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Analysis of Red-Light Violation Behavior of Pedestrian Two-Stage Crossing at a Signalized Intersection

Yongqing Guo [a*], Xiaoyuan Wang [b], Xinqiang Meng [a], Jie Wang [a], Yaqi Liu [a]

[a] *Shandong University of Technology, School of Transportation and Vehicle Engineering, Zibo 255000, China.*

[b] *Qingdao University of Science & Technology, College of Electromechanical Engineering, Qingdao 266000, China.*

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Abstract

Studying pedestrians' twice-crossing behavior is of great significance to enhance safety and efficiency for pedestrians at signalized intersections. However, researchers have paid little attention to analyze and model pedestrians' red-light running behavior on a two-stage crossing at signalized intersections. This paper focuses on analyzing the characteristics of pedestrian red-light violation behavior at the two stages, including the time distribution of violation behavior, the consistency of violation behavior, and the violation behavior in group. A goal-oriented and time-driven red-light violation behavior model was proposed for pedestrian two-stage crossing. A video-recording method was used to collect field data, and the results show that pedestrians in the two directions present different red-light violation behaviors in time selection and violation count, as well as, pedestrians in the two stages of a direction present different red-light violation behaviors in time selection. The main reasons leading to the phenomena were analyzed, regarding from people's cognitive psychology and visual perception. The results also show that the proposed model is effective in simulating pedestrian red-light violation behavior of twice crossing. This research provides a theoretical basis for optimizing signal timing, improving pedestrian safety and developing user-friendly transportation system.

Keywords: Pedestrian Two-Stage Crossing; Pedestrian Red-Light Violation; Pedestrian Twice-Crossing Model; Signalized Intersection.

1. Introduction

Pedestrian two-stage crossing is an important component of urban road network, and highly affects the network traffic operations. Studying the characteristics of pedestrian twice crossing behavior at signalized intersections, meets the needs of developing a "people-oriented" urban traffic system and is essential for improving traffic efficiency and pedestrian safety. In a two-stage crossing, a refuge island is established at the middle of a crosswalk and pedestrian crossings proceed in two steps (pedestrians can wait in the refuge island). By allowing pedestrians to wait halfway, refuge islands separate conflicts in time and place. Despite this fact, the proportion of pedestrians involved in red-light violations in the two-stage crossings remain high. Therefore, understanding pedestrian's twice-crossing violation behaviour is an essential issue especially in developing countries with large pedestrian population such as China.

1.1. Pedestrian's Red-Light Violation at Signalized Intersections

Pan [1] studied that the gap acceptance behavior of pedestrian red-light running at signalized intersections by field reaserch and behavior modeling. Zhou et al. [2] proposed a random decision simulation model for pedestrian red-light running behavior in group based on the Monte Carlo simulation method. Wang [3] quantitatively analyzed the relevant influencing factors on the pedestrian red-light violation using the survival analysis method. Pei [4] proposed a new

* Corresponding author: yongqing.guo@sdut.edu.cn

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signal timing plan to reduce pedestrian delay and the rate of pedestrian red-light violation. Chen [5] analyzed the remarkable factors affecting red-light running behavior for individual pedestrian and pedestrians in group, as well as predicted the probabilities of pedestrian red-light violation using a Logit regression model. Koh et al. [6] established a relationship of pedestrian violation behavior with waiting time, the number of conflicting traffic lanes, conflicting vehicular traffic volume and pedestrians' personal characteristics. Koh et al. [7] discussed the size of traffic gaps rejected and accepted by pedestrians and the behaviour of risky pedestrians. Zhuang et al. [8] analyzed pedestrians' choices after arrival, evaluated the safety of the choices, and built a model to identify the predictors of pedestrian choices. Onelcin et al. [9] investigates the pedestrians' delays and gap perceptions at various signalized intersections. Zhang et al. [10] used a binomial logistic model to investigate the factors affecting pedestrians' red-light running behaviors at intersection areas. Zhuang et al. [8] analyzed pedestrian choices after arrival, evaluated safety of the choices, and built a model to identify the predictors of pedestrian choices. Wael et al. [11] analyzed continuous pedestrian speed profiles to investigate sudden behavioural changes of pedestrians.

