategy can also be applied to a PHB crosswalk. Considering that there are similarities between the operating mechanisms of PHB and PUFFIN, it can be expected that the UD strategy may benefit PHB. Therefore, it is necessary to study the performance of PHB with the UD strategy under different roadway and traffic conditions.

2. Research Objectives

This study investigates the benefits of applying the UD strategy to the PHB crosswalk through simulations. The objectives of this study can be described as follows: (*a*) development of simulation models for the PHB crosswalk that reflect its operation process and the behavior of road users based on collected data; (*b*) application of the UD strategy to PHB and development of extended simulation models of PHB; (*c*) evaluation of the performance of PHB before and after applying the UD strategy, by utilizing simulation models and statistical methods; (*d*) discussion of the considerations or constraints for the practical application of the UD strategy to PHB.

3. Data Collection

The data used for this study were collected from two crosswalks in the city of Nanjing, China. One crosswalk is located in an arterial road (Longpan road), and the other is in a collector road (Huayuan road). Both crosswalks are located in the urban area of Nanjing, but not in the central business district or near a school. Currently, the two crosswalks are under the control of a pretimed signal. The data were collected by high-resolution cameras at peak (16 : 30–17 : 30) and off-peak (12 : 00–13 : 00) periods. The cameras were mounted on tall buildings to obtain elevated vantage points of the crosswalks, where pedestrian and vehicle signal heads can be observed simultaneously. This data collection method has several advantages. First, vehicles and pedestrians are not disturbed by the camera, because it is out of their sight (on the building). Second, fewer workers are required in the data collecting process. Third, the recorded videos can be watched repeatedly during the data extraction process.

In the data extraction process, road geometry data (including roadway direction, crosswalk length, crosswalk width, and the number of lanes) were measured or counted from satellite views of the two crosswalks (in Figure 3). Maximum speed limits for vehicles were obtained from roadside traffic signs. Vehicle volume, vehicle composition, pedestrian volume, pedestrian compliance rate, and signal timing parameters were extracted from the recorded videos through

Figure 3: Satellite views of Longpan road crosswalk and Huayuan road crosswalk.

Table 1: Basic information of two investigated crosswalks in the city of Nanjing.

Crosswalk name	Longpan road crosswalk		Huayuan road crosswalk	
Time period	12:00–13:00 (off-peak hour)	16:30–17:30 (peak hour)	12:00–13:00 (off-peak hour)	16:30–17:30 (peak hour)
Roadway direction	East to West		North to South	
Crosswalk length (m)	32		18	
Crosswalk width (m)	6		4	
Number of lanes	4 in each direction		2 in each direction	
Maximum vehicle speed limits (km/h)	60		40	
Vehicle volume (veh)	1572 (WB*) 1630 (EB*)	2009 (WB) 2024 (EB)	490 (NB*) 532 (SB*)	571 (NB) 733 (SB)
Vehicle composition	87.2% cars 9.5% buses 1.8% trucks 1.5% motorcycles	87.8% cars 9.9% buses 1.1% trucks 1.2% motorcycles	61.6% cars 9.4% buses 1.2% trucks 27.8% electric-bikes	62.0% cars 10.4% buses 0.8% trucks 26.8% electric-bikes
Pedestrian volume (ped)	48 (NB) 41 (SB)	75 (NB) 63 (SB)	33 (WB) 19 (EB)	45 (WB) 42 (EB)
Pedestrian compliance rate	85.0%		71.2%	
Cycle length (s)	96		46	
Length of pedestrian green interval (s)	25		10	
All-red time (s)	3		3	

Note: *WB = Westbound; EB = Eastbound; NB = Northbound; SB = Southbound.

manual counting. Vehicle and pedestrian speed data were extracted from the videos using video analysis software. Detailed basic information of the two investigated crosswalks during the two periods is listed and illustrated in Table 1 and Figure 4, respectively.

