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Analysis of Route Choice for Pedestrian Two-Stage Crossing at a Signalized Intersection

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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, limited attention has been paid to analyze and model pedestrians' behavior patterns of twice crossing. The purpose of this paper is to determine pedestrians' route choices for twice crossing at a signalized intersection, focusing on the waiting position (to cross the street) and walking route. A goal-oriented and time-driven model was proposed to analyze pedestrians' twice-crossing behavior at signalized intersections, where the two directions have different pedestrian signal timing. A video-recording method was used to collect field data in order to obtain pedestrian preferences in choosing a walking route. It was found that pedestrians in the two directions present different preferences toward walking route, in waiting position, directional change and route type. The results showed that the proposed model is effective in simulating pedestrian route-choice behavior of twice crossing. This research provides a theoretical basis for identifying pedestrian movement intention, optimizing signal timing, and improving pedestrian infrastructure at signalized intersections.

Keywords: Pedestrian Two-Stage Crossing; Route Choice; Pedestrian Behavior Model; Signalized Intersections.

1. Introduction

Signalized intersections play an important role in the urban road network, many of which are designed with two-stage pedestrian crossing. Studying the characteristics of pedestrian twice-crossing behavior at signalized intersections, meets the needs of developing a "people-oriented" urban traffic system and is of great significance 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). Two-stage crossing is an effective measure to increase the pedestrian flow rate and the intersection capacity. By allowing pedestrians to wait halfway, refuge islands separate conflicts in time and place. It is very helpful in the scenarios where elderly or disabled pedestrians cross an intersection.

1.1. Pedestrian Crossing Behavior at Signalized Intersections

Tong et al. [1] analyzed the formation mechanism of pedestrian flow expansion, defined the expansion coefficient, and verified it through the actual pedestrian data. Qu et al. [2] presented the spillover behavior of pedestrian crossing at signalized intersections. Li et al. [3] analyzed the main factors of influencing pedestrian crossing behavior, and proposed traffic organization and control measures by setting refuge islands and optimizing signal timing parameters. Li et al. [4]

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analyzed microscopic pedestrian crossing behavior and modeled pedestrians' crossing decisions. Sun et al. [5] developed a virtual force model that was used to simulate pedestrian behavior, based on the theory of social forces and adding with some parameters such as angles, velocity and position. Zhang [6] analyzed the speed characteristics and arrival patterns of pedestrians, as well as pedestrian-vehicle conflict characteristics. Wu et al. [7] developed two logistic models of predicting the accelerated behavior of pedestrian crossing and determining if pedestrians can cross the street. Onelcin et al. [8] investigated pedestrians' crossing speed, delay and gap perception at different signalized intersections, and analyzed the factors effecting the crossing speed. Hashimoto et al. [9] used a probabilistic model to estimate the pedestrian states, including position, crossing decision and motion type.

1.2. Pedestrian Two-Stage Crossing Behavior at Signalized Intersections

Yang [10] constructed a pedestrian twice-crossing delay model, based on vehicle headway, pedestrian arrival pattern and pedestrian signal timing. Li [11] studied pedestrian crossing theories and analyzed the applicability of different types of twice-crossing. Wang [12] studied the setup of two-stage crossing infrastructure at intersections under different signal control modes. Song et al. [13] realigned a signal phase sequence to design a new pedestrian two-stage crossing pattern to provide additional time for pedestrians. Li et al. [14] investigated pedestrians' crossing behavior of in inclement weather and compliance under different weather and road surface conditions at a busy two-stage crossing. Wang et al. [15] proposed a model to predict pedestrian delay of two-stage crossing at signalized intersection.