1.2. Pedestrian Twice-Crossing Behavior at Signalized Intersections

Yang [12] constructed a pedestrian twice-crossing delay model, based on vehicle headway, pedestrian arrival pattern and signal timing for pedestrians. Song et al. [13] realigned a signal phase sequence to design a new pedestrian two-stage crossing pattern to provide additional time for pedestrians. Wang et al. [14] Proposed a model to predict pedestrian delay of two-stage crossing at signalized intersection. Li et al. [15] investigated pedestrians' crossing behavior of in inclement weather and compliance under different weather and road surface conditions at a busy two-stage crossing. Li [16] studied pedestrian crossing theories and analyzed the applicability of different types of twice-crossing. Wang [17] studied the setup of two-stage crossing infrastructure at intersections under different signal control modes.

Existing research has focused on analyzing and modeling the characteristics of pedestrian red-light violation at signalized intersections with a one-stage crossing. But, only a few attempts have been made on pedestrian red-light violation at a two-stage crossing. Hence, there is a need for transport scholars to further analyze the characteristics of pedestrian's twice-crossing light violation. This study aims at constructing a model to present pedestrians' red-light running behavior and analyzing the characteristics of violation behavior at a two-stage crossing.

2. Definition and Model

2.1. Two Directions of Pedestrian Twice Crossing

There is a difference in the start of green signal in both directions of pedestrian twice crossing. If the green light of one direction started earlier than the opposite, this direction was referred to as direction A. The opposite was referred to as direction B, as shown in Figure 1.

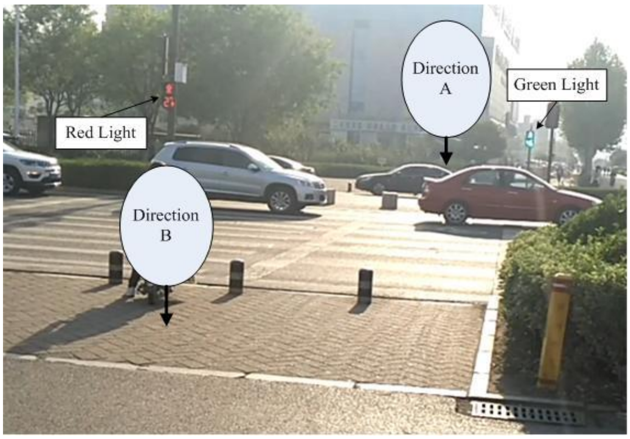

Figure 1. Directions A and B of pedestrian two-stage crossing

2.2. Modeling Pedestrian Red-Light Violation Behavior at a Two-Stage Crossing

Since the green light of direction A starts earlier than that of direction B, direction A has a longer effective green time than direction B. The sufficient green time allows pedestrians to put a high priority on safety, therefore the majority of pedestrians in direction A could follow traffic signals. However, a few pedestrians get involved in red-light running behavior before the start of the green interval, probably because they are lack of awareness of traffic rules or have impatient personality.

In direction B, the green light of the second stage starts earlier than that of the first stage. If pedestrian cannot cross the second stage in the green interval, they have to wait in the refuge island for the entire cycle of the next light before they can continue crossing. This is exactly what pedestrians are refusing to let it happen. Pedestrians in direction B would choose to run a red light to save time, although they know this is an unsafety practice. In the second stage, pedestrians' red-light violations usually appear at seconds after the green signal. Besides, the second stage starts the green light earlier than the first stage, which might result in pedestrians' cognitive confusion when they wait for the green light to pass the first stage, and thus lead to a red-light violation.

In direction A, just a few pedestrians get involved in light violation at seconds before they get green signal in the two stages. In direction B, a high percent of pedestrians involve in red-light running over a long period of time. Their violations happen at seconds before the green signal in the first stage and after the green signal in the second stage. Based on the above analysis, a goal-oriented and time-driven model is proposed to simulate pedestrians' red-light violation behavior in the two stages at signalized intersections, as shown in Figure 2.

