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Research Article

Comprehensive Evaluation of Operational Efficiency of Intersections in Arterial Considering Pedestrians Yield Rule

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Yield to pedestrians has become a new trend of civilized transportation in the metropolis. In order to evaluate the influence of yield behavior on the comprehensive operation efficiency of signalized intersections in arterial, the efficiency of the subject who gives way and the subject who is given up in the process of yielding to pedestrians was considered in this study, and the comprehensive operation evaluation of intersection in arterial was given. First, based on the rule of pedestrians yield, the concept of a safe headway gap of pedestrians was introduced in the process of conflict analysis of traffic flows at the intersection, and 3 situations were discussed, which are no yield, yield to 1 flow and 2 flows, to calculate the departure rate of traffic flow at the intersection. Furthermore, models of 3 evaluation indices were established, which are number of people passing per unit time, average delay per people, and average yield number per people at intersection. Moreover, the entropy weight method was taken to decide the weight of these 3 indices, and to calculate the comprehensive efficiency evaluation of intersection operation, with the standardized matrix. Finally, case study work was carried out to evaluate the comprehensive efficiency of 4 types of intersections in arterial considering pedestrians yield rule, which is the intersection between arterial and arterial (IAA), intersection between arterial and subarterial (IAS), intersection with one-time (IAA-1, IAS-1), and two-time (IAA-2, IAS-2) crossing of pedestrians. The relevant results show that the impact of an increase in the number of pedestrians on the combined efficiency of arterial intersections can vary dramatically in different scenarios. Therefore, in the implementation process of "yielding to pedestrians," the flow fluctuation characteristics and channelization of each intersection should be taken into account, and the corresponding phase changes should be based on pedestrian and vehicle volumes to improve the efficiency of all parts, such as pedestrians and drivers.

1. Introduction

With the promotion of civilized transportation, a series of new rules on yielding to pedestrians have been carried out in some metropolis in China, such as the "Regulations on the Promotion of Civilized Behavior in Hangzhou" and "Regulations on Road Traffic Management in Shanghai" [1]. Under these rules, vehicles have to yield pedestrians if there is potential conflict.

As the backbone of the urban road network, intersections along the main roads bring together a large amount of traffic and pedestrian flow, and the pedestrian flow of intersections at different locations has different characteristics. In the general intersection scenario, whether it is a flat or peak period, because of the interference in pedestrians or nonmotorized vehicles, there are situations where running vehicles have to yield, and this conflict is generally single-section, short period of time, but considering characteristics of traffic flow continuity in the main road, discrete of arrival aggregation of pedestrians when crossing the road, the stupid one-size-fits-all yielding in main road intersection especially in morning and evening rush hour, will lead to serious consequence, such as long vehicle queues, unbelievable delay and sharply falling-down of operating efficiency of intersections, and even more worse, in some situation, congestions in large area of road network, or even bankrupt.

Therefore, it is necessary to evaluate the operational efficiency of intersections in arterial considering rules of yielding to pedestrians, based on which decisions of yielding and yielding conditions can be made, and moreover, some suggestions can be given for the traffic management.

2. Literature Review

The policy preferences in the rule of pedestrians yield vary from country to country. The idea that pedestrians always have the right of way is an unsettled statement. For example, the traffic laws in the US give the right of way to pedestrians at an intersection while the vehicle is turning. In other situations, the law gives the right of way to no one but states who must yield in order to maintain safety on roads [2]. In developing countries, vehicles usually do not give the right of way to pedestrians, leaving them with the only choice to wait until an accepted gap is available. In Gulf Cooperation Council (GCC) countries where vehicles are the predominant mode of travel, pedestrians are receiving lesser priority [3].

In countries where yield rules exist, most yield rules are scene-specific and enforced to different degrees for conflicts in different scenes. In China, pedestrian yield is written into local laws and regulations and is a highly enforced concession rule.

Domestic and foreign studies on the comprehensive efficiency of intersections considering pedestrians yield rule mainly focus on intersection design forms, the new objects, the new evaluation models, and evaluation indexes for intersection efficiency evaluation. Such as Yi-Ming and Zhi-yuan conducted an evaluation of an intersection turning method in countries where the rule is driving on the left. He designed 24 simulation scenarios by considering different traffic volumes and vehicle ratios, using two types of indicators: average delay and the number of vehicles per hour passing an intersection [4]. Guo and Lu analyzed the delays of pedestrians and vehicles on the sidewalk, calculated the average delays of pedestrians and vehicles in the intersection by using the truncated Adams model and queuing theory, and proposed a multiobjective optimization model to minimize the delays of pedestrians and vehicles simultaneously in the signal cycle [5]. Xiu-Ying et al. studied the distribution of traffic delays generated by pedestrians-vehicle conflicts in unsignalized intersections [6]. Zheng Yi-Nan and Elefteriadou, Sankaran and Perumal developed a delay model for evaluating pedestrian's efficiency at signalized intersections by considering the yielding behavior of vehicles and pedestrians [7, 8]; Sherif et al. evaluated the operational efficiency of conventional intersections with two UAIDs schemes and selected three intersections on a main road for a case study [9]; Shi et al. studied the evaluation of the effects of different signal control strategies on traffic efficiency in parallel flow intersections and proposed a control strategy for intersection access efficiency optimization [9, 10].

There are two main types of yielding studies, in which one studies yielding behavior and its influencing factors, such as Steven et al. studied the factors influencing drivers to yield in front of unsignalized crosswalks by analyzing road and traffic characteristics, including intersection distance, vehicle and pedestrian flow, and travel lanes of test vehicles [11]. Jonathan and Van Houten, Gedafa Daba et al. studied the effect of yield signs on yielding behavior of pedestrians and vehicles [12, 13]. Schroeder and Rouphail studied the factors associated with yielding behavior of drivers in unsigned crosswalks and developed a yielding prediction model by Logit model [14]. Shui-Hai and Gou analyzed the yielding behavior between pedestrians and motorists based on evolutionary game theory and concluded that the ultimate efficient and effective goal is that pedestrians and motorists yield to each other [15]. Guan-Tao et al. conducted a statistical analysis of the yielding rate of motor vehicles, the attitudes of pedestrians and vehicle drivers toward yielding behavior, and the influence of driver characteristics on the frequency of yielding behavior based on the observed data from field surveys [16]. Wan-Jing et al. investigated different types of intersections in different areas of Shanghai and used the Raff method and the great likelihood estimation method to calculate the vehicle stopping yielding acceptance gap and refusal gap at intersections [17]. Ming-Yuan et al. used an ordered logistic regression model to study the influencing factors of drivers' yielding behavior and developed a driver yielding waiting time threshold model based on the nonset-price sensitivity analysis (KLP) method [18].

Another impact analysis based on yielding behavior at intersections, Dai-Li et al. used a model of queuing theory to model the capacity and delay of motor vehicles under different yielding probabilities [19]. Wu et al. considered the uncertainty of pedestrians-vehicle interaction decision and proposed a game theory-based human-vehicle interaction model, in order to study the impact of pedestrian on traffic efficiency under no signal control [20]. Wang et al. used traffic conflict techniques to study a cooperative pedestrians–vehicle yielding relationship between pedestrians and vehicles, which interweaves lane and crosswalk, and proposed a lane split yielding model based on the principles of pedestrians priority and efficiency [21]. Guirong and Sun proposed some strategies to improve the efficiency of right-turning motor vehicles at signalized intersections based on the yielding behavior of vehicles to pedestrians [22]. Xiao-Chen et al. investigated different types of intersections in Shanghai and analyzed the yielding behavior of drivers using the concept of the acceptable gap. The study showed that about 25% of the drivers' yielding behavior greatly affected the intersection passing efficiency and about 20% of the drivers' behavior of crossing pedestrian traffic with a very small acceptable gap posed a greater risk to intersection traffic safety [23].

From the literature review above, we can see that

(1) The existing research mainly focuses on vehicles, and nonmotor vehicles (such as bicycles and pedestrians) are often not considered or considered standard vehicles. There is no in-depth analysis of the characteristics of nonmotor vehicles, and the impact of nonmotor vehicles on comprehensive efficiency is not considered.

(2) In the existing research on the efficiency evaluation of intersections considering pedestrians, most

studies were based on the impact of pedestrian-vehicle conflict on vehicle efficiency, and however, in the efficiency evaluation, the evaluation indicators and research methods often make a low weight on pedestrians.

(3) Then, under different intersection scenarios and pedestrian flow conditions, the existing research lacks a complete analysis of the applicability of the rule.

(4) Moreover, the new rules of yielding to pedestrians in China have changed the drivers' noncompulsory, random, and game-playing, so it is necessary to evaluate the operation of intersections under the new rule.

To overcome the limitations of existing research, the structure of this paper is described as follows:

(1) Based on the rules of yielding to pedestrians, a safe yield gap is analyzed;

(2) The model for evaluating the comprehensive efficiency of main road intersection operation was constructed with the method of entropy weight. This model considers indicators such as the number of people passing per unit time, delays per person, and the number of times yielding per person in unit time;

(3) Case study is given to verify the effectiveness of the model above.

The contributions of this paper are as follows:

(1) The concept of a safe yield gap for yielding to pedestrians is proposed.

(2) Based on the results analysis of the comprehensive evaluation model in different intersection scenarios in this paper, reasonable suggestions are given to improve the overall operational efficiency of the intersection, considering rules of yielding to pedestrians in metropolis in China.

3. Method and Model

3.1. Safe Yielding Gap Analysis. There are various kinds of conflicts in intersections such as motor vehicles, nonmotorized vehicles, and pedestrians. Taking the north-south direction as an example, as shown in Figure 1, relying only on the signal phase setting cannot always completely separate these conflicts, so it is necessary to make a yield and clarify the right-of-way.

According to the existing yielding rules, vehicles yield to pedestrians, subarterial yield to arterial, turning traffic yield to straight traffic, etc. When the traffic participants arrive at the intersection, they yield for driver's safety by observing the operation of other traffic flows at the intersection. Under the existing phase setting of the intersection, when vehicles crossing the intersection, yielding behaviors can be divided into the following three situations based on the number of conflicting traffic flows.

Situation 1: vehicles are not required to yield and pass through the intersection normally.

Situation 2: vehicles yield to one conflicting traffic flow.

Situation 3: vehicles yield to two different conflicting traffic flows.

The model in this study is primarily based on motor vehicles yielding to pedestrians without considering specific events, such as the yield of nonmotorized vehicles to pedestrians or the yield of motorized vehicles to nonmotorized vehicles.

On the basis of pedestrians yield analysis, the safe yielding gap is calculated, as shown in Figure 2.

When the headway gap of pedestrians is greater than the threshold of the minimum headway gap of pedestrians α, the driver can safely pass the intersection without slowing down; when the headway gap of pedestrians is less than or equal to α, considering the safety of pedestrians, the driver needs to slow down or even stop to yield to the pedestrians. The threshold α of the minimum headway gap of pedestrians for vehicles to pass straightly is composed of three parts, the time t_{vc} for motor vehicles to cross the conflict area, the time t_{pc} for pedestrians to cross the conflict area, and the average reflection time t_s, as shown in the following equation:

$$\alpha = t_{vc} + t_{pc} + t_s, \quad (1)$$

where t_{vc} is the time (s) for motor vehicles to cross the conflict area; t_{pc} is the time for pedestrians to cross the conflict area (s); t_s is the average reaction (s) time for drivers to yield to pedestrians.

3.2. Efficiency Indexes for Intersection Operation. According to the related research [24], the evaluation indexes of intersection operation efficiency generally include saturation, delay, number of stops, and queue length. Combining with the characteristics of yielding to pedestrians, this paper used the indexes of the number of people passing per unit time, delay per capita, and the number of times per capita being yielded per unit time for the evaluation of intersection operation efficiency. The indexes are based on the departure rate analysis of vehicles in various situations under the rule of yield to pedestrians.

3.2.1. Calculation of Vehicle Departure Rate under the Pedestrians Yield Rule. For situation 1 of Section 3.1, in the case of saturated traffic, vehicles can leave the intersection at a departure rate μ_0 during the period without pedestrian's interference. When vehicles pass through the intersection consecutively, the minimum following time distance is α_0, as shown in (A.1) and (A.2) in "Appendix."