Table 1 shows that the pedestrian compliance rate of Longpan road crosswalk (85.0%) is higher than that of Huayuan road crosswalk (71.2%). This could be explained by the fact that Longpan road has four traffic lanes in each direction, which makes it riskier to cross the roadway during a red indicator. In contrast, Huayuan road has two lanes in each direction, involving less risk due to noncompliant behavior.

Figure 4 shows that the pedestrian and vehicle speed distributions at the two crosswalks are similar in shape. Most speeds are concentrated between the percentiles of 15% and 85%. The overall pedestrian and vehicle speeds at Longpan road crosswalk are higher than those at Huayuan road crosswalk. According to Figure 4(a), the 15th-percentile pedestrian crossing speeds (m/s) at Longpan road crosswalk and Huayuan road crosswalk are 1.3 and 1.05 m/s, respectively. A few pedestrians were observed to run across the roadway at speeds above 2.2 m/s. Those pedestrians either violated the signal rule or went faster to avoid the end of their crossing phase. According to field observation, the maximum vehicle speed limits of Longpan road and Huayuan road are 60 and 40 km/h, respectively. These two values approximately correspond to the 85th-percentile vehicle speed (km/h), as shown in Figure 4(b).

4. Methodology

In this section, traffic simulation software VISSIM [27] and its add-on module Vehicle Actuated Programming (VAP) [28] were used to develop the simulation models of the investigated crosswalks. We chose VISSIM as it is a widely used traffic

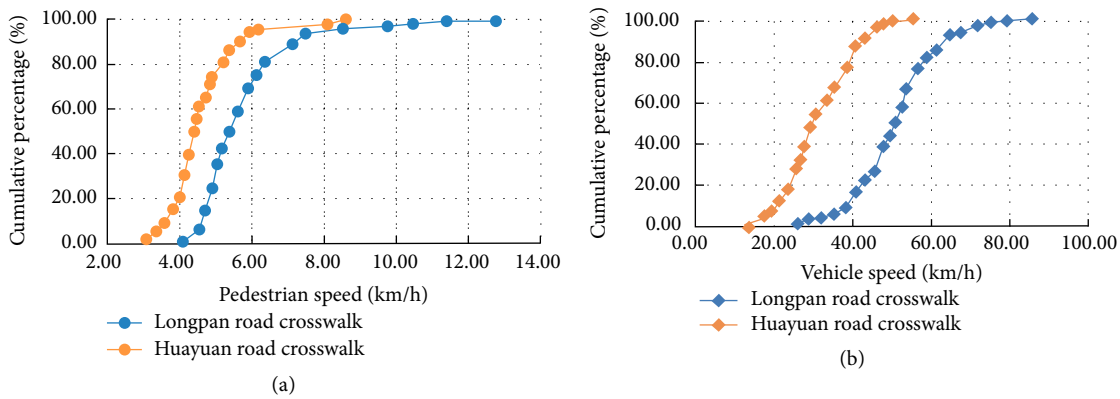

Figure 4: Cumulative distributions of (a) pedestrian speed and (b) vehicle speed at Longpan road crosswalk and Huayuan road crosswalk.

simulation tool, which allows user-defined signal control logic such as signalized MBC.

4.1. Basic Simulation Models. First, we developed the basic simulation models to simulate the current signal control logic (pretimed signal control) of each crosswalk for each period. Road geometry data, traffic volume, traffic composition, traffic speed distribution, and signal timing parameters were model inputs. To better reflect the different behaviors of pedestrians at the investigated crosswalks, we set up two separate links for pedestrians on each crossing direction in each model. One link was for pedestrians who complied with signal rule, and the other was for noncompliant pedestrians. Signal controllers were not set on the link for noncompliant pedestrians. Conflict areas were set up in each simulation model to handle pedestrian-vehicle conflict caused by noncompliant pedestrians or pedestrians who cross the road at the end of their respective phase. In conflict areas, pedestrians have priority over vehicles.