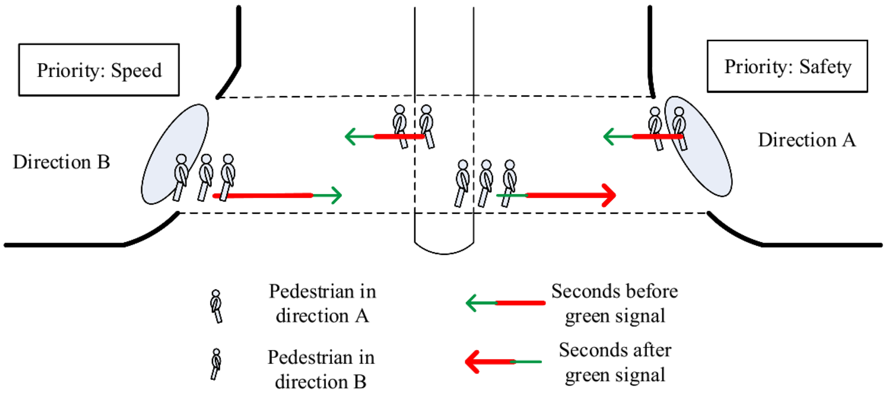

Figure 2. The model of pedestrian red-light violation behavior at a two-stage crossing

3. Research Method

In this study, field was collected at a signalized intersection with video recording technique. An unmanned aircraft system was used to gather pedestrian flow characteristics and behavior along the street. The two-stage pedestrian crossing (see Figure 4) at the intersection of Nanjing Road and Gongqingtuan West Road (see Figure 3) in Zibo City was selected. Eight hours of recordings were conducted in the normal working days during morning peak hours (7:00am to 9:00am). The pedestrian data was collected, mainly including the number of light violations and the time of light violations, in order to obtain the rate of pedestrian light violation of the two-stage crossing. It has been noted that the selected intersection is near a school zone, so a large proportion of pedestrians were university students. The pedestrian flow followed a negative binomial distribution, at least approximately. Data were analyzed in four aspects, the rate of light violation, the time distribution of light violation, the consistency of light violation, and light violation in group. Figure 5 presents the framework of data collection and analysis used in this study.

Figure 3. Location of the selected intersection (Nanjing Road and Gongqingtuan West Road)

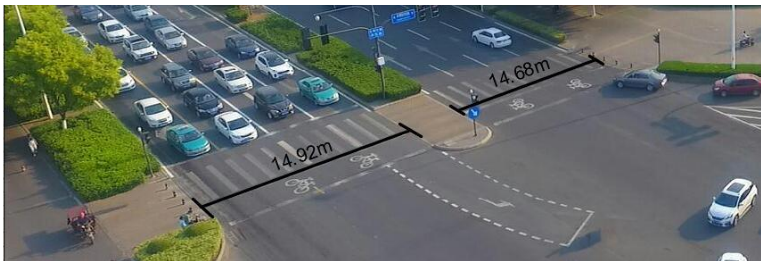

Figure 4. Dimensions of the selected pedestrian two-stage crossing

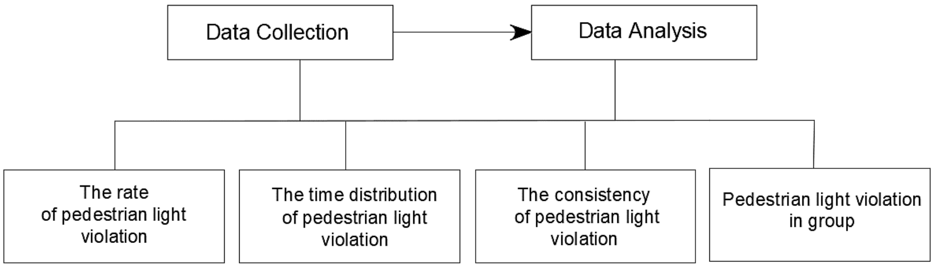

Figure 5. The framework of data collection and analysis

There is a difference in pedestrian signal timing between direction A and direction B. The signals for the two directions were with a predetermined time, as shown in Figure 6.