1.3. Pedestrian Crossing Trajectory at Intersections

Hu et al. [16] used the model of finite-state automaton to describe pedestrian movement as a continuous microscopic motion state, and summarized three types of pedestrian crossings by analyzing the actual pedestrian data. Jiang et al. [17] used a Kalman filtering-based tracking algorithm to detect and track pedestrian trajectories based on spatiotemporal information. Zeng et al. [18] proposed a hybrid model combining path finding and social force method to simulate pedestrian trajectory at signalized intersections, and used genetic algorithms to improve the prediction accuracy. Kalantarov et al. [19] used simulation experiments to predict the trajectory and decision-making of pedestrians by analyzing the movements of different body parts while walking under different pressures. Zhao et al. [20] used video-recording technology to extract the real pedestrian crossing trajectories, and analyzed the average speed and instantaneous speed of pedestrian street crossing. Song et al. [21] proposed a neural network approach to simulate pedestrian movement in different scenarios. Fang et al. [22] analyzed pedestrians' crossing patterns and investigated the reasons caused the patterns.

Existing research has focused on analyzing the characteristics of pedestrian crossing behavior at a one-stage crossing, such as the expansion phenomenon, speed distribution, and the affecting factors. However, there have been very few studies conducted on the behavioral characteristics of pedestrian two-stage crossing. This paper proposed a goal-oriented and time-driven model to simulate pedestrians' twice-crossing behaviors at signalized intersections, especially in selecting waiting position and route mode.

2. Definition and Classification

2.1. Waiting Locations

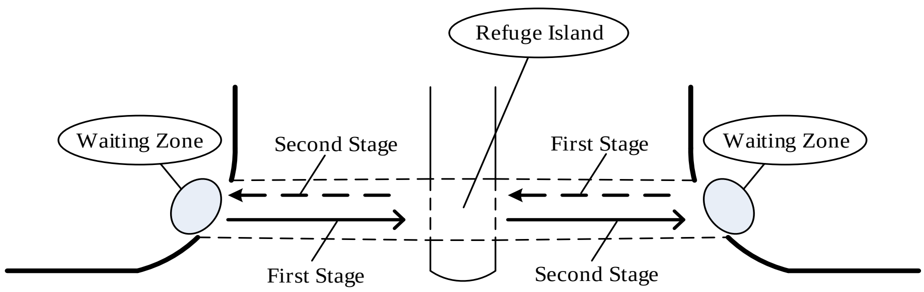

Figure 1. Waiting locations of pedestrian two-stage crossing

For a two-stage crossing, pedestrians cross the first stage, wait at the refuge island, and then cross the second stage to complete the crossing. In the process of two-stage crossing, pedestrians might experience waiting in three locations: the waiting zone before crossing the street, the refuge island, and the waiting zone after crossing the street. The three waiting locations are shown in Figure 1.

2.2. Classification of Waiting Zone and Refuge Island

In order to analyze pedestrian waiting positions, the waiting zones and refuge island were divided into three equal-width parts. According to the relative position with the intersection center, the three classifications were referred to as the near side, the middle, and the far side (shown in Figure 2).

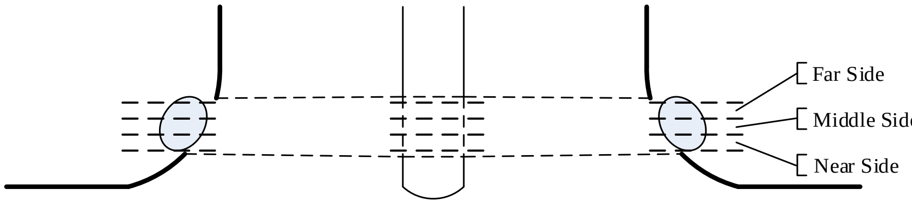

Figure 2. Classification of waiting zones and refuge island

2.3. 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 3.