The models were calibrated by key driving behavior parameters, including observed vehicles, minimum look-ahead distance, average standstill distance, additive part of safety distance, multiplicative part of safety distance, waiting time before diffusion, and minimum headway [29]. We tried several combinations of these parameters to minimize the difference in average vehicle delays between simulation models and reality (recorded videos). The final combination of driving behavior parameters was chosen as follows: 2 observed vehicles, 20 m minimum look-ahead distance, 2.5 m additive part of safety distance, 3.5 m multiplicative part of safety distance. The other key parameters were taken as the default values set in VISSIM.

4.2. Simulation Models for PHB. Next, in each basic model, signal control logic and timing parameters were adjusted to develop simulation models for PHB. Detectors were set on the stop line (corresponding to the curbside) of each pedestrian link. The length of the detector was set to 0 m to model the pedestrian push button. The duration of the flashing yellow indicator A_f (s) and steady yellow indicator A_s (s) were both set to 6 s. As the investigated two crosswalks were not in the central business district or near a school, the pedestrian walking interval t_w (s) was set to 7 s, according to the 2009 Traffic Signal Operations Handbook [30]. Pedestrian clearance time t_c (s) was calculated through Equation (1):

$$t_c = \frac{L_c}{V_p}, \tag{1}$$

where L_c is the length of the crosswalk (m), and V_p is the 15th-percentile pedestrian crossing speed (m/s). The buffer interval was set to 3 s and was included in the pedestrian clearance time according to MUTCD [8]. A minimum green time $G_{\min}$ (s) of 15 s was set for vehicles between two consecutive activations of pedestrians. That is, if either nearside or upstream button is pressed when the pedestrian clearance time is over, the system does not respond immediately. The pedestrian needs to wait at least 15 s to activate the system again. The main purpose of setting $G_{\min}$ is to prevent frequent requests from pedestrians, especially when pedestrian volume is high.

The alternating flashing red phase for vehicles is an important feature of PHB. This phase is synchronous with pedestrian clearance time. Vehicles can proceed if pedestrians have crossed half of the roadway. To model driver behavior in this phase, additional detectors were set on the crosswalk in each simulation model of PHB, as shown in Figure 5.

Figure 5 shows a north-to-south crosswalk and the layout of detectors in simulation models. Detector D1 was set to model the nearside push button of PHB. The other detectors were set to model the yielding behavior of the driver in the alternating flashing red phase. Signal control logic was set in such a way that the westbound cars can proceed when no pedestrian is at detectors D2, D3, and D5. The eastbound cars can proceed when no pedestrian is at detectors D2, D4, and D5. Please notice that Detectors D2 to D5 do not exist in reality. They were only set to model driver behavior.

The signal group and stage division in the simulation models of PHB are shown in Figure 6. In Figure 6, signal groups 1 and 2 represent vehicles in the two directions of the roadway. Group 3 represents pedestrians who respect with the signal rule. Group 4 represents noncompliant pedestrians who may enter the crosswalk during the pedestrian clearance interval. Signal stage 1 models the dark period of PHB, and it has a minimum duration time of $G_{\min}$. Interstage (1, 2) models the flashing yellow and steady yellow indicators of PHB. The