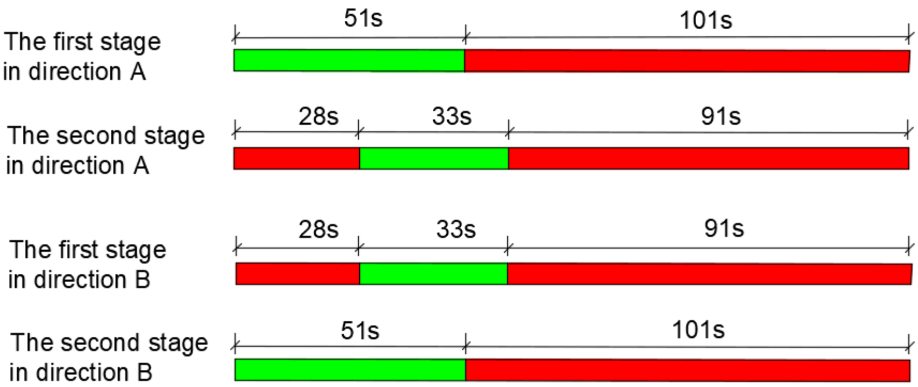

Figure 6. Pedestrian signal timing of the two directions

4. Results and Discussion

4.1. Analyzing Pedestrian Red-Light Violation Based on Delay Estimation

In this study, pedestrian twice-crossing delay was estimated using a model proposed by Wang et al. [13] (2010). The pedestrian delays of the two stages were calculated separately. The delay of the first stage crossing can be computed as a one-stage crossing delay. The HCM pedestrian delay model (see Equation 2) was used calculate the pedestrian delay. Pedestrians need to wait on the refuge island for crossing the second stage, which creates the second part of the delay. The delay of the second stage crossing was calculated using Equation 3 (see Wang et al. (2010) for details).

$$d = d_x + d_{x,y} \quad (1)$$

$$\mathrm{d_x} = \frac{0.5 \times (\mathrm{C} - \mathrm{walk_x})^2}{\mathrm{C}} \quad (2)$$

$$\mathrm{d_{x,y}} = \frac{\mathrm{C} - \mathrm{walk_x}}{\mathrm{C}} \mathrm{d_{r,x}} + \frac{\mathrm{walk_x}}{\mathrm{C}} \mathrm{d_{w,x}} \quad (3)$$

$$d_{r,x} = t \quad (4)$$

$$d_{w,x} = \frac{0.5(a+t)^2 + ar_x}{walk_x} \quad (5)$$

With;

$\mathrm{t = T - w \pm nC}\ (0 < t < C)$

$\mathrm{n} = 0, 1, 2, 3, \ldots$

$\mathrm{a = walk_x - walk_y - t}$

Where, d_x = total first-stage crossing average delay for pedestrians (s/person); $d_{x,y}$ = total second-stage crossing average delay for pedestrians (s/person); $d_{r,x}$ = average delay of second-stage crossing for pedestrians who arrive at first-stage crosswalk during FDW(the flashing Don't Walk clearance interval) and Stop intervals(s/person); $d_{w,x}$ = average delay of second-stage crossing for pedestrians who arrive at first-stage crosswalk during Walk interval(s/person); $walk_x$ = Walk interval for first stage(s); $walk_y$ = Walk interval for second stage(s); and r_x= FDW and Stop intervals (s).

Based on the equations above, it was estimated that 59.9s of average pedestrian delay was for direction A and 93.6s was for direction B. It has been found that the light violation rate is highly associated with pedestrian delay at signalized intersections. In China, pedestrians could tolerate a maximum waiting time of 90s in a high-density intersection. If pedestrians had to wait over the limit, they would be more likely to against the traffic signals. Therefore, direction B would have a higher percent of red-light violation than direction A, because pedestrians could not tolerate the waiting time beyond their limits.

4.2. Analyzing Pedestrian Red-Light Violation Using Field Data

4.2.1. The Rate of Pedestrian Red-Light Violation

The observed intersection was installed with countdown signals, which can inform pedestrians in advance about the remaining time to cross or the time needed to wait for crossing. According to the time that red-light violations occurred, the violations were divided into two types, at seconds before green signal and after green signal. The data were collected including 447 pedestrians in direction A and 578 pedestrians in direction B. The rates of different types of pedestrian red-light violation in the first stage are shown in Table 1. In direction A, 10% of pedestrians violate red light at seconds before green signal and only1.67% of pedestrians run red light at seconds after green signal. Most violations appear at seconds before green light, this might be because these pedestrians were lack of awareness of traffic rules or had impatient personality.