For situation 2 of Section 3.1, according to the relevant references [25], it can be considered that the pedestrian's arrival obeys the Poisson distribution, and the time distance of pedestrians obeys the shift negative exponential distribution, under this premise: the pedestrians gap required for a motor vehicle to cross a pedestrian is $\alpha \le h_p < \alpha + \alpha_0$, and when the number of vehicle is k, the pedestrians gap

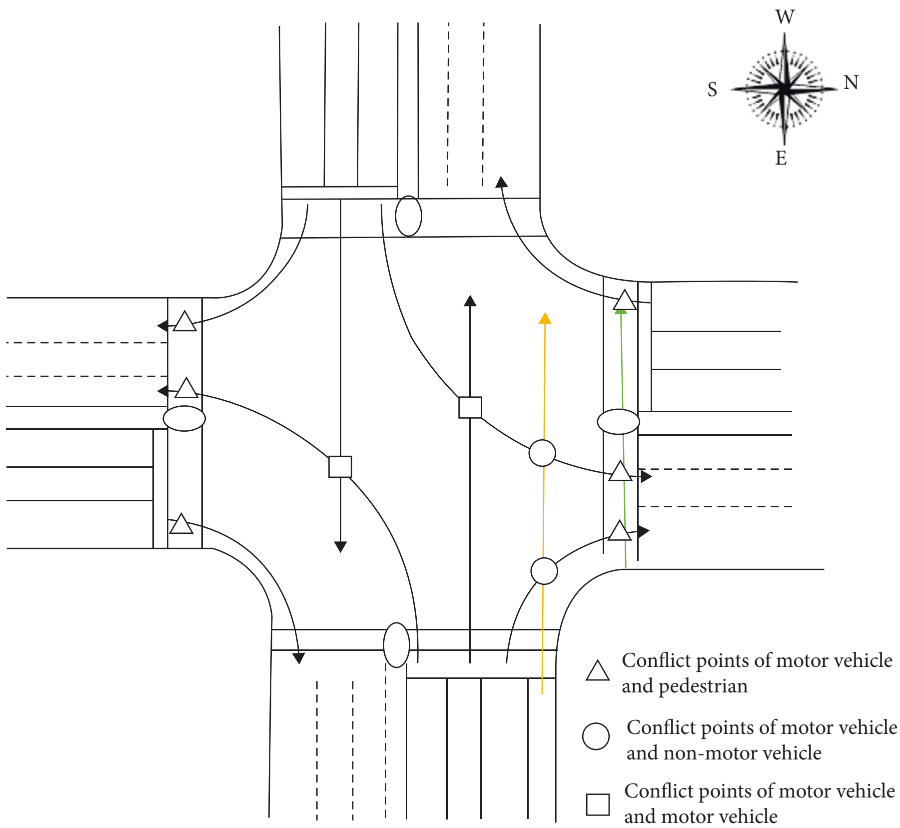


FIGURE 1: Diagram of internal conflict at intersection (take north-south direction as an example).

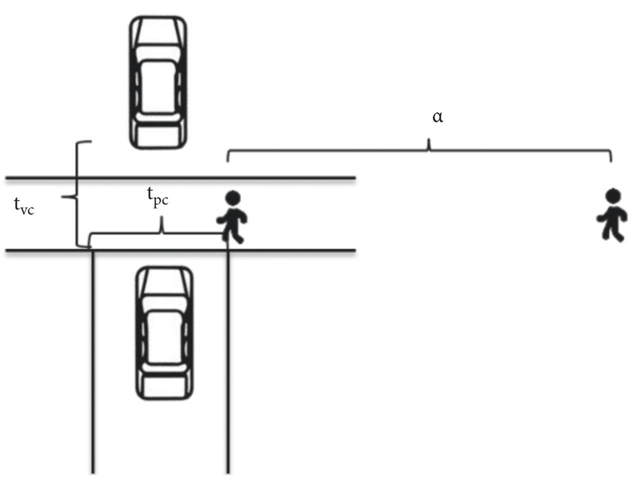


FIGURE 2: Diagram of safe gap for pedestrians yield.

required is $\alpha + (k-1)\alpha_0 \leq h_p < \alpha + k\alpha_0$. The probability of pedestrians appearing to be able to cross the gap of k vehicles is P_k, and then, the vehicle departure rate per unit time under the influence of discrete pedestrians is μ_1, as shown in (A.4) in "Appendix."

The phase time T_i is divided into four stages according to the normal traffic flow running state, as shown in Figure 3. The first $[0, t_e]$ stage is full red time, the traffic completely stops phase, the departure rate is 0; the second $[t_e, t_e + t_{sv}]$ stage is saturated traffic dissipates after crossing the yield gap, and the departure rate is μ_1; the third $[t_e + t_{sv}, T_i - t_{np}]$ stage is discrete arrival vehicles yield, and the departure rate is $\min(\mu_1, \lambda)$; the fourth $[T_i - t_{np}, T_i]$ stage is that there is no conflict and no yield, and the departure rate increased to μ_0 where T_i is the phase time (s); t_e is the vehicle complete stop time (s); t_{sv} is the vehicle dissipation time (s); and the t_{np} is the pedestrians early end time (s).

In the case where the vehicle yields at only one location, according to the dissipation time of the traffic within the phase, three different vehicle arrival and departure situations are obtained as shown in Figure 4. The corresponding three forms of traffic dissipation are as follows.

Form 1: the traffic flow is cleared in the second and third stages, as shown in Figure 4(a), and the phase green light lasts long enough, and the traffic can dissipate with the saturation departure rate μ_1.

Form 2: the traffic flow is cleared in the fourth stage, as shown in Figure 4(b), and the phase green time lasts long, and the traffic flow can completely dissipate with the departure rate μ_0.

Form 3: the vehicles are oversaturation, and the traffic flow is unable to dissipate, as shown in Figure 4(c), and the phase green time is not enough to dissipate the traffic flow.

For situation 3 of Section 2.1, the vehicle needs to yield at multiple locations, and first, based on the vehicle travel direction, the passing through crosswalk is defined as crosswalks 1 and 2, as shown in Figure 5.

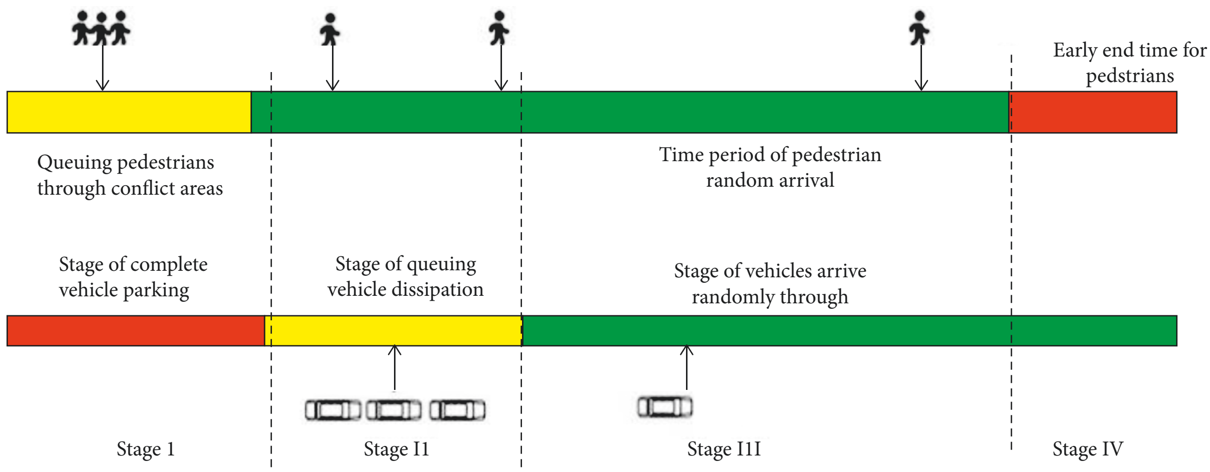


Figure 3: Signal phase stage in different traffic and pedestrian flow.

Then, according to the signal when the traffic flow in the crosswalk 2 position, using the same analysis principle in situation two, the signal light is divided into five stages (as shown in Figure 6).

Stage 1: the traffic flow cannot leave the intersection;

Stage 2: dissipation of saturated traffic at crosswalks 1 and 2 to meet the safe yield gap between pedestrians;

Stage 3: discrete arriving vehicles crossing the crosswalks 1 and 2 when the yield gap between pedestrians is enough;

Stage 4: discrete vehicles crossing the crosswalks 2 in the pedestrians' gap;

Stage 5: pedestrian's green light ends early.

As shown in the figure, t_{sp-2} is the pedestrians dissipation time (s) at the crosswalk 2; t_{sv-2} is the vehicle dissipation time (s) at the crosswalk 2; t_w is the vehicle travelling time (s) from the crosswalk 1 to the crosswalk 2; t_{np-2} is the pedestrians phase early end time (s) at the crosswalk 2; t_{sv-1} is the vehicle dissipation time (s) at the crosswalk 1; t_{np-1} is the pedestrians phase early end time (s) at the crosswalk 1.

Based on the analysis above, the departure rate μ for each stage can be calculated as shown in (A.5) in "Appendix."

3.2.2. Model of the Number of People Passing per Unit Time. This paper analyzes the conflicting yield situation under the signal phase design, and the number of vehicles passing in the phase is calculated based on the arrival rate and departure rate. For the scenario of unsaturated phase traffic, all arriving vehicles can pass. However, for the scenario of saturated phase traffic, the number of passing vehicles can be calculated by the sum of the number of passing vehicles per phase duration t_j; the passing capacity model of vehicle is expressed by the following equation:

$$N_{vi} = \begin{cases} \lambda_v T_i, & \text{Vehicles in phase are not saturated,} \\ \sum t_j \mu_j, & \text{Vehicles in phase are saturated,} \end{cases} \tag{2}$$

where t_j is the duration of each phase of the traffic flow within the phase (s); μ_j is the departure rate (pcu/s) of the phase j.

Based on the number of passing vehicles and the occupancy rate of each type of vehicle, the model of the number of people passing can be obtained as shown in the following equation:

$$N = \lambda_p \cdot C + \sum_{m=1}^{2} p_m \cdot N_{mv}, \tag{3}$$

where C is the signal cycle duration (s); p_m is the average occupancy rate of the m type vehicle (person/vehicle), where 1 represents minibus, 2 represents bus, and 3 represents nonmotorized vehicles; N_{mv} is the number (pcu) of m vehicle passing in the cycle.

Combining with the cycle, the number of people passing per unit time can be calculated by the following equation:

$$\overline{N} = \frac{N}{C}. \tag{4}$$

3.2.3. Per Capita Delay Model

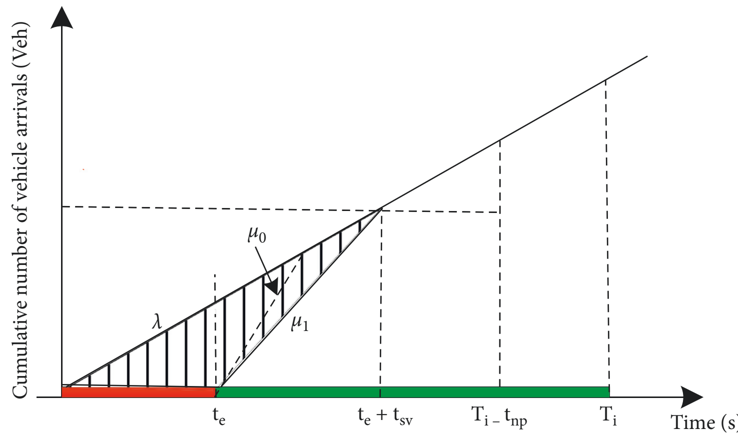
(1) Delay in All Vehicles. The vehicle delay is calculated by using the result of the steady-state delay model, and the vehicle dissipation time t_{sv} can be calculated as shown in (A.6) in "Appendix."

The vehicle delay is composed of two parts, one is the delay caused by the signal setting, as shown in (A.7) in "Appendix." According to the time interval when the traffic is dissipated (as shown in Figure 4), three types of delay due to yielding to pedestrians are obtained, as shown in (A.8) in "Appendix."