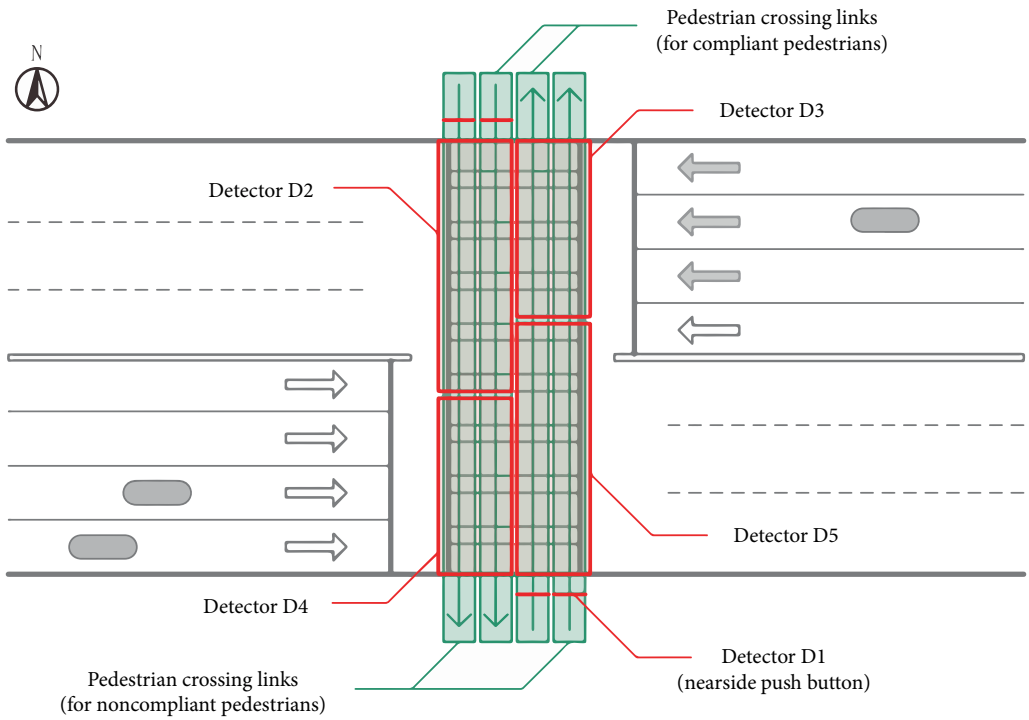

Figure 5: Detectors to model drivers' yielding behavior at PHB crossing.

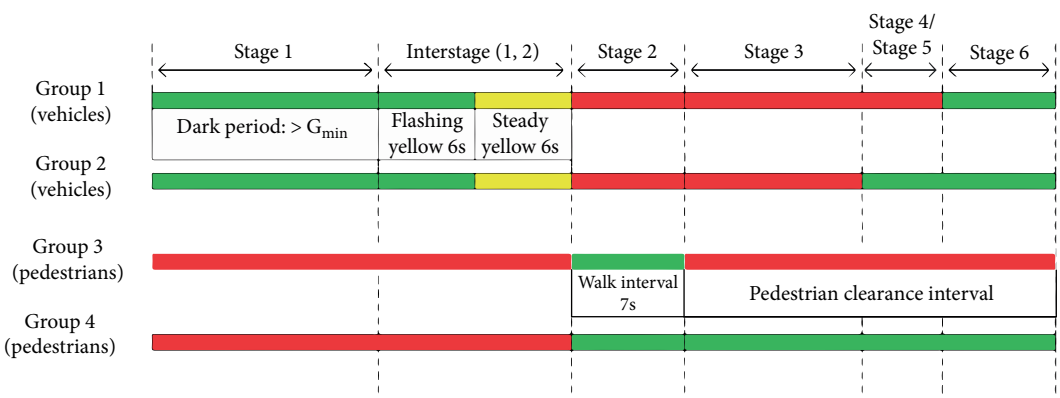

Figure 6: The signal group and stage division in simulation models for PHB.

flashing yellow indicator is treated as a green indicator for vehicles in the simulation models. Stage 2 models the "WALK" interval of PHB. Stages 3 to 6 model the pedestrian clearance interval of PHB. In Stage 3, no vehicles in either direction are allowed to proceed. In stage 4 and 5, vehicles in only one direction may proceed if conditions are met, as explained above. In Figure 6, one such stage is indicated. Another stage presents green for group 1 and red for group 2. In stage 6, vehicles in both directions may proceed; however, the pedestrian clearance interval is not terminated.

