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Pedestrians' Speed Analysis for 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

Pedestrian walking speed is an important and essential parameter for designing traffic signals at signalized intersections. However, there is a lack of understanding of pedestrian speed characteristics in a twice crossing. This paper focuses on analyzing the differences of pedestrians' crossing speeds between the two stages, and identifying the major factors affecting the speed changes. Pedestrians were classified by age, gender and group size, and pedestrians' speed characteristics of each group were analyzed. Besides, each age group were divided into five categories by gender and group size, and the effect sizes of gender and group size on speed-changing at the two stages were examined. The results show significant differences in walking speed on different gender and age groups, as well as on different group size. The young group has different factors affecting the speed change in the two directions, and the middle-aged and old groups have same factors affecting the speed change in the two directions. This study proposed a goal–oriented and time-driven behavior model for pedestrian two-stage crossing at signalized intersections, where the two directions have different pedestrian signal timing. The results also show that the proposed model is effective in simulating pedestrian speed characteristics 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: Two-Stage Crossing; Pedestrian Walking Speed; Pedestrian Behavior Model; Signalized Intersection.

1. Introduction

Pedestrian two-stage crossing is an important component of urban road network, and highly affects the network traffic operations. In a two-stage crossing, a refuge island is established at the middle of a crosswalk, which provides a protected space for pedestrians to cross street. Pedestrian signal design is mainly based on pedestrians' crossing speed, so insufficient understanding of pedestrian speed would lead to undesirable consequences such as large delays and red-light violations. Studying the speed characteristics of pedestrian twice crossing at signalized intersections is essential for improving traffic efficiency and pedestrian safety, especially in developing countries with large pedestrian population such as China.

1.1. Pedestrian Crossing Behavior at Signalized Intersections

Hashimoto et al. [1] proposed a probabilistic model based on the dynamic Bayesian network to recognize pedestrian behavior and pedestrian position information at signalized intersections. Yang et al. [2] proposed four accelerated failure time duration models to examine the significant risk factors affecting duration times for pedestrian's waiting behaviour.

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

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Jiang et al. [3] investigated the effects of mobile phone distractions on pedestrian crossing behaviour, including scanning frequency, fixation points and fixation times toward traffic signals, and visual attention on the traffic environment. Yang [4] built a pedestrian twice-crossing delay model, considering pedestrian arrival distribution, vehicle headway, and pedestrian signal timing. Li [5] analyzed pedestrian walking characteristics and psychological features and proposed the applicability of different types of twice-crossing. Wang [6] explored pedestrian path choice and analyzed the demand factors of pedestrian twice crossing. Song et al. [7] readjusted signal timing sequence to design a new pedestrian two-stage crossing pattern to provide additional time for pedestrians. Li et al. [8] analyzed pedestrians' crossing behaviour at a two-stage crossing in adverse weather conditions. Wang et al. [9] developed an improved model for predicting pedestrian delay at signalized intersections with a two-stage crossing design. Ni et al. [10] conducted intercept survey to explore pedestrian's perception, and found that pedestrians are in favour of the presence of Refuge Island.

1.2. Pedestrian Crossing Speed at Signalized Intersections

Zhang et al. [11] analyzed the temporal and spatial characteristics of pedestrian speed at signalized intersections, according to different gender, age and group size. Zhang et al. [12] analyzed the effects of age, gender, and the length of the crosswalk on pedestrian speeds at signalized intersections. Zhao et al. [13] used video-recording technology to extract the real pedestrian crossing trajectories, and analyzed the average speed and instantaneous speed of pedestrian street crossing by age group. Wang [14] analyzed the speed characteristics of pedestrian crossing during yellow and clearance intervals. Duim et al. [15] assessed the walking speed of elderly people and compared the results with the international standards for pedestrian crossing. Muley et al. [16] presented the analysis of the three types of pedestrian speed at signalized crosswalks: entry speed, crossing speed and exit speed. Iryo-Asano et al. [17, 18] modelled pedestrians' sudden speed changes when they crossed the signalized crosswalks under uncongested conditions. Onelcin et al. [19] investigated pedestrians' crossing speed, delay and gap perception at different signalized intersections, and analyzed the factors effecting the crossing speed by group size, age, items carrying and gender.