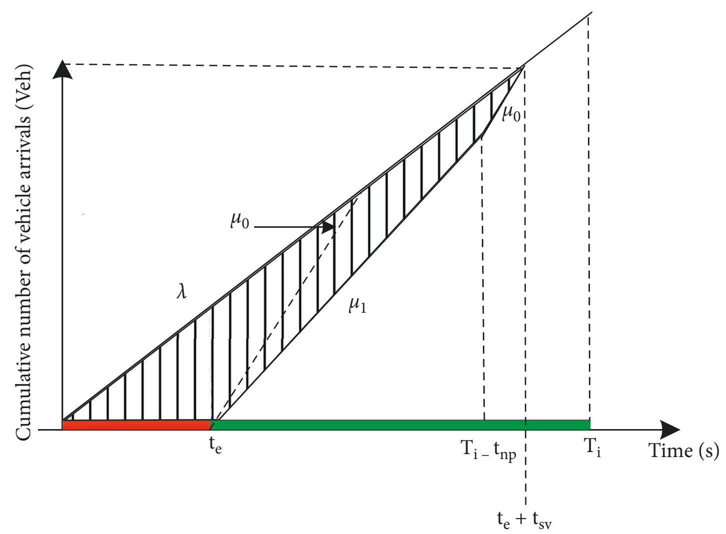
L is the number of vehicles that have not dissipated in the previous phase of the $T_i - t_{np}$ and is based on the model of number of passing vehicles, as shown in the following equation:

$$L = \lambda\left(T_i - t_{np}\right) - \sum t_i \mu_i + t_{np}\mu_0, \tag{5}$$

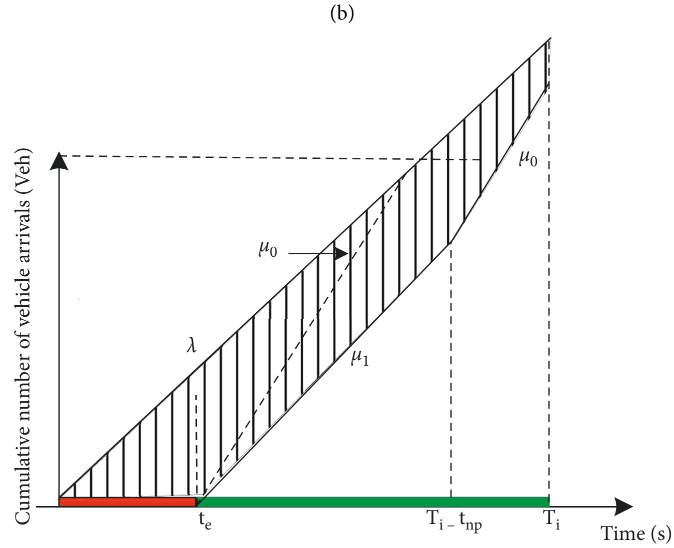
where t_{μ_0} is the time required for the vehicle to dissipate at the drive-off rate μ_0, which can be calculated by the following equation:



(a)



(b)



(c)

FIGURE 4: Three types of vehicle cumulative dissipation. (a) Cumulative vehicle dissipation form 1. (b) Cumulative vehicle dissipation form 2. (c) Cumulative vehicle dissipation form 3.

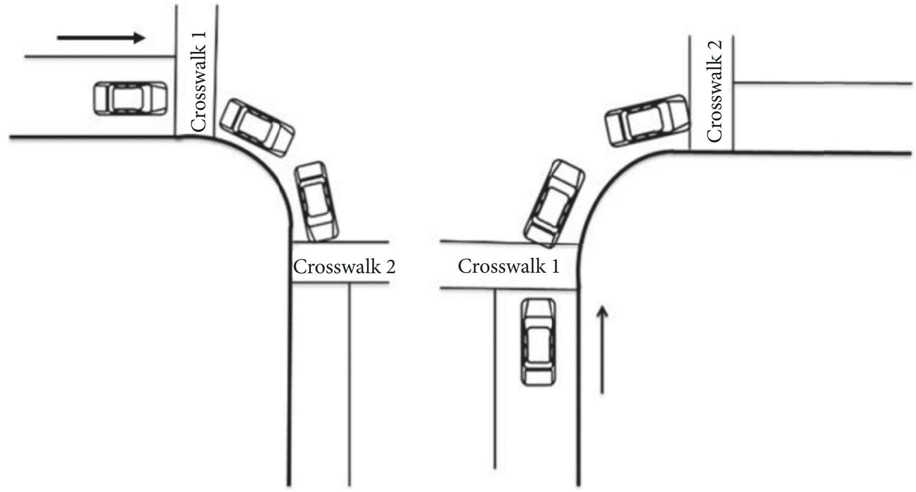


Figure 5: Location distribution of crossing.

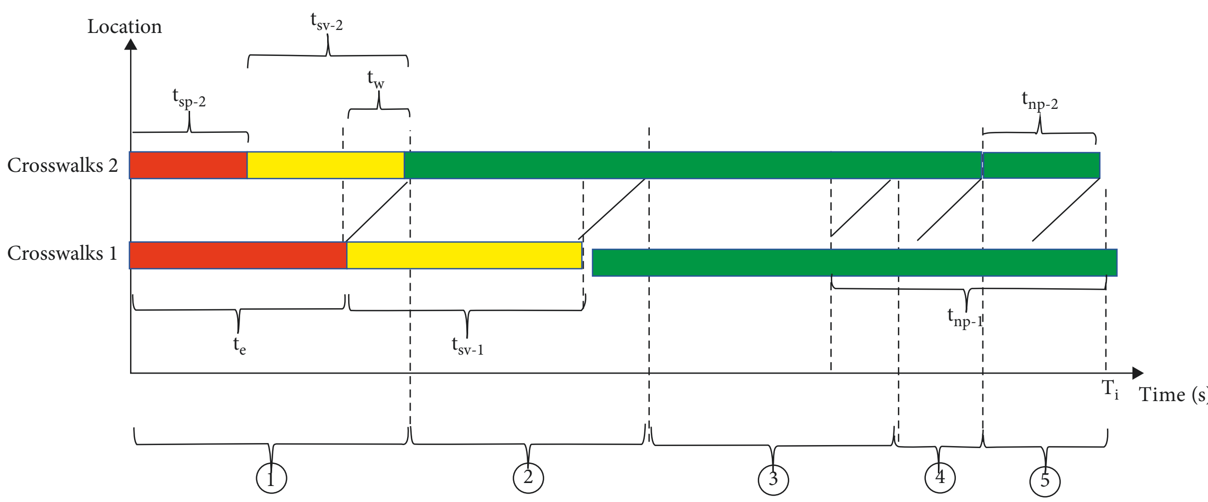


Figure 6: Phase analysis diagram of multitime yield.

$$t_{\mu_0} = \frac{L}{(\mu_0 - \lambda)}. \tag{6}$$

According to the model, the delay of each lane and inlet lane can be calculated for each cycle, and then, the intersection vehicle average delay can be calculated by the following equation:

$$\overline{d}_v = \frac{\sum_i D_{vi}}{N_{vi}}, \tag{7}$$

where N_{vi} is the number of vehicles import lane i.

(2) Delays per Pedestrians. The delay of pedestrians was calculated based on the rule of pedestrians yield. According to the fact that pedestrians have the highest level of right-of-way, this paper only considers the delay of pedestrians waiting during red light periods. The relationship between one-time crossing of pedestrians and two-time crossing of pedestrians is shown in Figure 7.

Based on the above analytical calculations, the pedestrian's delay per cycle D_p can be represented as shown in (A.10) in "Appendix."

The dissipated time of pedestrians in the passing vehicle and in the delay model was calculated as follows [26]: the pedestrians are considered as spheres with collision volume, as shown in Figure 8. The dissipated time of pedestrians can be calculated by parameters such as the characteristics of the pedestrian's queue and the width of the crossing lane, as shown in the following equation:

$$t_{sp} = \frac{w_v + w_p^2 \lambda_p \left(C - t_{pg}\right)/l_s}{v_p - w_p^2 \lambda_p / l_s}, \tag{8}$$

where w_v is the average width of the vehicle (m); w_p is the average width (m) of the pedestrians; t_{pg} is the green light time (s) of pedestrians; l_s is the width (m) of the sidewalk; and v_p is the average crossing speed (m/s) of the pedestrians.

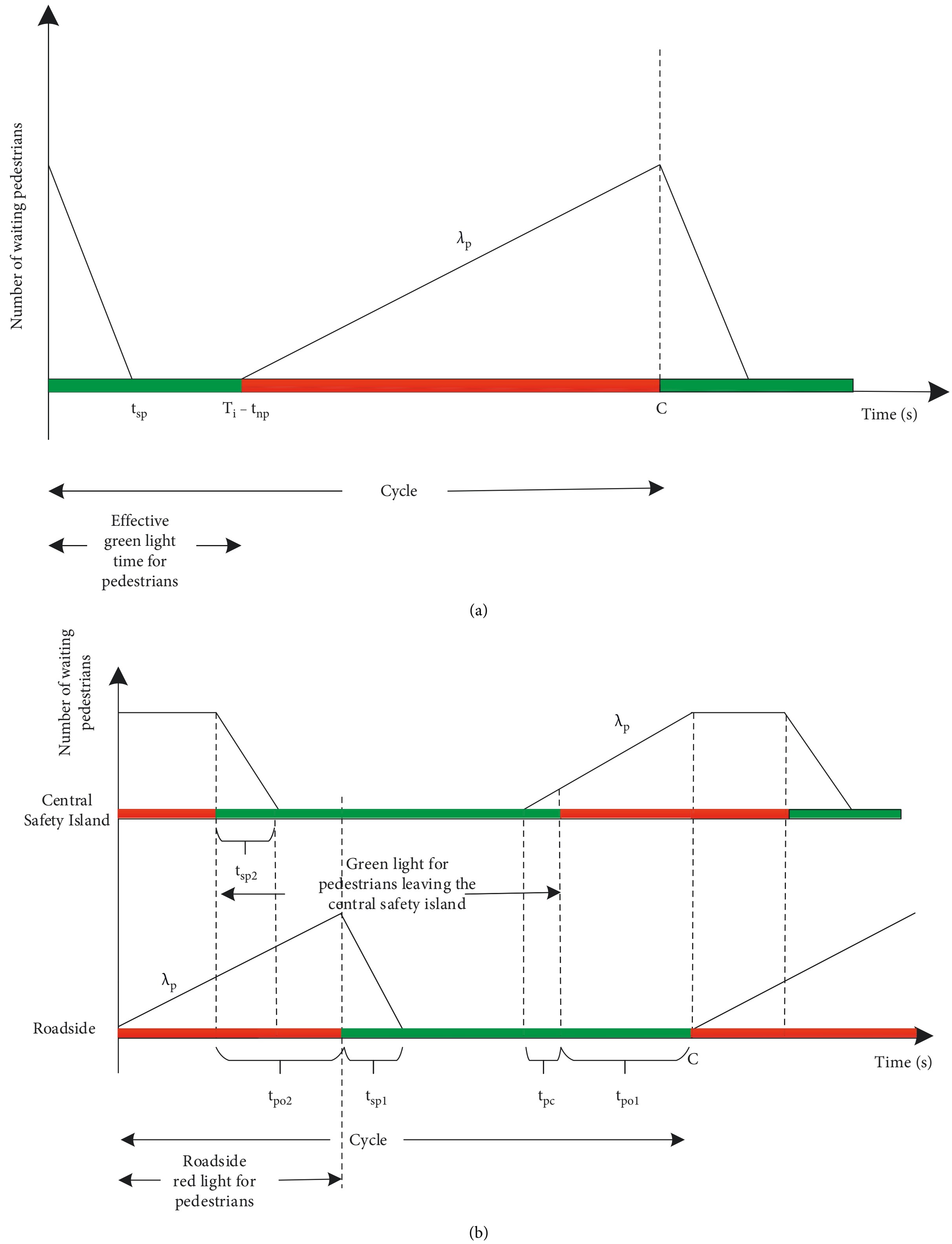


Figure 7: Diagram of pedestrians convergence and dispersion. (a) Pedestrian's one-time crossing convergence and dispersion map. (b) Pedestrian's two-times crossing convergence and dispersion diagram.

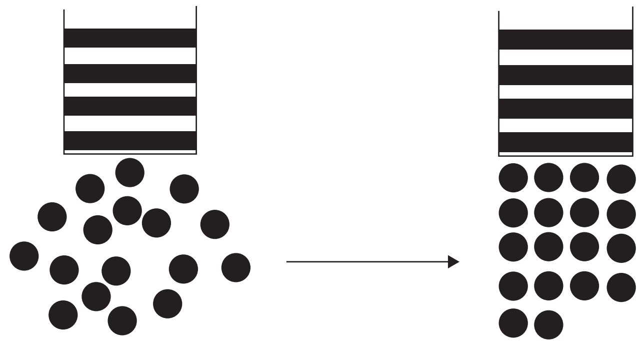


Figure 8: Diagram of pedestrians dispersion time calculation.