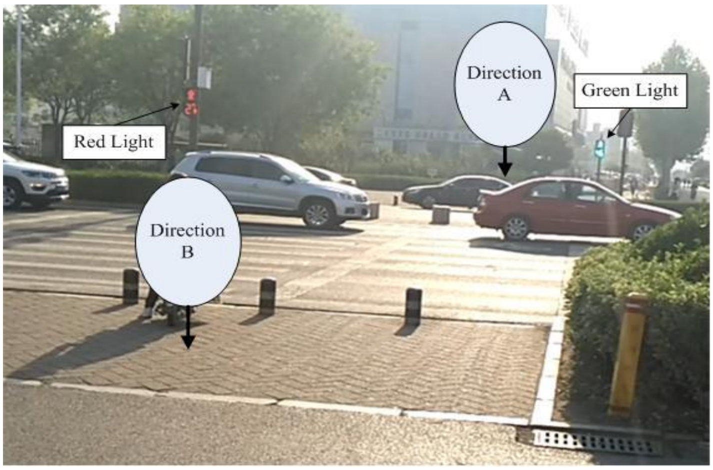

Figure 3. Directions A and B of pedestrian two-stage crossing

2.4. Classification of Walking Route

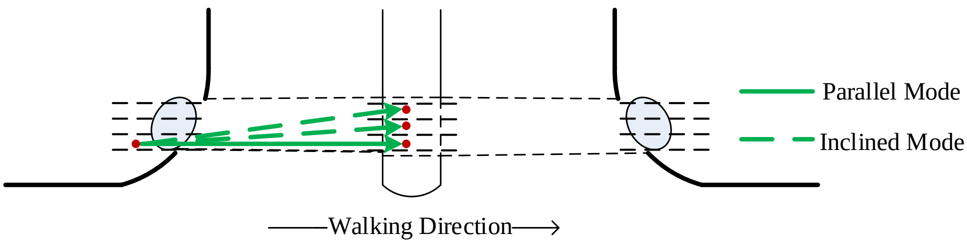

Figure 4. Examples of the parallel and inclined modes for the first stage

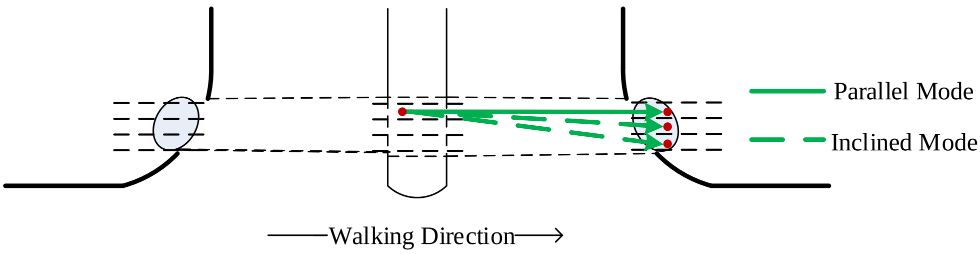

Figure 5. Examples of the parallel and inclined modes for the second stage

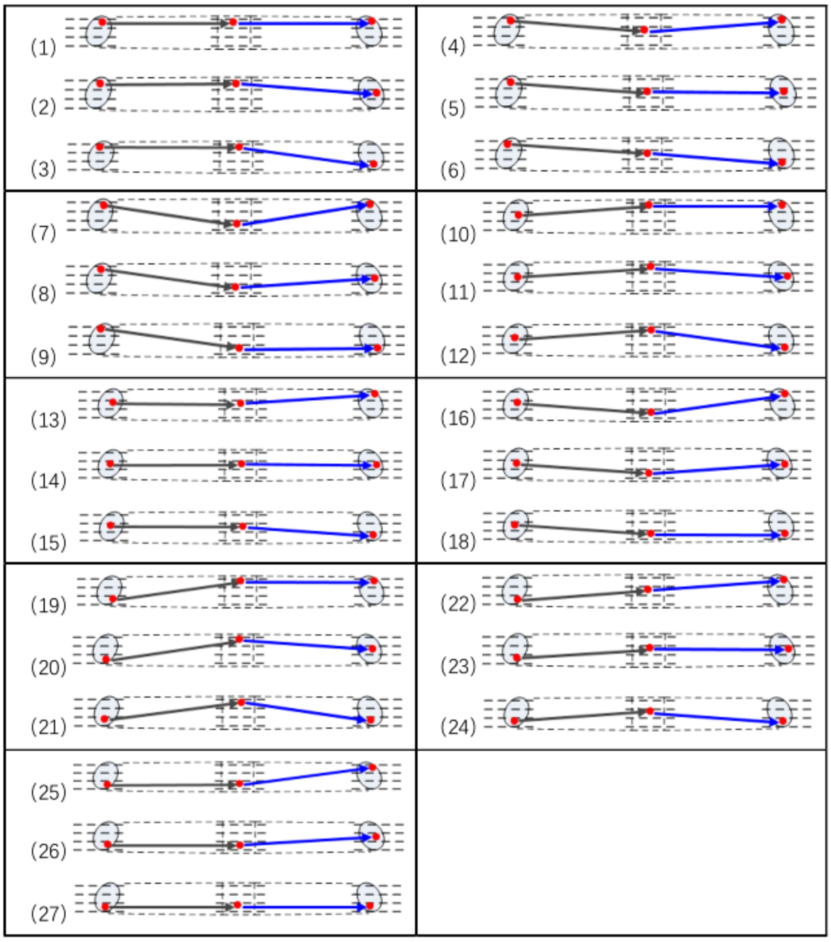

Figure 6. Twenty-seven possible walking routes for a two-stage crossing

As mentioned above, pedestrians might experience waiting in three zones. Each zone were divided into three parts. Each waiting position were considered to be one node, and two adjacent nodes were connected by a straight line. If a straight line was parallel with the longitudinal crosswalk line, the walking route would be referred to as parallel mode; if a straight line had an angle with the line of crosswalk, the walking route would be referred to as inclined mode. Examples of the parallel and inclined modes for the first and second stages are shown in Figures 4 and 5, respectively. According to the above-mentioned classifications, there are a total of 27 possibilities for a two-stage crossing, as shown in Figure 6.

3. Modeling Pedestrian Two-Stage Crossing Behavior

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 relatively long green time allows pedestrians to pursue a higher level of comfort, so pedestrians in direction A tend to go after "larger waiting space" and "shorter walking distance". Due to a limited green time, pedestrians in