Existing research has focused on analyzing the characteristics of pedestrian walking speed on a one-stage crossing at signalized intersections. However, there have been very few studies conducted on the speed characteristics of pedestrian two-stage crossing. This paper focuses on the speed characteristics of pedestrian twice crossing at a signalized intersection, in different groups of gender, age and group size.

2. Definition and Model

2.1. Two Directions of Pedestrian 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.

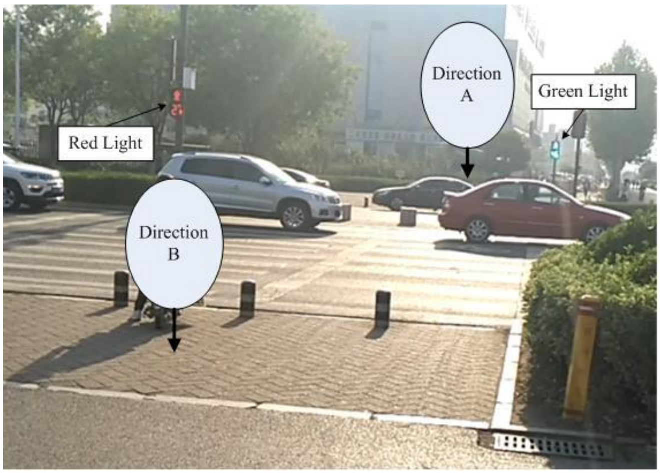

Figure 1. Directions A and B of pedestrian two-stage crossing

2.2. Modeling Pedestrian Twice-Crossing Behavior (Speed Analysis)

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 can walk at a slow pace to go after "shorter walking distance". Because of a difference in pedestrian signal timing in the both directions, a high-density bi-directional pedestrian flow is formed in the first stage of direction B and the second stage of direction A. In the second stage with a density condition, pedestrians of direction A choose to slow down to avoid conflicts with opposite pedestrians, to achieve a straightline crossing.

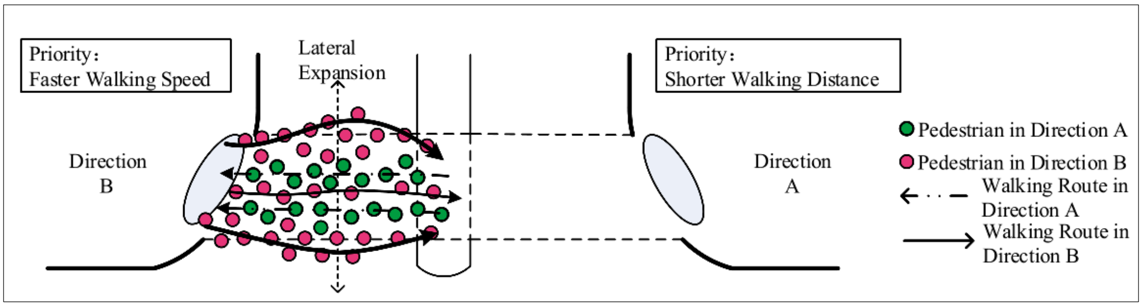

Figure 2. The goal-oriented and time-driven model of pedestrian two-stage crossing

Due to a limited green time, pedestrians in direction B have a deep desire for "faster walking speed". In the interspersed bi-directional pedestrian stream, pedestrians in direction B choose to detour to prevent conflicts with opposite pedestrians, because the detour could provide uncrowded room for pedestrians to reach a high walking pace. This would cause a significant spatial expansion of pedestrian flow in the lateral direction. Based on the above analysis, a goal-oriented and time-driven behavior model was proposed to simulate pedestrian twice-crossing speed at signalized intersections, as shown in Figure 2.