Then, the delay per pedestrian is

$$\overline{d}_p = \frac{D_p}{\lambda_p \cdot C}. \quad (9)$$

(3) Delays per Capita. The intersection per capita delay is calculated by the total delay of traffic participants at the intersection, as shown in the following equation:

$$\overline{d} = \frac{D_v + D_p}{N}, \quad (10)$$

where D_v is the total motor vehicle delay at the intersection (s); D_p is the total delay (s) of pedestrians at the intersection; N is the total number of people passing at the intersection, including pedestrians and nonmotorized vehicles (person).

3.2.4. Model of the Number of Yielded Lanes per Capita per Unit of Time. During the conflict between pedestrians and vehicles, there are two kinds of yielding behaviors: slowing down to yield and braking to yield, and the braking rate is used as the distinguishing value of the two behaviors. When the braking rate is greater than or equal to 1, the behavior of vehicles is braking to yield, and when the braking rate is less than 1, it is slowing down to yield. Therefore, the yielding efficiency of intersections can be evaluated based on the number of vehicles stopped and the number of yielded vehicles per capita. The boundary value of vehicle yielding behavior can be calculated as shown in (A.11) in "Appendix."

The calculation of average vehicle delay can be calculated as shown in (A.12) in "Appendix."

The average number of vehicle stops can be calculated from the vehicle yield boundary and the average vehicle delay, as shown in (A.13) in "Appendix."

Based on the number of motor vehicle stops, the number of times the intersection was yielded to per capita per unit time can be calculated as shown in the following equation:

$$r = \frac{s_v}{C \cdot N_p}, \quad (11)$$

where s_v is the number of motor vehicle stops (times); N_p is the number of pedestrians crossing the intersection (person).

3.3. Evaluation Model of Comprehensive Efficiency with Entropy Weight Method. Entropy is a concept in information theory. It is used to measure the disorder degree of system. The entropy weighting method is a commonly used multiindicator statistical method. The entropy value can be used to judge the dispersion degree of a certain indicator, and it can also describe the influence of the indicator on the comprehensive evaluation model [27]. The main feature is to maximize the original data and transform the multiple original indicators into several comprehensive indicators. This method can avoid the interference of subjective factors and determine the weights of each indicator objectively. The steps of the entropy weighting method to determine weights are as follows:

(1) For n each indicator, m sample value is taken, and x_{ij} is the value of the j indicator of the i sample.

(2) Standardization of indicators.

Positive indicators: standardization of the number of people passing per unit time, as shown in the following equation:

$$x_{ij}' = \frac{x_{ij} - \min\left\{x_{1j}, \ldots, x_{nj}\right\}}{\max\left\{x_{1j}, \ldots, x_{nj}\right\} - \min\left\{x_{1j}, \ldots, x_{nj}\right\}}. \quad (12)$$

Negative indicators: standardization of delays per capita, number of courtesies per capita per unit of time, as shown in the following equation:

$$x_{ij}' = \frac{\min\left\{x_{1j}, \ldots, x_{nj}\right\} - x_{ij}}{\max\left\{x_{1j}, \ldots, x_{nj}\right\} - \min\left\{x_{1j}, \ldots, x_{nj}\right\}}. \quad (13)$$

(3) Calculate the entropy value corresponding to the indicator, as shown in the following equations:

$$E_j = -In(n)^{-1} \sum_{i=1}^{n} p_{ij} Inp_{ij}, \quad (14)$$

$$p_{ij} = \frac{x_{ij}'}{\sum_{i=1}^{n} x_{ij}'}, \quad (15)$$

where E_j is the information entropy value; p_{ij} is the occupancy ratio of sample normalized.

(4) Calculate the weights as shown in the following equation:

$$\omega_j = \frac{1 - E_j}{n - \sum E_j}, \quad (16)$$

where ω_j is the index weight.

(5) Calculate the results of the comprehensive efficiency evaluation model as shown in the following equation:

$$Sc = \sum_{j=1}^{m} \omega_j x_{ij}', \quad (17)$$

where Sc is the comprehensive efficiency evaluation value.

Table 1: Signal phase and pedestrians crossing pattern of intersections surveyed.

	Hechuan Road (arterial) Wu Zhong Road (arterial)	Zhayin Road (arterial) Yinhang Road (arterial)	Nenjiang Road (arterial) Zhongyuan Road (sub)	Zhoujiazui Road (arterial) Longchang Road (sub)
Intersection level	Arterial and arterial	Arterial and arterial	Arterial and subarterial	Arterial and subarterial
Pedestrians crossing form	All cross the street at once	East import road one crossing the rest of the import road secondary crossing	All cross the street at once	Arterial secondary crossing subarterial one crossing
Number of signal phases	4	3	3	5
Intersection type	1 time, arterial and arterial	2 times, arterial and arterial	1 time, arterial and sub-arterial	2 times, arterial and subarterial
Conflict type	Human-vehicle	Human-vehicle and vehicle-vehicle	Human-vehicle and vehicle-vehicle	Human-vehicle

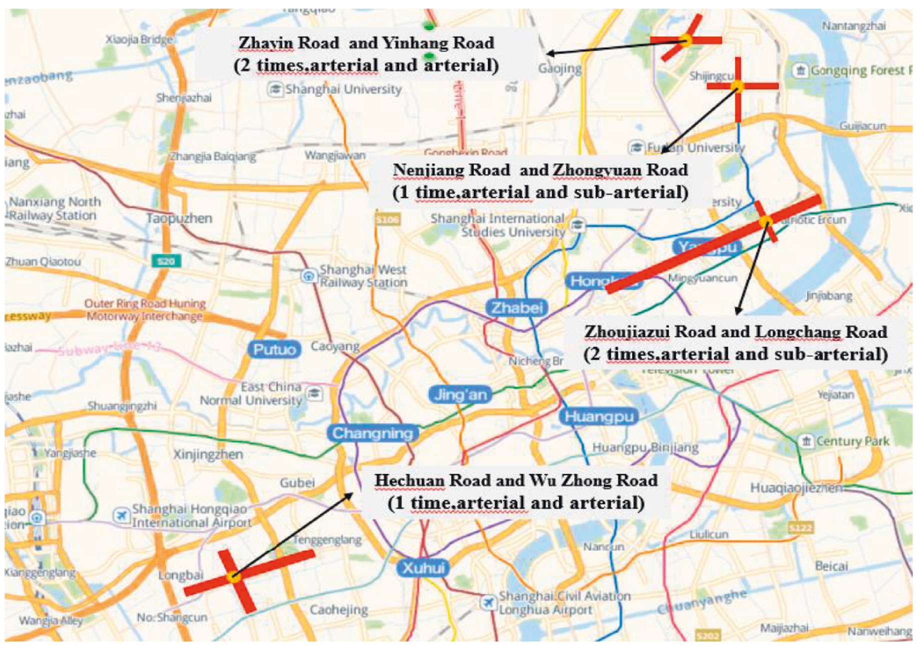


Figure 9: Location distribution of intersections at arterial in case study. (Source: http://en.tongdajiaju.cn/maps.html).

4. Case Study

4.1. Data Survey. In order to comprehensively evaluate the comprehensive efficiency of different intersections and ensure representativeness and typicality, the study is based on the following three basic principles:

(1) The intersection without obvious slope, no sight distance obstruction, the surrounding view is open, and there is no visual impact on yielding to pedestrians;

(2) The intersections where pedestrian and vehicle traffic flows are stable, and there are conflicts between pedestrians and vehicles;

(3) The intersections where sufficient numbers of vehicles yield to pedestrians exist. We selected four intersections in the 13th Five-Year Plan of Shanghai [28].

As shown in Table 1, the specific locations are shown in Figure 9, which are distributed in the areas with the dense pedestrian flow in the combination of urban and rural areas, relatively dense pedestrian traffic (maximum pedestrian flow at pedestrian crossings within the intersection is not less than 20% of the maximum planned capacity of the pedestrian crossing), including the types of IAA-1, IAA-2, IAS-1, and IAS-2, which includes all types of arterial intersections. Relevant data show that the evening peak lasts longer than the morning peak and is more congested, so we collected for 10 days during the weekday evening peak (16:45–17:45) at four intersections when the weather was fine. The model parameters were calibrated, and the relevant evaluation indexes were calculated by using the data from 5 arterial roads (as shown in Figure10).

4.2. Model Parameter Calibration. Referring to the relevant literature [29–34], analyzing the characteristics of vehicles and pedestrians, the data were counted at 5 minute intervals during the survey period, total frequency of 120 groups, and combined with the actual survey data, the values of the model parameters are shown in Table 2.

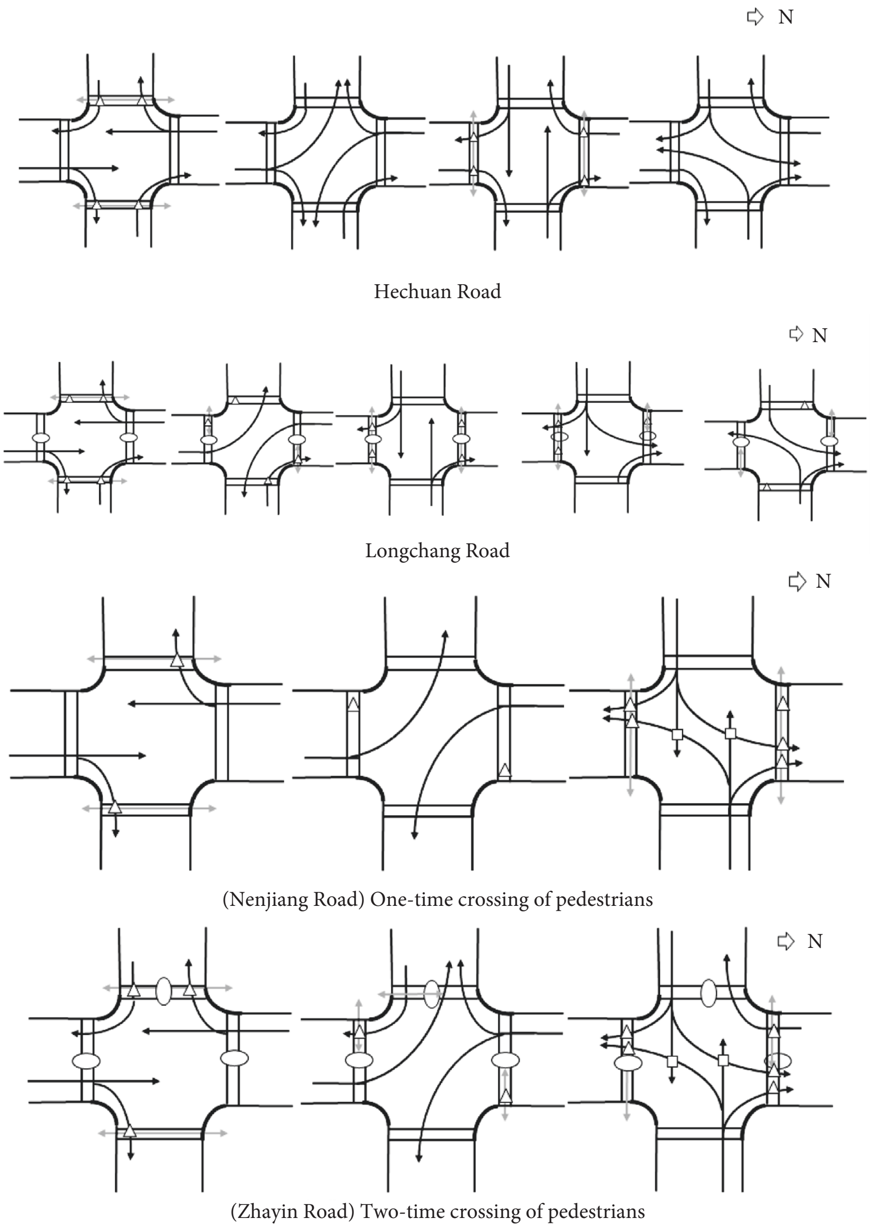


Figure 10: Phase sequence of the intersection.

In addition, the Kolmogorov-Simonov test (K–S test) in SPSS statistical analysis software is used to analyze the Poisson distribution test for the samples of pedestrians arrival data, and the asymptotic significance p values were all greater than 0.05 (as shown in Table 3), indicating that the pedestrians arrivals conformed to the Poisson distribution and met the conditions of model.

In order to determine the impact of yielding to pedestrians on the efficiency of the arterial intersections under different pedestrian flows, according to the Urban Road Engineering Design Specification, under the premise that the upper limit of a single crosswalk is taken as 1580 people per hour, the maximum pedestrian flow rate within the existing intersection is 0.33. Then, the intersection pedestrians are determined to take a range of [200, 4700], which is divided into 20 intervals with an interval step of 225. Finally, we determine the pedestrian flow of each direction according to the proportion of the current value.