direction B mainly pursue "faster walking speed" to complete the crossing as soon as possible. Because of the difference in signal timing in both directions, the interspersed bi-directional pedestrian flow appears in the first stage of direction B and the second stage of direction A, as shown in Figure 7. This segment forms a multi-lane pedestrian flow and causes a significant expansion in the lateral direction.

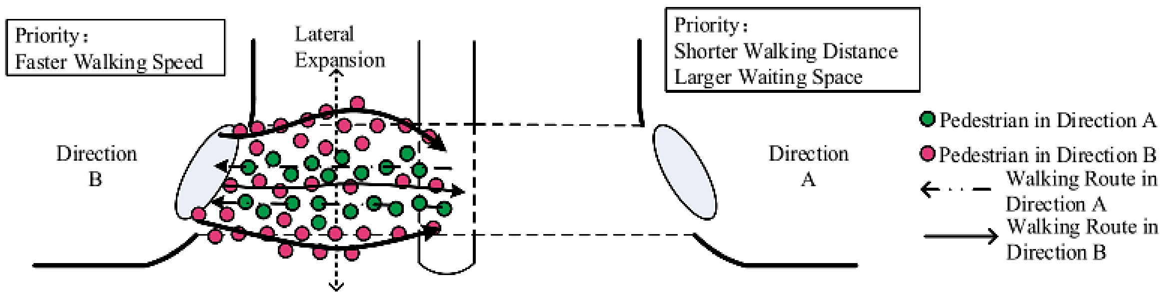

Figure 7. The goal-oriented and time-driven model for pedestrian two-stage crossing

In the interspersed bi-directional flow, pedestrians in direction A complete the entire crossing as long as they cross the second stage. Under the situation (with relatively long green time), pedestrians in direction A usually choose to go straight to seek the shortest possible. When facing conflicts with pedestrians in the opposite, they generally slow down or stop to avoid conflicts, to keep their walking straight. This could lead to a decrease in walking speed.

In a limited green time, pedestrians in direction B usually choose to detour to avoid conflicts with opposite pedestrians to complete crossing, which results in a lateral expansion of pedestrian flow. A detour is involved in a slightly longer distance than a direct route, but it can provide uncrowded room for pedestrians to achieve a high walking pace. Based on the above analysis, a goal-oriented and time-driven model was constructed to simulate pedestrians' twice-crossing behavior at signalized intersections, as shown in Figure 8.