In direction B, 45.71% of pedestrians violate red light at seconds before green signal and only1.43% of pedestrians run red light at seconds after green signal. It was seen that the majority of violations occur at seconds before the light turns green. One reason is that the second stage starts the green light earlier than the first stage, which results in pedestrians' cognitive illusion when they waited for the green light to pass the first stage and so leads to red-light running behavior. The second reason is that pedestrians in direction B attempted to reduce exposure time of conflicts with the opposite when crossing the first stage, and to gain more time to finish crossing. The high violation rate reflects that the walk signals cannot provide time which is long enough for pedestrians to cross. It seems that the traffic signals were designed mainly with the needs of vehicles, and little consideration was given to pedestrians.

Table 1. Pedestrians' red-light violation rate of crossing the first stage

	No Violation	Red-light Violation	
		At seconds before green light	At seconds after green light
Direction A	88.33%	10.00%	1.67%
Direction B	52.86%	45.71%	1.43%

Table 2 shows the rates of pedestrian red-light violation in the second stage. In direction A, 83.33% of pedestrians comply with traffic signals when they cross the second stage. Pedestrians in direction A waited on the refuge island for the phase of the second stage. Among them, a few chose to against a red light, this might be due to negative impacts of pedestrians' violations in the opposite.

In direction B, 58.57% of pedestrians violate red light at seconds after green signal. Because the second stage starts the green light earlier than the first stage, if pedestrians did not cross the second stage in the green interval, they would have to wait in the median island until the next green light to complete the crossing. Pedestrians were not willing to wait so long, thus they chose to violate at seconds after the light changed from green to red.

Table 2. Pedestrians' red-light violation rate of crossing the second stage

	No Violation	Red-light Violation	
		At seconds before green light	At seconds after green light
Direction A	83.33%	13.33%	3.33%
Direction B	41.43%	0.00%	58.57%

In summary, pedestrian light violations mainly happen at seconds before the light turns to green, in the two stages of direction A and the first stage of direction B. Pedestrians run a red light at seconds after the light changes from green to red in the second stage of direction B.

4.2.2. The Time Distribution of Pedestrian Red-Light Violation

Pedestrians' light violations happen at seconds before the light changes to green or after the light turned to red. The time of a violation was measured starting from the time that the pedestrian light changes. The times of violations were divided into five groups: 0~3s, 4~7s, 8~15s, 16~30s, and >30s. The time distribution of red-light violation for the two directions are shown in Figure 7. In the first stage of direction A, most violations (83.3%) occur from 0s to 3s. This might be due to pedestrians' inappropriate crossing habit, to be specific, pedestrians were used to enter a crosswalk at a few seconds before they got green signal. In the second stage, the light violations happen in 7s. It might be due to pedestrians' inappropriate crossing habit, in addition to the negative impact of pedestrians' violation in the opposite.

In the first stage of direction B, the violations are uniformly distributed in three time ranges of 0~3s, 4~7s and 16~30s. It has been noticed that the second stage starts a green phase 28s (in the range of16~30s) earlier than the first stage. This setting was more likely to produce a cognitive illusion on pedestrian, and thus result in light violations happened in the time rang of 16~30s. In the second stage of direction B, most violations happen in the time rang of 4~7s (after the light turns red). When pedestrians did not cross the second stage in green interval, they had to wait for the entire cycle of the next light. To avoid the situation, they run a red light after the light turned red. The violations occurred in 4~7s, probably because after the light changed red, pedestrians might hesitate for a moment and then go on. It reflects that pedestrians feel a little bit guilty for their violation behavior, although they take the action eventually.