On this basis, the model-calculated values of the relevant indicators were compared with the actual observed indicator values, as shown in Table 4. The maximum error of the three indicators is 2.81%, and the mean value is 1.63%, which is within the error tolerance [25] and can be used for further research and analysis in the follow-up.

According to different pedestrian traffic, the corresponding three index matrices are calculated, and the model data of vehicles in each pedestrian traffic scenario are used as the base sample data, the weights of the individual evaluation indicators are determined by using formula (12)–(16), and the final evaluation model is obtained as shown in the following equation:

Table 2: Parameter calibration of model.

Parameters	t_s	τ	v_p	v	a_v	w_v	w_p	p_1	p_2
Parameter description	Driver yield response time	Minimum interval length for shifting negative exponential shift	Pedestrians speed	Vehicle speed	Vehicle acceleration	Vehicle width	Average width of pedestrians	Number of passengers in minibuses	Number of passengers in buses
Take value	1	1.5	1.2	15	4	6 (Small) 12 (Large)	0.5	1.4	40
Unit	s		m/s	km/h	m/s^2	m		Person/car	

Table 3: Results of Kolmogorov-Smirnov test.

Pedestrians data location		East of Zhoujiazui Road	East of Nenjiang Road	West of Nenjiang Road	North of Nenjiang Road	East of Zhayin Road	South of Zhayin Road	North of Hechuan Road
Number of cases		120	120	120	120	120	120	120
Poisson parameters^{a,b}	Average value	15.5000	18.0000	10.6667	11.0000	7.5000	7.5000	9.0000
Most extreme difference	Absolute	0.075	0.092	0.064	0.076	0.059	0.068	0.067
	Positive	0.075	0.092	0.064	0.076	0.059	0.068	0.060
	Negative	0.069	0.034	0.039	0.049	0.028	0.062	0.067
Kolmogorov-Simonov Z		0.817	1.004	0.705	0.834	0.642	0.744	0.739
Asymptotic saliency (two-tailed)		0.517	0.266	0.703	0.490	0.805	0.637	0.646

Note. [a]The test distribution is Poisson distribution; [b]Calculated from the data; [C]Due to the limitation of space, the table only lists the test results of pedestrians sampling data at 7 crosswalks with heavy traffic at 4 intersections.

Table 4: Comparison of calculation value of model with the actual observed value.

Intersection name	Number of passers per unit time (%)	Delays per capita (%)	Number of times per unit time per capita yielded (%)
Hechuan Road and Wuzhong Road	5.94	−5.31	−2.88
Zhayin Road and Yinhang Road	2.18	1.99	-0.93
Nenjiang Road and Zhongyuan Road	4.13	5.74	2.87
Zhoujiazui Road and Longchang Road	−5.13	−2.17	2.14
Average error	1.78	2.81	0.30

$$Sc = 0.47 \times \overline{N}_{ij}' + 0.0887 \times r_{ij}' + 0.4413 \times \overline{d}_{ij}'. \quad (18)$$

4.3. Discussion of Evaluation Results. In the case of considering a series of intersection evaluation indicators, the variation trend of the number of people passing per unit time, the number of people passing per unit time, the delay per capita, and the variation trend of average yield number per people at an intersection are shown in Figures 11–13.

According to Figure 11, the number of the person passing per unit time at arterial intersections increases linearly with the increase in pedestrian flow. For each additional interval step of pedestrians, the average increment of this indicator for IAA-1, IAA-2, IAS-1, and IAS-2 is all around 0.06 (people/sec), and the different types of intersections are inconspicuous. The number of people passing per unit time for IAS-1 is much higher than at other intersections. It may be due to the number of motor vehicles, and buses at this type of intersection are high, and it has a greater impact on the comprehensive efficiency of the intersection. Therefore, in practice, the yielding of buses should be avoided as much as possible, and besides, the separation of buses from pedestrians and signal control should be considered.

According to Figure 12, the per capita delay of all arterial road intersections increased with the increase of pedestrian flow, and the increase of this indicator was 5.64, 27.91, 3.24,

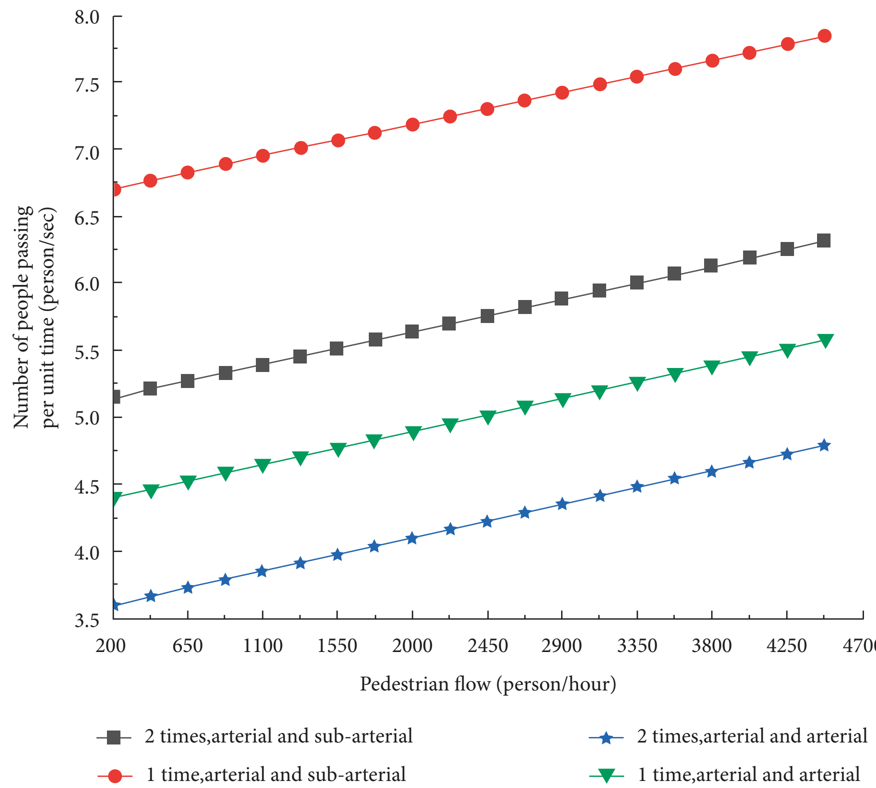


Figure 11: Variation trend of number of people passing per unit time.

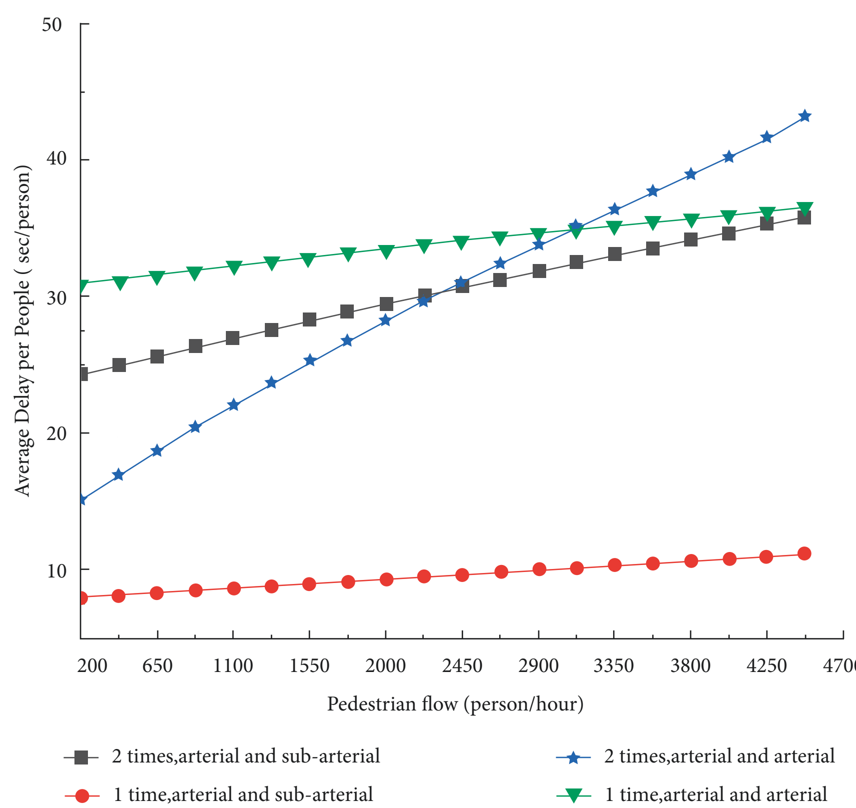


Figure 12: Variation trend of average delay per people.

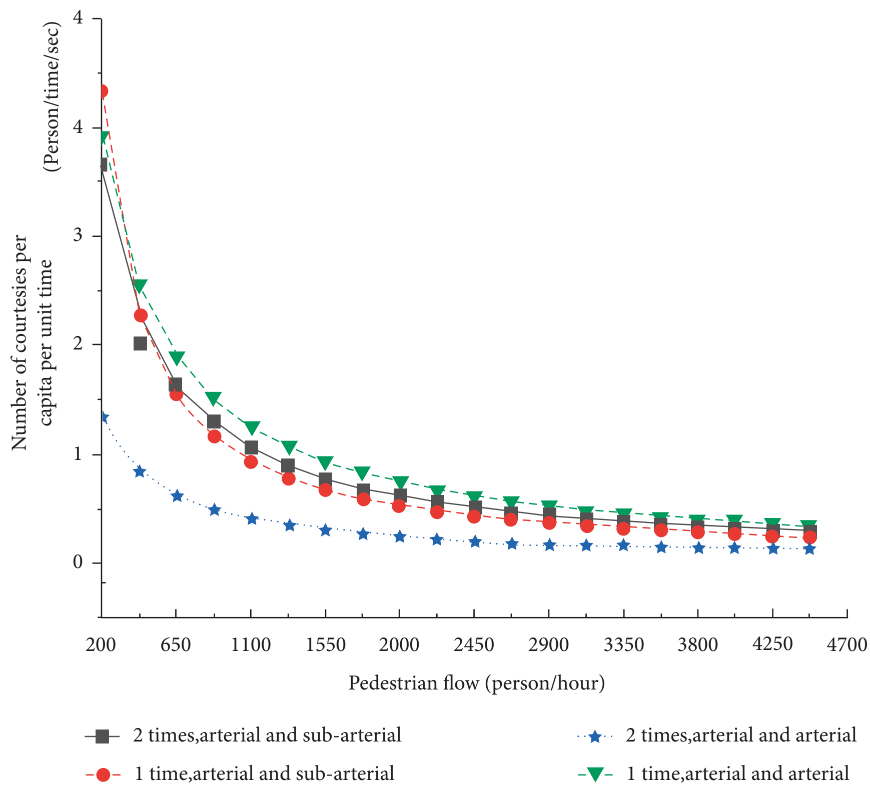


Figure 13: Variation trend of average yield number per people at an intersection.

and 11.45(sec/person) for four types of intersections: IAA-1, IAA-2, IAS-1, and IAS-2. The increase of per capita delay for each type of intersection was 18.3%, 183.4%, 40.7%, and 47.2%, respectively. Among them, the increase in per capita delay of IAS-1 is the smallest, which indicates the speed of overall pedestrians-vehicle dissipation is the fastest. About the IAA-2, the per capita delay increases rapidly. When the pedestrian flow is below 2250 person/hour, the per capita delay is less than IAA-1 and IAS-2. Also, when the pedestrian flow is in the interval [2250, 3125], the per capita delay exceeds IAS-2. Then, the per capita delay is the largest for IAA-2 when the pedestrian flow exceeds 3125 persons/hour. It shows that the existing pedestrian signal timing is only applicable to low pedestrian flows, but for high flow scenarios, the intersection per capita delay increases rapidly, and it causes a sharp decrease in service level. In addition, for the two-time crossing of pedestrians, the increase in per capita delay for IAS-2 is smaller than IAA-2, which is due to the fact that subarterials are the one-time crossing of pedestrians, and the per capita delay varies less with the traffic volume.