4.3. Simulation Models for PHB with UD Strategy. Based on the simulation models for PHB, pedestrian upstream detectors (push buttons) were placed on each side of the crosswalk to simulate the UD strategy. The nearside detectors (as shown in Figure 5) are still retained in this type of model. Pedestrians can be detected at the nearside position of the crosswalk. The distance D_u (m) between each upstream detector and the crosswalk was calculated through Equation (2):

$$D_u = \left(A_f + A_s\right) \cdot V_p, \tag{2}$$

where A_f and A_s are flashing yellow and steady yellow indicator duration time (s), respectively, and V_p is the 15th-percentile pedestrian crossing speed (m/s). We chose the 15th-percentile pedestrian crossing speed to calculate D_u, because in this way, 85% of pedestrians would have a higher speed than V_p, and there would be a low risk of missing the "WALK" signal.

4.4. Delay Calculation. Delay was chosen as the measure of effectiveness (MOE) to evaluate the system performance in

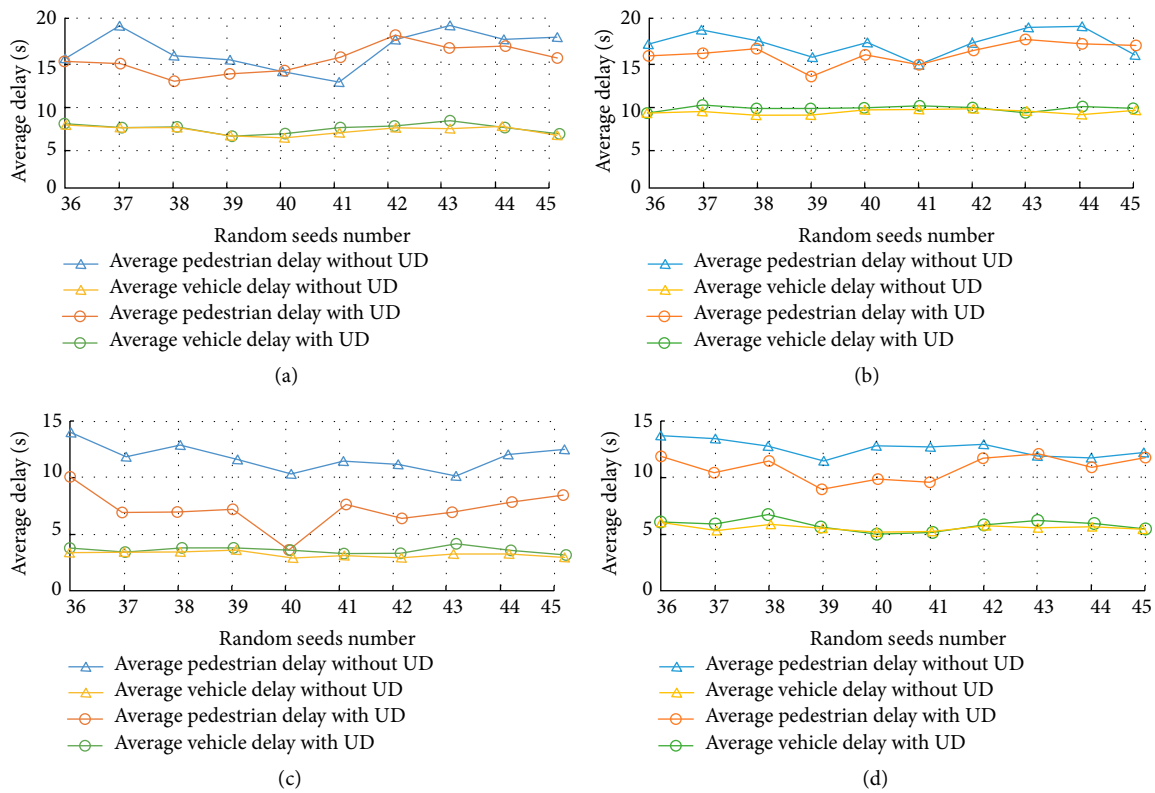

Figure 7: Simulation results of PHB models with and without UD strategy: (a) Longpan road crosswalk in off-peak hour; (b) Longpan road crosswalk in peak hour; (c) Huayuan road crosswalk in off-peak hour; (d) Huayuan road crosswalk in peak hour.