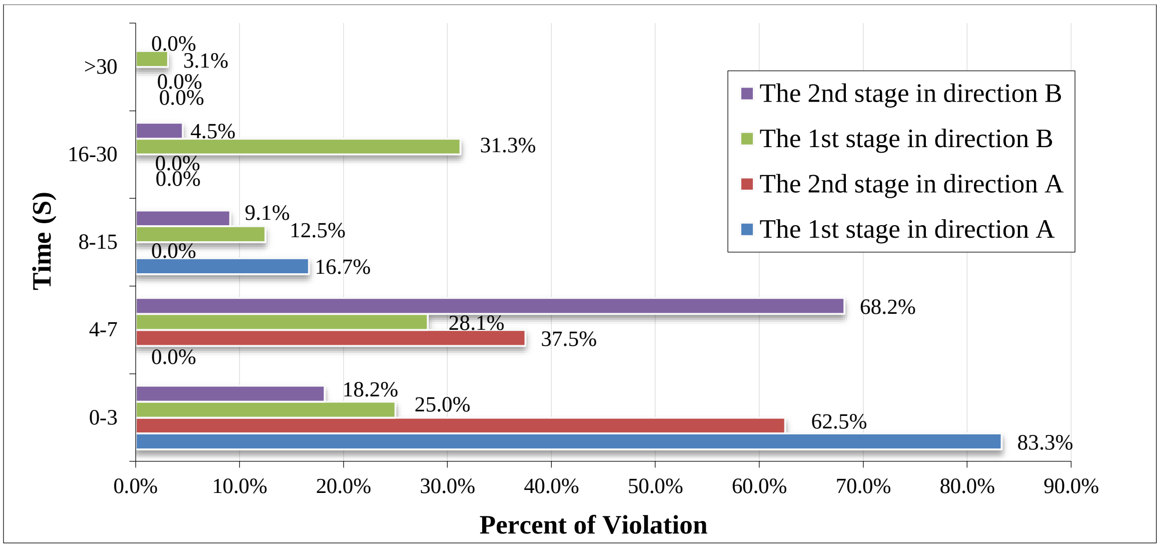

Figure 7. The time distribution of red-light violation for the two directions

4.2.3. The Consistency of Pedestrians' Red-Light Violation Behavior In The Two Stages

In order to determine the consistency of violation behavior in the two stages, the violation behavior were divided into four categories: 1) violation happened in the first stage only; 2) violation happened in the second stage only; 3) violations happened in the two stages; 4) no violation in the two stages. The consistency of violation behavior in the two stages are shown in Figure 8.

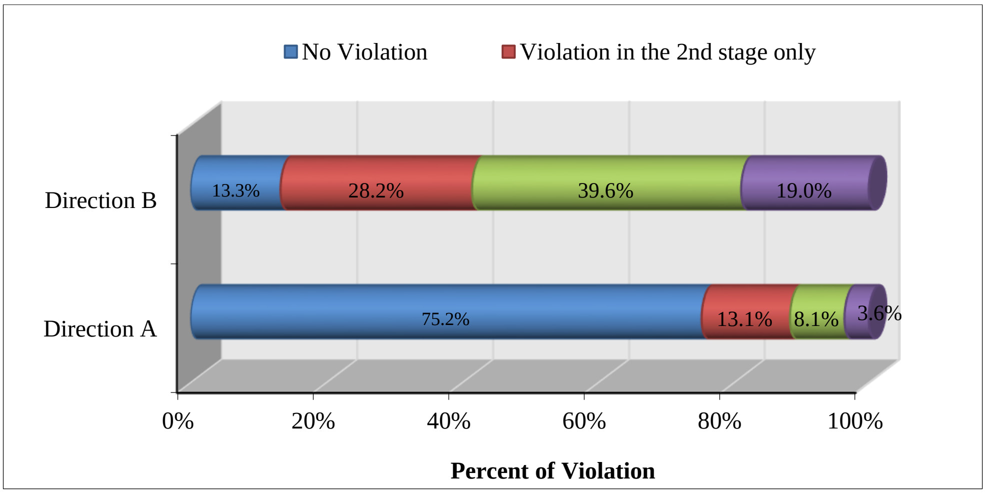

Figure 8. The consistency of violation behavior in the two stages

In direction A, most pedestrians (75.2%) follow the traffic lights continually, and only a very few (3.6%) involve in red-light running behavior in the two stages. For those involving in the two stages, pedestrians might have something urgent to deal with. In the process, pedestrians essentially regarded the signalized intersection as a non-signalized one, and ignored the traffic lights and took the gaps in vehicle stream.