According to Figure 13, the number of yielded per capita per unit at arterial intersections increases with the increase of pedestrian flow, and the numerical indices decrease with the increase of pedestrian flow. Therefore, the fewer the number of yielding per unit time for individual pedestrian, the higher the efficiency of yielding, which is similar to the actual situation; the average decrease of this indicator for IAA-1, IAA-2, IAS-1, and IAS-2 are 3.57, 1.20, 4.09, and 3.38 (times/(sec-people)) respectively; especially when the pedestrian flow is in the interval [200, 1800], the most decrease of this indicator is in scenario of IAS-1, and the least decrease of this indicator is in scenario ofIAA-2. And the reason may be related to vehicle arrival rate of intersection. In the case of high vehicle flow, the low and medium levels of pedestrian flow will make a great change in the efficiency of yielding. When the pedestrian flow increases to 1800, the change in efficiency is smaller.

According to Figure 14, analyzing the standard deviation of the three efficiency indicators, the standard deviation of the number of people passing per unit time, and the delay per capita, the IAA-2 is the largest, and about the standard deviation of the number of times being yielded per capita, the IAS-1 is the largest. For the IAA, the change in pedestrian flow has a greater impact on the index of the number of times per capita being yielded for the one-time crossing of pedestrians, and it has a greater impact on the index of the number of delays per capita and the number of people passing per unit time for the two-time crossing of pedestrians. For the IAS, the change in pedestrian flow has a greater impact on the index of the number of times per capita being yielded for the 1-time crossing of pedestrians, and it has a greater impact on the index of the number of delays per capita and the number of people passing per unit time for the two-time crossing of pedestrians. For the one-time crossing of pedestrians, the change in pedestrian flow has a greater impact on the number of yielded persons per capita and the number of persons per unit time at IAS. For the two times crossing of pedestrians, the change of

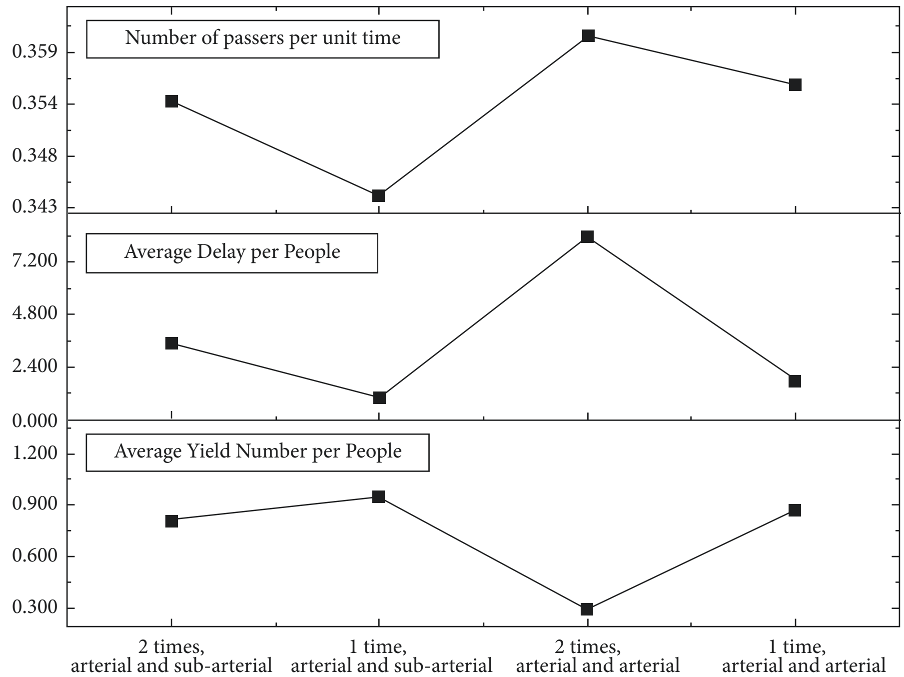


Figure 14: Variation of the standard deviation of three efficiency evaluation indices.

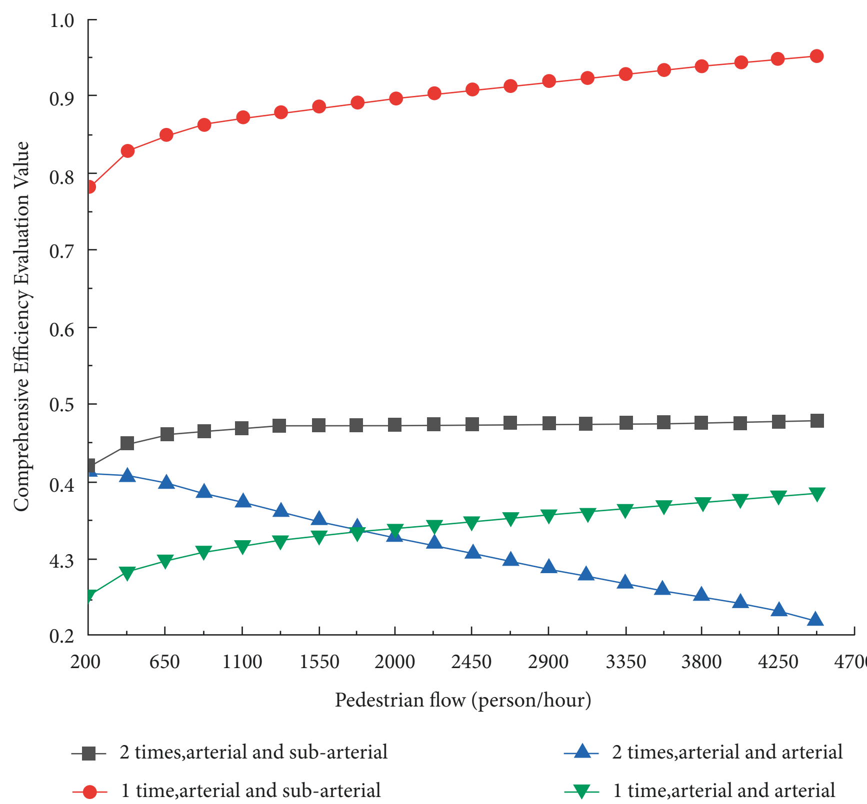


Figure 15: Relationship between comprehensive efficiency evaluation value and pedestrian flow volume.

pedestrian flow has a greater impact on the number of yielded per capita at IAS.

According to Figure 15, analyzing the relationship between the comprehensive efficiency evaluation value of intersection operation and pedestrian flow, when the pedestrian flow increases to the maximum, the increment of the comprehensive efficiency evaluation value of the IAA-1, IAA-2, IAS-1, and IAS-2 is 0.134, −0.192, 0.171, and 0.056,

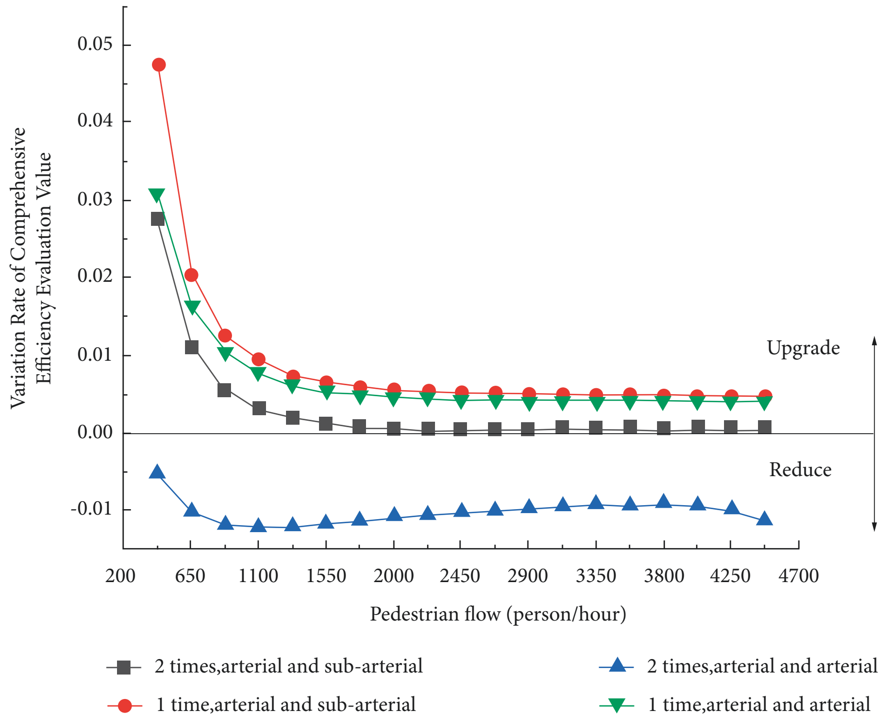


Figure 16: Relationship between variation rate of comprehensive efficiency evaluation value at intersection and pedestrian flow volume.

respectively. For the one-time crossing of pedestrians, with the increase in pedestrian flow, the comprehensive efficiency evaluation value can also increase steadily. For the two-time crossing of pedestrians, the comprehensive efficiency evaluation value of IAS did not show significant changes when the pedestrian flow is larger than 650; while for the IAA, the comprehensive efficiency evaluation value decreased with the increase of pedestrian flow, and it decreased significantly after the pedestrian flow per hour at the intersection was larger than 1800. Therefore, in practice, we should strengthen the law enforcement of yield behavior to pedestrians in the scenario of large pedestrian flow; at the intersection with the 2-time crossing of pedestrians, yield behavior to pedestrians in the low pedestrian flow should be coming in the notice. In addition, based on the evaluation of the intersection and the existing efficiency, channelization, and intersection traffic flow conditions, with the increase in pedestrian flow, the efficiency of the IAA, IAS-1, and IAS-2 increases by 52.9%, 21.9%, and 13.3%, respectively. However, the efficiency of the IAA-2 decreases by 46.5%. Therefore, it should be combined with the characteristics of the evening peak fluctuation of pedestrians, considering measures such as right turn signalized control, optimization of phase sequences, and signal timing to reduce the probability of yielding to pedestrians as much as possible and improve the overall operational efficiency of the intersection.

According to Figure 16, the relationship between the change of the comprehensive intersection efficiency evaluation and pedestrian flow is analyzed, from which we can see that when the pedestrian of IAS-2, IAA, and IAS-1 increases, the change of the comprehensive efficiency evaluation is positive, but the range of variation becomes gradually smaller.

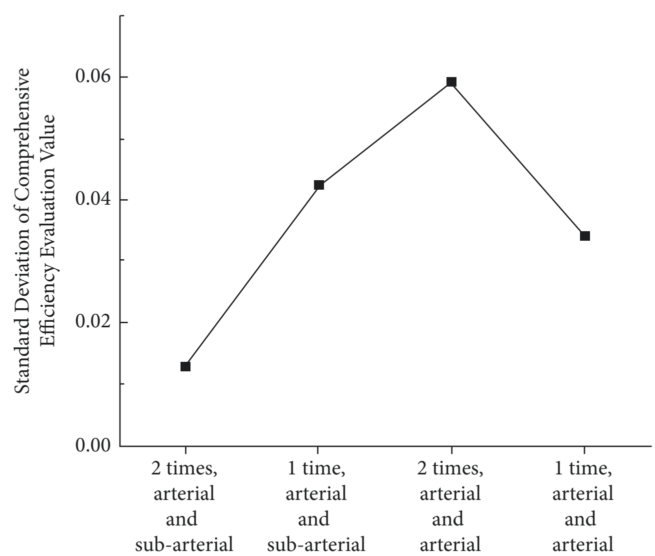


Figure 17: Standard deviation of comprehensive efficiency evaluation value of different types of intersection.

For the IAA-2, the increase in pedestrian flow makes the change of the comprehensive efficiency evaluation always negative. Among these, the pedestrian flow of the IAS-2 is in the interval [425, 875]; the pedestrian flow of the IAS and IAA-1 is in the interval [425, 1100], and their increases all make the positive change rate of the comprehensive evaluation value larger than 0.01; while for the IAA-2, when the pedestrian flow in the interval [650, 2900] and [4475, 4700], the increase of pedestrian flow causes the negative change rate of the comprehensive evaluation value larger than 0.01; the interval with a greater change rate indicates that pedestrian

Table 5: Intersection phase sequence collocation.