each simulation model. The average delays of vehicles (d_v) and pedestrians (d_p) in each model were calculated through Equations (3) and (4), respectively:

$$d_v = \frac{\sum_i Q_{v,i} d_{v,i}}{\sum_i Q_{v,i}}, \tag{3}$$

$$d_p = \frac{\sum_j Q_{p,j} d_{p,j}}{\sum_j Q_{p,j}}, \tag{4}$$

where d_v and d_p stand for the average vehicle and pedestrian delay (s), respectively; $d_{v,i}$ is the average vehicle delay in the i th ($i = 1, 2$) direction obtained through the simulation model(s); $Q_{v,i}$ is the vehicle volume in the ith direction (veh/h); $d_{p,j}$ is the average pedestrian delay on the jth ($j = 1, 2, 3, 4$) link obstained through simulation model (s); and $Q_{p,j}$ is the pedestrian volume on the jth link (ped/h).

5. Results and Discussion

A total of 12 simulation models were developed, among which 8 were dedicated to PHB with and without the UD strategy. The remaining four were dedicated to pretimed signal control. The four models were used primarily for data input and parameter calibration (as described in the previous section), and their simulation results were not included in the discussion. Furthermore, we simulated the eight models to obtain the average pedestrian and vehicle delays. To overcome the stochastic arrival characteristics of pedestrian and vehicle, each model was simulated under 10 different random seeds for a period of 3600 simulation seconds. The first 600 s were used for initialization, meaning data were collected in the later 3000 s. The simulation results are presented in Figure 7.

In Figure 7, each crosswalk has 20 scenarios. After the UD strategy was applied, most of the scenarios show a reduction in pedestrian delay and an increase in vehicle delay. Some scenarios show an increase or no change in pedestrian delay. Other scenarios show a reduction or no change in vehicle delay. These results indicate that the stochastic arrival characteristics may have impact on pedestrian and vehicle delays.

To interpret the simulation results more effectively, a paired t-test was conducted to compare the difference between pedestrian and vehicle delays statistically (with and without the UD strategy). The null hypothesis (H_0) was set such that there is no difference between the delays before and after the UD strategy is used. The t-test statistic is calculated through Equation (5):

$$t = \frac{D}{s_d / \sqrt{n}}, \tag{5}$$

where t is the t-test statistic; D is the difference in sample means; s_d is the standard deviation of the sample differences; and n is the number of observations. The p-value can be obtained from the t-distribution. Under a significance level of 0.05, a p-value less than 0.05 suggests that H_0 can be rejected,

Table 2: Paired t-test results under a significance level of 0.05.

Crosswalk name	Longpan road crosswalk		Huayuan road crosswalk	
Time period	Off-peak hour	Peak hour	Off-peak hour	Peak hour
p-value for pedestrian delay	0.0471	0.0030	<0.0001	0.0006
p-value for vehicle delay	0.0094	0.0152	0.0024	0.0106

Table 3: The average delay change rates for each crosswalk under each period.

Crosswalk name	Longpan road crosswalk		Huayuan road crosswalk	
Time period	Off-peak hour	Peak hour	Off-peak hour	Peak hour
Average pedestrian delay change rate	−7.59%	−7.37%	−38.49%	−13.51%
Average vehicle delay change rate	3.92%	3.23%	6.12%	4.51%

i.e., there is a significant difference between the delays. The t-test results are shown in Table 2.