4. Research Method

In this study, filed data 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 intersection of Nanjing Road and Gongqingtuan West Road in Zibo City was selected (see Figure 8). Eight hours of recordings were conducted in the normal working days during morning peak hours (7:00 am to 9:00 am). The pedestrian data was collected, especially of waiting position and walking route, in order to obtain pedestrians' route selections of 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 three aspects including pedestrian flow, walking trajectory and waiting position. Figure 9 presents the framework of data collection and analysis used in this study.

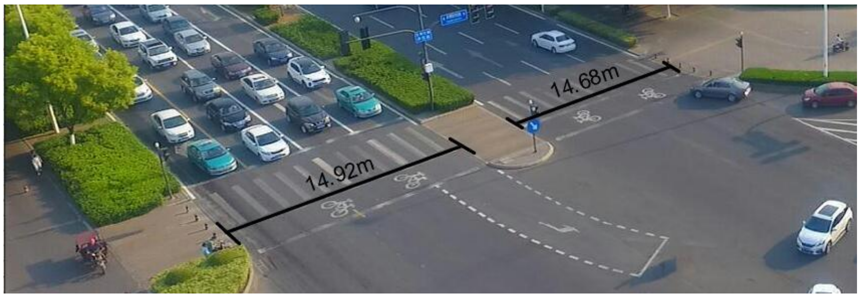

Figure 8. The intersection of Nanjing Road and Gongqingtuan West Road

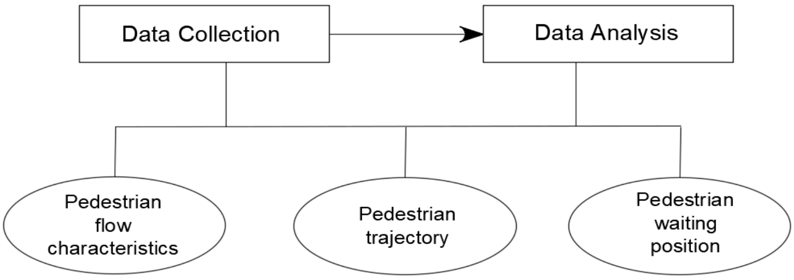

Figure 9. The framework of data collection and analysis

5. Results and Discussion

The data were collected including 447 pedestrians in direction A and 578 pedestrians in direction B. Figures 10 and 11 show the route choice probabilities of pedestrian two-stage crossing in directions A and B, respectively. In direction A, pedestrians were most likely to choose the route of "starting from the far side-parallel mode in the first stage-parallel mode in the second stage", and the choice probability is 28.33%. They were less likely to select the route of "starting from the near side-inclined mode in the first stage-inclined mode in the second stage" (0%) and "starting from the middle-inclined mode in the first stage-parallel mode in the second stage" (0%). In direction B, pedestrians were most likely to choose the route of "starting from the near side-parallel mode in the first stage-parallel mode in the second stage", and the choice probability is 22.86%. They were less likely to select the route of "starting from the far side-inclined mode in the first stage-inclined mode in the second stage" (0%) and "starting from the middle-inclined mode in the first stage-inclined mode in the second stage" (0%).