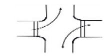
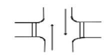
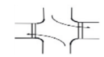
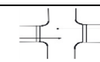
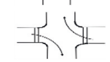
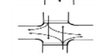
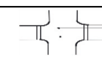
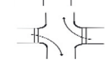
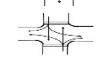
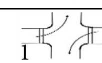
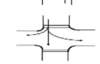
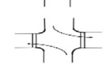
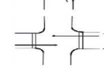
Intersection	Cycle	Phase	Time
Hechuan Road (arterial) Wu Zhong Road (arterial)	205		Green29s, Red171s, Yellow3s, Full red2s
			Green85s, Red115s, Yellow3s, Full red2s
			Green36s, Red164s, Yellow3s, Full red2s
			Green35s, Red165s, Yellow3s, Full red2s
Zhayin road (arterial) Yinhang road (arterial)	230		Green77s, Red147s, Yellow3s, Full red3s
			Green44s, Red180s, Yellow3s, Full red3s
			Green91s, Red133s, Yellow3s, Full red3s
Nenjiang Road (arterial) Zhongyuan Road (sub)	127		Green56s, Red66s, Yellow3s, Full red2s
			Green23s, Red99s, Yellow3s, Full red2s
			Green33s, Red89s, Yellow3s, Full red2s
Zhoujiazui Road (arterial) Longchang Road (sub)	247		Green33s, Red200s, Yellow3s, Full red2s
			Green75s, Red158s, Yellow3s, Full red2s
			Green35s, Red198s, Yellow3s, Full red2s
			Green30s, Red203s, Yellow3s, Full red2s
			Green49s, Red184s, Yellow3s, Full red2s

Table 6: Data of Intersections Research.

Intersection 1	Import road	Lane width	Lane type	Small vehicles	Large vehicles	Average number of pedestrians coming in	Average number of pedestrians leaving	Ratio of large vehicles
		3.75	Straight ahead	702	24			0.033
	East	3.75	Turn left	204	0	24	66	0.000
		3.75	Turn right	72	0			0.000
		3.75	Straight ahead	372	6			0.016
	South	3.75	Turn left	264	6	36	48	0.022
Hechuan Road (arterial) Wu Zhong Road (arterial)		3.75	Turn right	54	0			0.000
		3.75	Straight ahead	375	24			0.060
	West	3.75	Turn left	276	12	36	102	0.042
		3.75	Turn right	204	0			0.000
		3.75	Straight ahead	252	18			0.067
	North	3.75	Turn left	228	6	108	156	0.026
		3.75	Turn right	372	0			0.000
Intersection 2								
		3.75	Straight ahead	217	0			0.000
	East	3.75	Turn left	120	7	90	97	0.055
		3.75	Turn right	105	37			0.261
		3.75	Straight ahead	105	15			0.125
	South	3.75	Turn left	127	7	90	60	0.052
Zhayin Road (arterial) Yinhang Road (arterial)		3.75	Turn right	150	30			0.167
		3.75	Straight ahead	337	0			0.000
	West	3.75	Turn left	67	15	22	7	0.183
		3.75	Turn right	15	0			0.000
		3.75	Straight ahead	98	10			0.093
	North	3.75	Turn left	135	0	37	112	0.000
		3.75	Turn right	60	0			0.000
Intersection 3								
		3.25	Straight ahead	312	28			0.082
	East	3.25	Turn left	84	28	216	344	0.250
		3.25	Turn right	72	0			0.000
		3.25	Straight ahead	424	68			0.138
	South	3.25	Turn left	248	12	132	152	0.046
Nenjiang Road (arterial) Zhongyuan Road (sub)		3.25	Turn right	100	32			0.242
		3.25	Straight ahead	228	0			0.000
	West	3.25	Turn left	48	0	128	84	0.000
		3.25	Turn right	256	0			0.000
		3.25	Straight ahead	432	60			0.122
	North	3.25	Turn left	84	4	132	72	0.045
		3.25	Turn right	32	0			0.000

Table 6: Continued.

Intersection 1	Import road	Lane width	Lane type	Small vehicles	Large vehicles	Average number of pedestrians coming in	Average number of pedestrians leaving	Ratio of large vehicles
Intersection 4								
		3.25	Straight ahead	432	30			0.065
	East	3.25	Turn left	186	12	186	258	0.061
		3.25	Turn right	18	0			0.000
		3.5	Straight ahead	666	24			0.035
	South	3.5	Turn left	252	0	30	18	0.000
		3.5	Turn right	156	0			0.000
Zhoujiazui Road (arterial) Longchang Road (sub)		3.25	Straight ahead	474	30			0.060
	West	3.25	Turn left	198	24	24	78	0.108
		3.25	Turn right	108	0			0.000
		3.5	Straight ahead	234	42			0.152
	North	3.5	Turn left	66	0	18	36	0.000
		3.5	Turn right	222	18			0.075

Table 7: Number of pedestrians passing in five minutes.

Hechuan Road				Zhayin Road				Nenjiang Road				Zhoujiazui Road				Longchang Road			
East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North
1	1	5	8	5	3	1	4	17	14	10	13	12	2	2	2	12	20	26	35
0	2	1	7	5	7	1	2	16	10	16	10	13	4	1	1	13	19	26	30
5	7	1	6	11	5	5	4	20	4	9	12	12	7	1	1	12	23	19	37
1	2	1	5	10	5	4	5	21	9	9	7	17	3	4	3	11	15	26	35
1	5	4	9	6	13	1	3	25	12	8	11	23	2	0	0	13	18	27	11
1	1	3	7	5	9	3	2	16	16	5	13	22	2	4	3	13	11	18	20
2	5	5	12	6	12	3	3	10	17	14	18	14	3	7	2	9	17	25	42
3	4	2	9	8	12	3	6	16	13	17	9	13	2	2	4	12	10	23	53
1	5	1	5	7	2	1	3	14	8	4	5	22	4	0	1	15	12	27	39
2	2	2	9	15	5	2	1	16	14	17	11	12	3	0	3	5	14	26	41
2	1	2	7	5	8	1	6	15	9	10	15	22	4	4	0	15	10	21	34
3	1	0	10	5	4	3	5	15	15	8	23	16	3	0	0	13	25	28	32
1	1	4	8	5	9	2	2	22	16	11	6	15	1	2	0	9	15	18	28
0	0	6	5	8	8	3	8	13	14	13	9	12	3	1	1	10	16	26	32
2	2	4	8	5	4	1	5	22	18	8	15	20	2	0	5	14	17	26	30
2	0	4	11	5	5	0	4	17	7	10	7	16	3	0	1	15	20	17	31
1	2	2	7	8	4	2	0	22	6	8	12	19	2	3	3	10	17	28	36
3	4	2	11	9	10	0	5	21	8	5	15	9	1	2	0	10	14	25	24
3	1	1	10	10	8	2	7	22	15	12	14	11	1	0	3	12	13	19	32
0	5	3	9	10	3	2	4	26	7	10	9	14	2	0	3	10	13	31	32
2	2	2	11	12	11	1	5	22	8	10	14	20	3	1	0	26	15	27	32
2	1	5	15	6	4	3	3	15	9	11	9	19	3	1	1	19	21	21	38
1	4	8	10	7	2	2	3	13	9	5	13	19	1	2	3	15	12	24	28
0	4	5	8	5	9	0	2	18	14	8	12	24	3	5	1	18	16	23	32
1	5	2	13	7	12	1	1	21	8	10	14	12	3	2	1	15	18	21	54
4	5	5	4	4	9	5	3	12	8	6	11	10	2	2	1	16	23	28	38
2	1	1	6	5	8	4	3	20	13	13	13	22	3	4	0	12	21	24	39
2	3	3	8	8	7	0	5	16	12	9	8	13	4	1	1	21	16	30	33
1	5	1	10	7	6	2	2	21	10	5	9	12	5	1	1	12	30	19	40
2	0	3	8	5	11	2	2	13	6	14	10	18	3	2	1	20	23	27	30
0	4	1	13	9	8	1	3	16	8	10	9	16	1	3	3	26	20	25	44
2	4	5	15	7	7	1	5	23	9	10	13	21	2	0	3	16	21	38	48
5	3	4	11	11	10	2	2	15	14	11	17	21	2	3	1	19	17	26	33
1	0	3	6	10	9	3	4	14	12	11	9	15	2	2	3	16	24	25	40
1	5	3	7	4	7	4	4	21	8	7	7	15	5	1	1	23	20	31	35
1	5	4	11	5	3	2	4	14	8	10	16	12	3	3	1	16	18	21	40
4	4	4	11	5	6	1	1	17	10	10	14	23	6	2	1	21	21	25	36
2	2	3	14	8	9	2	2	14	15	11	7	23	4	4	4	17	21	14	43
4	2	4	4	6	4	4	7	12	8	9	11	15	4	1	4	11	23	30	41
1	2	3	13	10	6	5	5	16	9	11	7	12	4	1	2	16	17	21	41
1	7	3	10	5	6	4	3	8	16	12	13	13	0	4	1	15	14	20	37
2	5	2	8	4	10	3	4	16	8	11	9	17	1	0	2	17	11	25	40
4	4	5	6	12	10	0	4	17	21	12	17	10	4	1	2	13	22	22	33
1	2	3	11	9	10	2	1	16	6	15	13	12	1	0	0	17	22	19	39
2	4	4	9	9	13	2	2	12	9	8	20	13	5	4	0	17	19	24	47
2	2	3	9	5	2	3	3	20	11	14	10	15	1	1	1	16	21	35	37
0	0	7	4	10	8	1	7	15	9	11	11	18	0	3	0	14	22	34	26
0	3	2	15	2	9	3	3	14	12	18	16	14	3	3	4	11	20	28	36
0	2	1	12	6	11	0	5	26	17	9	8	14	8	2	1	16	23	24	39
1	3	1	10	8	9	0	4	17	7	7	6	21	1	3	2	19	25	18	37
1	2	5	10	9	3	1	5	22	5	10	9	21	3	0	0	22	20	34	45
5	4	4	9	5	6	2	1	18	13	16	14	14	3	3	1	10	21	14	33
1	5	2	4	12	6	0	6	18	10	9	6	21	3	5	0	15	23	28	37
1	3	3	5	2	8	0	5	19	6	17	9	15	3	4	0	12	20	29	33
3	3	5	11	6	9	4	1	15	8	10	18	15	1	1	0	16	19	23	53
1	2	6	11	9	8	3	6	12	19	10	4	22	3	0	0	15	14	23	44
2	3	7	4	10	4	1	2	21	13	13	14	13	0	1	1	10	19	23	49
1	5	2	4	4	5	2	1	16	12	10	6	13	4	2	4	12	17	25	34
3	1	2	7	10	11	2	1	13	12	6	12	13	3	1	2	15	14	21	34

Table 7: Continued.