In Table 2, all p-values are less than 0.05, indicating that there is a significant difference between pedestrian and vehicle delays with and without the UD strategy for each situation. In addition to the paired t-test, we calculated the average delay change rate for each crosswalk and period. In this simulation, the average delay change rate refers to the change rate for the average pedestrian or vehicle delay of all the random seeds. The results are shown in Table 3.

The combination of the results in Tables 2 and 3 show that the UD strategy applied to PHB reduces pedestrian delay but increases vehicle delay. More conclusions can be derived from the results in Table 3 as follows:

(i) For both crosswalks, the off-peak period (−7.59% at Longpan road crosswalk and −38.49% at Huayuan road crosswalk) experiences a greater reduction in pedestrian delay than the peak period (−7.37% at Longpan road crosswalk and −13.51% at Huayuan road crosswalk). This could be explained by the fact that there is greater pedestrian demand in the peak period; thus, the performance of the UD strategy is less effective in peak periods.

(ii) For both crosswalks, the off-peak period (3.92% at Longpan road crosswalk and 6.12% at Huayuan road crosswalk) experiences a greater increase in vehicle delay than the peak period (3.23% at Longpan road crosswalk and 4.51% at Huayuan road crosswalk). This could be explained as there are more vehicles in the peak period, and they are less sensitive to increased pedestrian calls caused by the UD strategy.

(iii) By comparing the pedestrian and vehicle delays at each crosswalk for each period, it can be derived that a higher reduction in pedestrian delay leads to higher increase in vehicle delay. This is due to the trade-off effect between the two users at MBC. However, the magnitude of the reduction in pedestrian delay is higher than the increase in vehicle delay. This indicates that the increase in the average benefit per pedestrian exceeds the reduction in the average benefit per vehicle.

(iv) In both peak and off-peak periods, Huayuan road crosswalk receives a greater reduction in pedestrian delay and greater increase in vehicle delay than those of Longpan road crosswalk. This is partly because Longpan road crosswalk has a higher pedestrian volume as analyzed above and partly because it has a longer crossing distance, as shown in Table 1. This indicates that the performance of the UD strategy is less effective at crosswalks with long crossing distance and high pedestrian volume.

In addition to the above stated findings, there are factors that can affect the results in Table 3. First, our simulation assumes that all pedestrians use the upstream push button, including the noncompliant ones; however, the push button is less effective if ignored by a portion of pedestrians. Therefore, the visibility of the upstream push button should be sufficient to guide the pedestrians. Next, if a large portion of pedestrians were to cross the road in groups, the efficiency of the UD strategy would be increased. That is because grouped pedestrians can be treated as approximately one pedestrian. In addition, during pedestrian clearance time, our simulation models of PHB follow the rule that vehicles can proceed if pedestrians have cleared their half of the roadway. However, if drivers take more cautious actions, such as waiting behind the stop line during the pedestrian clearance time, the UD strategy causes a greater vehicle delay than listed in Table 3.

In conclusion, with the results in Table 3 and the discussions above, it can be argued that although UD strategy increases vehicle delay, it is within a reasonable range, and the magnitude of the reduction in pedestrian delay is greater than that of the increase in vehicle delay. The reduction in waiting time can also motivate pedestrians to respect the signal rule. This promotes walking and enhances traffic safety. Moreover, the UD strategy does not change the operation process of PHB but rather only increases the frequency of pedestrian call. Therefore, its influence on driver compliance is limited. Furthermore, adding an upstream push button can create a friendly environment for pedestrians to activate the crosswalk signal in advance, feel considered and respected, and more people will be inclined to walk.

6. Considerations for Application

Although UD strategy requires more pedestrian detectors and signal poles to be employed (increasing costs), long-term benefits are perceived. Considering the benefits that UD strategy

brings to PHB, it is worth discussing the considerations for the application of this strategy in practice.