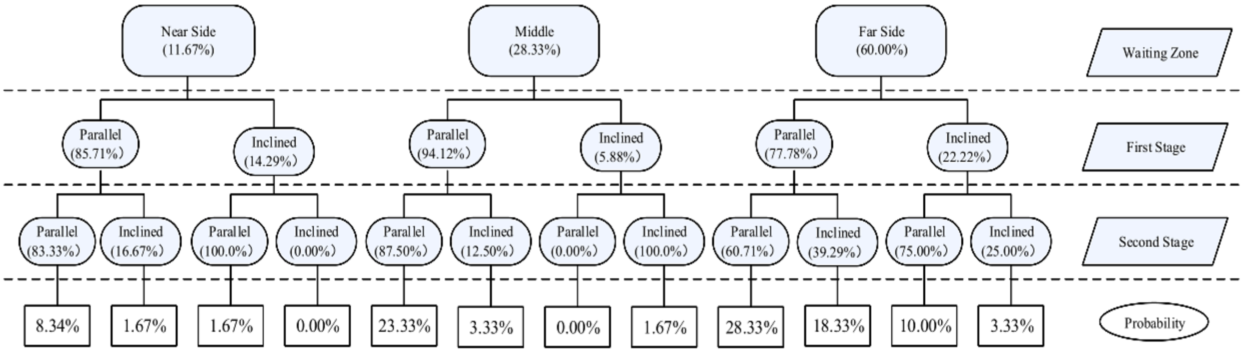

Figure 10. The probabilities of pedestrians' route choice in direction A

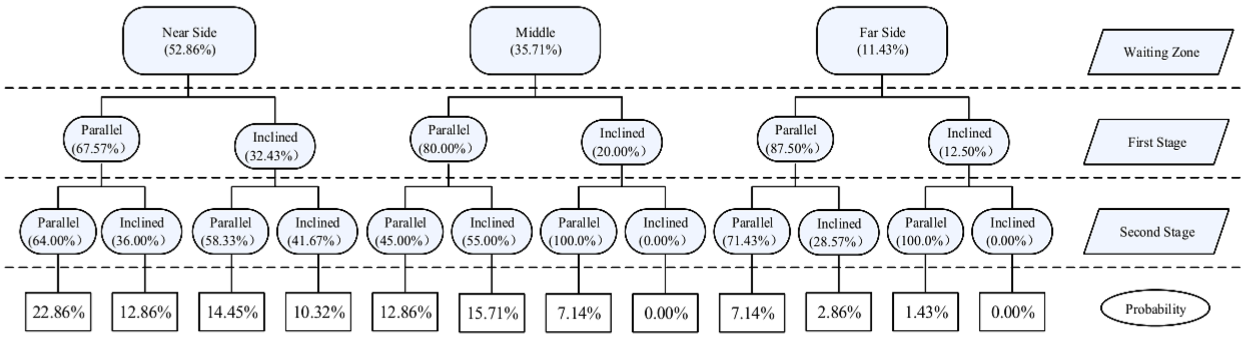

Figure 11. The probabilities of pedestrians' route choice in direction B

Considering the waiting position before crossing, the probability of selecting the far side in direction A (60%) is very close to that of selecting the near side in direction B (52.86%). The probability of selecting the near side in direction A (11.67%) is very close to that of selecting the far side in direction B (11.43%). It can be seen that pedestrians' waiting positions before crossing in the two directions present an approximately symmetric distribution, as shown in Figure 12.

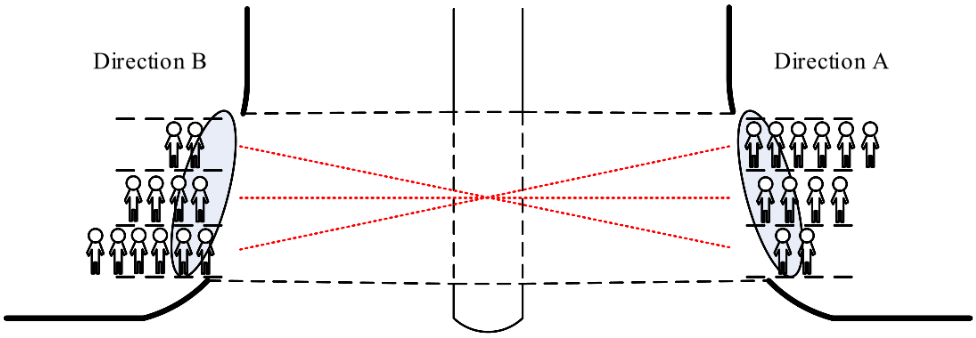

Figure 12. A symmetric distribution of pedestrians' waiting positions

According to the results of this study, a detailed discussion is shown as follows:

- More than half of pedestrians in direction A chose the far side to the intersection center to wait before crossing the street. One main reason is that the green time in this direction is relatively long, which provides pedestrians time to pursue a higher level of comfort. The far side has additional space (open area between crosswalk and roadside greenbelt), which provides pedestrians more room and ease crowding. It reflects pedestrians' goal pursuit of "wider waiting space" in direction A.
- More than half of pedestrians in direction B chose the near side to wait before they crossed the street. This might be because that the limited green time in direction B makes pedestrians select a shorter walking distance, the near side appears to be shorter in visual perception. By selecting a walking distance that seems to be shorter, pedestrians tended to achieve a faster walking pace. It reflects pedestrians' goal pursuit of "faster walking speed" in direction B.
- In direction A, the percent of pedestrians starting from the far side and completing the first stage by inclined mode is pretty high. This is because the far side has the highest number of pedestrians, they tended to spread out over a

large area to mitigate crowding as crossing the street. It also reflects pedestrians' goal pursuit of "wider waiting space" in direction A.