Hechuan Road				Zhayin Road				Nenjiang Road				Zhoujiazui Road				Longchang Road			
East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North
2	2	3	10	6	8	3	4	20	10	10	16	21	0	5	0	18	15	18	33
2	2	1	13	7	5	3	3	29	6	9	12	12	1	0	4	9	14	29	32
6	1	1	4	5	4	0	5	16	11	12	7	17	4	3	1	9	7	23	37
6	3	1	8	9	4	2	4	21	12	11	10	14	1	2	1	7	16	18	25
2	3	1	11	10	6	2	6	14	12	9	20	15	1	4	1	17	11	16	34
2	3	1	7	11	9	0	0	13	9	9	8	19	1	2	2	10	6	26	31
2	3	5	13	9	7	3	5	17	16	10	14	13	1	4	0	11	12	16	28
5	3	4	7	4	6	2	4	19	13	17	16	10	1	2	2	6	16	15	41
1	2	2	6	3	6	0	1	23	9	12	8	17	2	2	3	5	24	26	39
1	2	4	13	10	3	0	3	17	8	9	7	12	2	2	3	11	12	16	40
4	2	3	6	5	13	1	0	14	16	8	7	13	1	1	1	8	9	19	25
3	1	4	10	4	13	7	1	18	14	7	12	10	3	3	3	15	12	20	42
0	2	5	8	6	3	3	2	12	12	8	14	14	2	2	1	2	13	15	37
1	6	1	5	8	10	2	3	34	17	13	6	10	0	1	3	11	12	18	42
2	2	1	8	2	12	2	2	16	12	14	11	13	3	3	0	14	12	19	39
1	0	3	11	9	6	1	1	20	7	18	7	13	4	3	1	7	12	13	40
1	2	1	6	6	2	2	4	20	13	11	16	20	4	2	1	5	7	16	27
3	4	4	14	8	9	0	0	16	8	9	13	17	0	3	1	14	10	15	38
2	6	4	6	4	8	0	3	19	12	8	12	23	5	0	2	11	6	17	38
1	4	3	11	5	5	1	0	14	10	10	6	18	1	1	0	13	12	17	35
2	2	2	10	9	8	0	2	22	6	10	15	14	0	1	1	10	17	27	24
3	2	2	4	6	13	1	6	17	10	11	7	20	2	1	2	4	15	29	7
1	0	4	8	7	9	1	1	16	10	8	9	18	1	2	7	9	12	14	18
2	0	3	7	10	7	1	3	17	12	9	5	13	4	1	0	16	17	20	37
2	2	5	4	9	9	0	2	31	14	5	12	12	0	0	4	17	11	20	32
2	4	5	7	7	8	2	6	14	10	12	9	19	3	3	2	7	11	21	26
0	6	2	8	12	10	1	4	25	10	10	17	15	1	1	0	5	17	24	25
1	5	2	11	8	2	0	3	20	15	9	16	18	3	1	0	11	9	26	31
1	0	1	10	9	10	5	4	23	18	12	16	15	5	3	0	17	14	19	45
2	3	2	7	9	8	2	6	12	8	9	9	11	0	3	1	14	13	27	25
3	1	4	6	17	7	2	2	14	10	8	12	8	2	6	2	7	13	15	38
2	5	4	4	5	9	1	1	32	7	17	8	16	2	1	1	9	14	13	38
2	3	4	6	14	7	5	3	10	10	13	7	11	3	4	0	7	6	16	22
4	2	1	7	7	12	3	4	13	10	7	12	7	1	1	1	12	12	20	27
2	7	4	5	14	8	2	3	16	7	12	9	13	4	5	0	4	17	25	37
1	4	3	14	7	12	2	4	23	13	15	9	12	3	1	2	10	6	22	36
7	3	6	6	10	7	0	3	15	14	21	6	14	1	1	1	9	10	24	20
3	7	4	15	1	15	1	0	28	4	10	13	15	5	1	0	4	14	18	25
2	3	0	8	4	7	0	1	22	13	12	10	13	4	2	2	15	14	22	28
1	1	5	5	5	9	2	1	20	14	17	4	25	1	4	3	6	23	25	29
1	2	4	13	14	11	1	2	21	16	13	7	8	1	0	1	15	13	22	34
2	3	1	7	6	6	3	5	19	10	12	10	17	2	2	2	8	15	13	35
3	2	2	4	7	12	0	3	20	12	7	10	14	4	3	1	17	16	34	34
0	3	6	13	8	7	2	6	44	12	7	8	20	1	5	1	15	12	19	31
2	3	4	11	9	5	3	3	23	9	10	19	22	4	2	2	5	20	26	38
2	1	2	14	7	5	4	4	20	14	10	6	19	3	2	4	18	11	18	37
1	0	5	17	7	10	0	5	11	16	11	11	13	1	0	0	13	14	27	46
7	3	7	6	8	6	0	1	12	11	9	14	21	1	2	2	15	14	20	44
2	4	0	6	7	2	5	2	20	5	15	12	10	2	3	1	15	8	26	35
2	2	1	10	7	4	0	0	14	7	11	10	16	5	1	0	16	16	23	26
1	4	0	12	12	4	2	3	21	17	6	9	11	7	1	3	17	20	30	46
5	6	2	13	11	11	0	0	19	10	11	5	17	6	3	1	13	8	21	37
1	2	5	10	8	2	3	5	20	8	15	9	9	7	1	1	15	14	14	46
3	7	0	13	5	9	0	0	14	18	12	17	17	1	0	2	9	11	23	33
2	3	4	15	7	11	3	5	26	14	7	10	21	0	4	2	10	10	42	32
4	6	1	5	13	9	2	1	13	5	11	8	7	0	4	1	14	14	28	36
2	2	5	10	6	6	1	6	25	9	15	14	12	0	3	3	14	12	13	52
2	5	2	7	3	12	3	1	8	10	9	11	10	2	4	1	7	18	31	56
0	7	1	13	6	6	0	6	11	17	7	9	23	4	0	1	12	17	30	38

Table 7: Continued.

Hechuan Road				Zhayin Road				Nenjiang Road				Zhoujiazui Road				Longchang Road			
East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North
1	5	2	14	7	11	3	4	13	6	11	12	17	0	1	2	14	15	27	43
4	5	2	18	15	3	2	2	10	8	17	10	16	3	0	0	20	9	35	34

flow has a greater impact on the comprehensive efficiency evaluation of the intersection.

According to Figure 17, analyzing the standard deviation of the comprehensive evaluation value, the standard deviation of the IAA-2 and IAS-1 are larger, and the standard deviation of the IAS-2 is the smallest; combined with the comprehensive efficiency evaluation value of Figure 16, it reflects that there are two cases of large standard deviation, one is that the increase of pedestrian flow will improve the efficiency of the intersection, and on the opposite site, the increase of pedestrian flow will reduce the comprehensive efficiency of the arterial intersection.

5. Conclusion

According to the rule of "yield to pedestrians," this paper first analyzes the behavior of pedestrians' yield. Moreover, based on the entropy weight method, we proposed a model of comprehensive efficiency evaluation to evaluate the operational efficiency of main road intersections. This model contains three main indexes: number of people passing per unit time, delay per capita, and number of times being yielded per unit time, and finally, we verified the validity of the model by living examples. The following conclusions were proposed as follows:

(1) Each main road intersection canalization characteristic, traffic composition, and flow characteristics are very different, and each efficiency index evaluation result is not the same. Therefore, the method by using entropy weight can better integrate the situation of each index to evaluate the intersection efficiency of yielding to pedestrians.

(2) Yield to pedestrians is implemented commonly, and under yielding rules, the efficiency of yielding to pedestrians in different arterial intersections will change with the size of pedestrian flow. This paper evaluated arterial intersections by considering the index of yielding efficiency. Based on the evaluated results, the following conclusions can be drawn: the operational efficiency of different types of arterial intersections is not equally sensitive to changes in pedestrian flow. Regarding the one-time crossing of pedestrians, the comprehensive efficiency of intersection increases with the increase of pedestrian flow. About the two-time crossing of pedestrians, in the intersection between arterial and subarterial, the change of pedestrian flow fails to result in significant changes in the comprehensive efficiency, and in the intersection between arterial and arterial, the comprehensive efficiency evaluation value decreases with the increase of pedestrian flow. In addition, about the two-time crossing of pedestrians, in the intersection between arterial and subarterial, the comprehensive efficiency decreases significantly in scenarios of large pedestrian flow. Therefore, in practice, in the intersection with the one-time crossing of pedestrians on arterial roads, we should strengthen the law enforcement of yield behavior to pedestrians in the scenario of large pedestrian flow; about the intersection with the two-time crossing of pedestrians, yield behavior to pedestrians in the low pedestrian flow should be in notice.

(3) "Yield to pedestrians" does not fully apply to all intersections. It should be combined with the characteristics of the evening peak fluctuation of pedestrians, motor vehicle traffic at each intersection, and the channelization traffic, to reduce the probability of yielding to pedestrians as much as possible. Considering measures such as right turn signalized control, optimization of phase sequences and signal timing, and the overall operational efficiency of the intersection can be improved.

However, there are still some limitations in this paper.

(1) In the analysis of yield gaps based on yielding to pedestrians, some microscopic characteristics of pedestrian groups are considered, such as pedestrian crossing speed, pedestrian volume, and a series of other parameters; however, individual microcharacteristics of pedestrians, such as age and gender, were not studied. Individual microcharacteristics are more important for security and can be further refined in combination with individual microcharacteristics.

(2) In addition, results in the study are very dependent on local traffic rules and the traffic habits of cities in China, so further research is needed for other regions and countries.

Appendix

Equations

$$\mu_0 = \frac{S}{3600}, \tag{A.1}$$

$$\alpha_0 = \frac{3600}{S}, \tag{A.2}$$

where S is the lane saturation flow (pcu/h).

The lane saturation flow is calculated as follows: according to the urban road intersection planning specification (GB50647-2011), based on the average signal intersection lane basic saturation flow, it is corrected for different lanes as shown in the following equation:

$$S = S_b \cdot f_w \cdot f_z, \tag{A.3}$$

where S_b is the average signal intersection lane basic saturation flow (pcu/h); f_w is the lane width correction factor; f_z is the turning lane turning radius correction factor.

$$\mu_1 = \frac{\lambda_p e^{-\lambda_p(\alpha-\tau)}\left(1-e^{-\lambda_p n\alpha_0}\right)}{\left(1+\lambda_p\tau\right)\left(1-e^{-\lambda_p\alpha_0}\right)}, \tag{A.4}$$

where λ_p is the pedestrian's arrival rate (per/s); τ is the minimum interval length of the shift negative exponential shift; n is the maximum number (pcu) of vehicles accommodated by the lane.

$$\mu = \begin{cases} 0, & \text{Phase1}\left[0, t_e + t_w\right], \\ \min\{\mu_1, \mu_2\}, & \text{Phase1, 2}\left[t_e + t_w, T_i - t_{np-1} + t_w\right], \\ \mu_2, & \text{Phase}l3\left[T_i - t_{np-1} + t_w, T_i - t_{np-2}\right], \\ \mu_0, & \text{Phase}l5\left[T_i - t_{np-2}, T_i\right], \end{cases} \tag{A.5}$$

where μ_1 and μ_2 are the departure rate (pcu/s), which is effected by pedestrians at the crosswalk 1, 2.

$$t_{sv} = \frac{t_e\lambda_v}{\mu - \lambda_v}, \tag{A.6}$$

where t_{sv} is the vehicle dissipation time (s); λ_v is the arrival rate of vehicle (pcu/s); μ is the departure rate of vehicle (pcu/s).

$$D_{vi1} = \frac{\lambda\mu_0}{2(\mu_0-\lambda)}t_e^2, \tag{A.7}$$

$$D_{vi2} = \begin{cases} \dfrac{\lambda\mu_1}{2(\mu_1-\lambda)}t_e^2 - \dfrac{\lambda\mu_0}{2(\mu_0-\lambda)}t_e^2, \\ \dfrac{\lambda t_e^2 + (\lambda t_e + L)\left(T_i - t_e - t_{np}\right) + Lt_{\mu_0}}{2} - \dfrac{\lambda\mu_0}{2(\mu_0-\lambda)}t_e^2, \\ \dfrac{\lambda t_e^2 + (\lambda t_e + L)\left(T_i - t_e - t_{np}\right) + \left(2L - (\mu_0-\lambda)t_{np}\right)t_{np}}{2} - \dfrac{\lambda\mu_0}{2(\mu_0-\lambda)}t_e^2, \end{cases} \tag{A.8}$$

$$D_{vi} = D_{vi1} + D_{vi2}, \tag{A.9}$$

where D_{vi1} is the vehicle delay (s) caused by signal setting; D_{vi2} is the delay (s) caused by vehicles yielding to pedestrians; D_{vi} is the delay (s) of the second inlet lane.

$$\% \; D_p = \begin{cases} \dfrac{\left(C - T_i + t_{np}\right)^2\lambda_p + \left(C - T_i + t_{np}\right)\lambda_p t_{sp}}{2} & \text{pedestrian crossing in the one} - \text{time} \\ \dfrac{\left(C - t_{pg1} + t_{sp1}\right)\lambda_p\left(C - t_{pg1}\right) + \left(2C - 2t_{pg1} + t_{pc} - t_{po1} + t_{sp2}\right)\lambda_p\left(t_{pc} + t_{po1}\right)}{2} & \text{pedestrian crossing in the two} - \text{times} \end{cases}, \tag{A.10}$$

where t_{sp} is the time (s) of pedestrians dissipation; t_{pg1} is the time (s) of curb pedestrians entry green light; t_{sp1} is the time (s) of curb pedestrians dissipation; t_{pc} is the time (s) of pedestrians from the curb to the safety island; t_{po1} is the green-light time (s) of the 2-time crossing of pedestrians in the pedestrians can only cross from the import side of the crosswalk; safety t_{sp2} island pedestrians dissipation time (s); t_{po2} is the green-light time (s) of 2-time crossing of pedestrians in the pedestrians can only cross from the exit side of the crosswalk.

$$d_l = \frac{v}{a}, \tag{A.11}$$

where v is the normal speed of the vehicle through the intersection (m/s); a is the plus (minus) speed (m/s^2) of the vehicle.

$$\overline{d}_v = \frac{D_v}{N_v}, \tag{A.12}$$

where D_v is the total delay (s) of vehicles; N_v is the number of vehicles passed during the cycle (vehicles).

$$s = \frac{\overline{d}_v}{d_l}. \tag{A.13}$$

Data Availability

All the data used to support the findings of this study are included in Tables 3–4 in this article, and Tables 5–7; (1) Table 5: intersection phase sequence collocation; (2) Table 6: data of intersections research; (3) Table 7: number of pedestrians passing in five minutes.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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