To enhance upstream push button visibility (rather than being ignored by pedestrians), the surface of the button can be set to face the walking path of pedestrians. To help pedestrians understand the function of the upstream push button more fully, an educational sign can be mounted immediately above the button. This sign should provide information for pedestrians such as (*a*) crosswalk ahead, (*b*) request the system to cross the street, and (*c*) pedestrians are not allowed to cross the street at the location of the upstream push button. The content of the sign can be composed of a finger pointing to a button and illustrative words. The style of the sign can be designed according to the examples provided by MUTCD [8].

This UD strategy is appropriate for crosswalks at the midblock location. However, it is not appropriate for common intersections with four crosswalks, as the upstream push button cannot clearly indicate which crosswalk it serves. Nevertheless, the UD strategy can be adopted if the intersection uses an exclusive pedestrian phase (also called a pedestrian scramble or Barnes Dance) [31], which does not provide ambiguous information.

7. Conclusions

Walking, as a healthy and environment-friendly mode of travel, has been revived in many cities around the world, and it also represents a potential method for alleviating traffic congestion. To encourage more people to choose walking, traffic facilities should be properly designed to ensure pedestrian safety and convenience. The MBC structure improves safety and facilitates roadway crossing for pedestrians at locations away from intersections. PHB is a type of signalized MBC and has a wide range of applications. Although PHB has superior performance, pedestrian waiting time still needs to be optimized to improve compliance and provide equal treatment of pedestrians and vehicles.

This study applies the UD strategy to PHB to reduce pedestrian waiting time. The main idea of the UD strategy is to provide an earlier activation of the pedestrian stage. For this purpose, additional push buttons need to be installed at positions upstream of the crosswalk. To evaluate the effectiveness of PHB with the UD strategy, data were collected at two crosswalks in the city of Nanjing through video recording. Traffic simulation software VISSIM and its add-on module Vehicle Actuated Programming (VAP) were used to develop simulation models. First, basic simulation models were developed according to the current signal control methods of the investigated crosswalks. These models were mainly used for data input and parameter calibration. Secondly, signal control logic was adjusted to PHB in each model with the other parts remaining unchanged. Driver yielding behavior during pedestrian clearance time was also modeled in VISSIM by adding additional detectors on the crosswalk. Lastly, the upstream detectors were added to develop simulation models for PHB with the UD strategy.

The simulation models of PHB (with and without the UD strategy) were simulated under different random seeds to reflect the stochastic characteristics of pedestrian and vehicle. The delay was chosen as the measurement of effectiveness (MOE). A paired t-test was conducted to statistically evaluate the performance of the UD strategy. The simulation results and paired t-test indicate that the UD strategy for PHB reduces pedestrian delay and increases vehicle delay. However, the magnitude of reduction in pedestrian delay is larger than the increase in vehicle delay. The UD strategy for PHB is found to be more effective for crosswalks with relatively short crossing length and low pedestrian volume. Furthermore, it is more effective in off-peak hours as greater reduction in pedestrian delay can be achieved. We believe the UD strategy for PHB is beneficial to encourage walking. Factors concerned with the application of UD strategy in practice were explored and discussed which include the application range of the UD strategy, pedestrian signage, and signs related to the upstream push buttons.

Regarding simulations, this study also has limitations. The designed model can appropriately reflect the signal control of the PHB. However, the behavior of the drivers it contains is not sufficiently comprehensive. Drivers may take more cautious actions during flashing yellow periods and provide longer pedestrian clearance time than represented in the model assumptions. Accordingly, accurate data of driving behavior should be gathered to make the model more consistent with reality. Furthermore, more crosswalk samples need to be collected to determine whether the UD strategy for PHB is applicable to a wider range of crosswalks. Future research can implement the UD strategy for PHB in real applications, and evaluate how pedestrians and vehicles respond to this control method (e.g., the pedestrian compliance rate with UD strategy).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The earlier version of this manuscript was presented at 98th TRB Annual Meeting and was only used for exchanging ideas and experiences at this meeting. The manuscript has not yet been published in any journal, nor has it been indexed by any database.

Conflicts of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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