In direction B, 39.6% of pedestrians violate the light in the first stage only and 28.2% violate the light in the second stage only. The two stages have a high percent of violation, which indicates that the signals of direction B cannot provide sufficient time for pedestrian crossings. Thus, most pedestrians have to against a red light once to complete their crossings. Even worse, some elderly or disabled pedestrians (19%) violate twice to complete their crossings. It reflects that the pedestrian signal pattern need to be improved or the green time need to be extended in direction B.

4.2.4. The Percent of Red-Light Violation in Group

To analyze the effect of group size on red-light violation behavior, pedestrians in group were classified according to age and gender. Pedestrians' age was categorized in three groups: the young group (18-35 years old), the middle-aged group (35-60 years old), and the old group (over 60 years old). When two or more pedestrians crossed street in a group, they showed similar behavior and thus were considered as a whole. The age attribute of the coupled group was defined based on the age of the oldest pedestrian in group. If all the pedestrians in a group were male/female, it was called male/female team. If pedestrians in a coupled group included man and woman, the group was called mixed-sex group. The rates of pedestrian red-light violation in group by age and gender are demonstrated in Table 3.

Direction A: The second stage has more pedestrian violations in group than the first stage. This indicates that pedestrians in group are more likely to get involved in light violation, if they are affected by pedestrian violation in the opposite. Among the three age groups, the highest violation rate appears to be in the middle-aged group, especially in the male team. It shows that two or more middle-aged male pedestrian together are more likely to exhibit aggressive walking behavior. The young group has the lowest violation rate, because most young people were college students, who had a strong sense of following traffic rules. The teams consisting of both man and woman cross street with a low violation rate, especially in the young and old groups. This reflects that mixed-sex team may have an impact on reducing pedestrian light violation at signalized intersections. Male team occur violation more frequently than female team in the young and middle-aged groups, and the trend is less obvious in the old group. This presents male pedestrians' physical strength and adventurous psychology when crossing streets, and male team may make the effects more significant. However, old men may be gradually losing their physical strength and adventurous psychology.

Direction B: The second stage has much more light violations than the first stage. This indicates that pedestrians in group are less likely to wait in the refuge island for the next light to finish crossings. Pedestrians in a group often force vehicles to yield in behavior during pedestrian red signals. In addition, female team has more violations than male team in the old group, and the opposite appears in the young and middle-aged groups. This might be associated with old people's physical and mental characteristics.

Table 3. The rates of pedestrian red-light violation in group by age and gender

			Violation in the 1st Stage	Violation in the 2nd Stage
Direction A	Young	Male team	2.25%	3.75%
		Female team	0.00%	1.25%
		Mixed-sex team	0.00%	1.25%
	Middle-aged	Male team	5.25%	8.75%
		Female team	1.25%	5.25%
		Mixed-sex team	2.50%	6.25%
	Old	Male team	1.25%	4.25%
		Female team	1.50%	3.25%
		Mixed-sex team	1.25%	2.25%
Direction B	Young	Male team	5.56%	1.11%
		Female team	3.33%	1.11%
		Mixed-sex team	3.33%	2.22%
	Middle-aged	Male team	5.56%	1.11%
		Female team	3.33%	1.11%
		Mixed-sex team	2.22%	1.11%
	Old	Male team	1.11%	1.11%
		Female team	2.22%	2.22%
		Mixed-sex team	1.11%	1.11%

5. Conclusion

This paper presents pedestrians' red-violation behavior for twice crossing at a signalized intersection, focusing on the time distribution of violation behavior, the consistency of violation behavior, and the violation behavior in group. A goal-oriented and time-driven model was proposed to analyze pedestrians' light violation behavior for twice-crossing at a signalized intersection, where the two directions have different pedestrian signal timing. It was found that pedestrians in the two directions present different violation behaviors. Direction B has higher violation rates, more dispersion of time distribution, and more pedestrians violating lights twice, than direction A. The results also show that the proposed model is effective in simulating pedestrian light violation behaviour at a two-stage crossing. The proposed model can be used in optimizing signal timing, improving pedestrian infrastructure, and pedestrian intention recognition, to gain a better understanding of pedestrians' two-stage crossing behavior. Further studies are required to confirm the above findings by collecting more field data from various signalized intersections.

6. Funding

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7. Conflicts of Interest

The authors declare no conflict of interest.

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