- The majority of pedestrians in direction A crossed the second stage using the parallel mode. In this direction, the relatively long green interval allows pedestrian to go after a shorter walking distance. A high-density bi-directional pedestrians flow appears in the second stage. When occuring conflicts with opposite pedestrians, pedestrians would much rather avoid conflicts by lowering their speeds than detouring with a longer distance. It reflects pedestrians' goal pursuit of "shorter walking distance" in direction A.

It is important to note that, an actual walking route of the parallel mode may be not an exact straight line. The parallel mode could be simply classified into three types: the parallel line, the convex arc (the convex side close to the intersection center), and the concave arc (the convex side away from the intersection center). The details are illustrated in Figure 13.

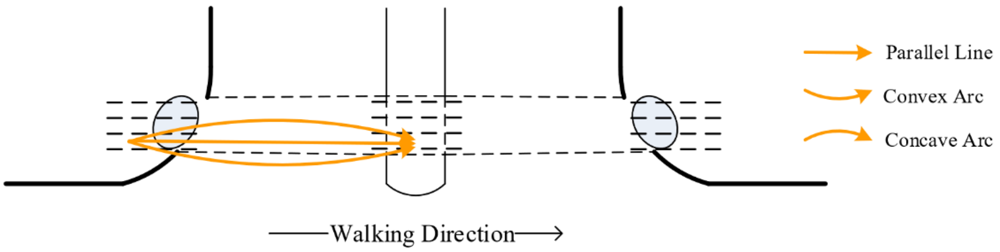

Figure 13. Three types of the actual walking route of the parallel mode

It can be seen from Tables 1 and 2, that in the interspersed bi-directional pedestrian stream, 51% of pedestrians in direction A chose the parallel line, and most pedestrians in direction B chose the modes of convex arc (46%), concave arc (15.51%), and inclined line (30.49%). Pedestrians' route modes can reflect their selected strategy to avoid conflicts with opposite pedestrians. In direction B, the route modes of convex arc, concave arc and inclined line indicate that pedestrians take a detour to avoid conflicts, in order to increase their speeds in less crowded space. This reflects pedestrians' goal pursuit of "faster walking speed" in direction B.

Table 1. Pedestrians' route modes of second stage in direction A

Parallel Mode			Inclined Mode
Parallel line	Convex Arc	Concave Arc	
51.00%	9.00%	11.67%	28.33%

Table 2. Pedestrians' route modes of first stage in direction B

Parallel Mode			Inclined Mode
Parallel line	Convex Arc	Concave Arc	
8.00%	46.00%	15.51%	30.49%

In summary, the results show that the proposed model is effective in simulating pedestrians' route choice for two-stage crossing at a signalized intersection. As described by the model, in the high-density bi-directional flow, pedestrians in direction A preferred to choose the mode of parallel line, aiming to achieve "shorter walking distance". Pedestrians in direction B preferred to choose the modes of inclined lines and curves, aiming to reach "faster walking speed".

6. Conclusion

This paper presents pedestrians' route choices for twice crossing at a signalized intersection, focusing on the waiting position and walking route. A goal-oriented and time-driven model was proposed to analyze pedestrians' twice-crossing behavior at signalized intersections, where the two directions have different pedestrian signal timing. It was found that pedestrians in the two directions present different preferences toward walking route, in waiting position, directional change and route type. Pedestrians in direction A are more likely to start from the far side and go straight across the street, while pedestrians in direction B are more likely to start from the near side and traverse along a curve. The results showed that the proposed model is effective in simulating pedestrian route-choice behavior. 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 larger sample size from more signalized intersections.

7. Funding

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8. Conflicts of Interest

The authors declare no conflict of interest.

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