3. 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 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, especially of the time required by pedestrians to cross street, in order to obtain pedestrians' walking speeds 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. 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)

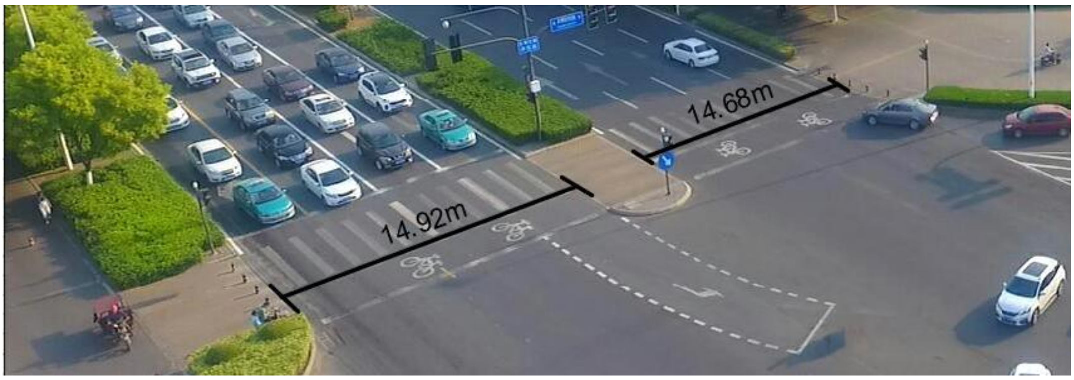

Figure 4. Dimensions of the selected pedestrian two-stage crossing

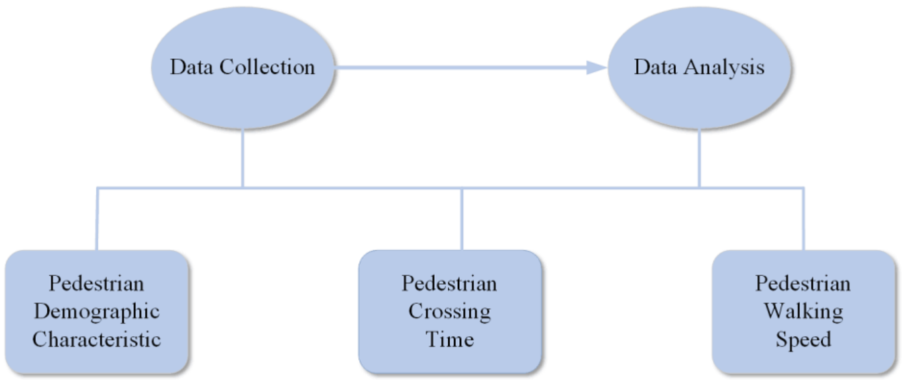

Figure 5. The framework of data collection and analysis

4. Results and Discussion

4.1. Pedestrian Twice-Crossing Speed of the Both Directions

The data were collected including 447 pedestrians in direction A and 578 pedestrians in direction B. The average speeds of pedestrian two-stage crossing in the two directions are shown in Figure 6. It was found in direction A, the average walking speed of 1.3m/s for the first stage (FS) and 1.27 m/s for the second stage (SS). The variation of walking speed is higher in the FS than in the SS. Statistical analysis was performed using SPSS Statistics 23.0 where the confidence interval was set at 95%. T-test for pedestrian crossing speed shows that the speeds are not significantly different in the FS and SS in direction A ($p = 0.210>0.05$). It was observed the average walking speed of 1.31m/s for the FS and 1.59 m/s for the SS in direction B. T-test for pedestrian crossing speed shows that the speeds are significantly different in the FS and SS in direction B ($p = 0.000<0.05$). The results presented above indicate:

- ***Direction A***: Compared to the SS, the FS has a higher velocity variation, which reflects a greater diversity of pedestrian behaviors in the FS. For example, some pedestrians chose to cross the FS quickly, and then wait in refuge island for the green light to pass the SS. While, someones adjusted their walking paces with signal timing accordingly, to prevent waiting in refuge island. The relatively long green time allowed pedestrians to walk at a slow pace in the FS. Pedestrians tended to speed up to cross the SS, but their speeds remained roughly unchanged, with the interference from the opposite pedestrians under a density condition.
- ***Direction B***: The average walking speed of the SS is greater than that of the FS, mainly because pedestrians conflicted with the opposite side under a high-density bidirectional flow in the FS. Without the interference from the opposite, pedestrians' walking speeds increased significantly in the SS. Another reason of the big increase in speed is limited remaining green time.

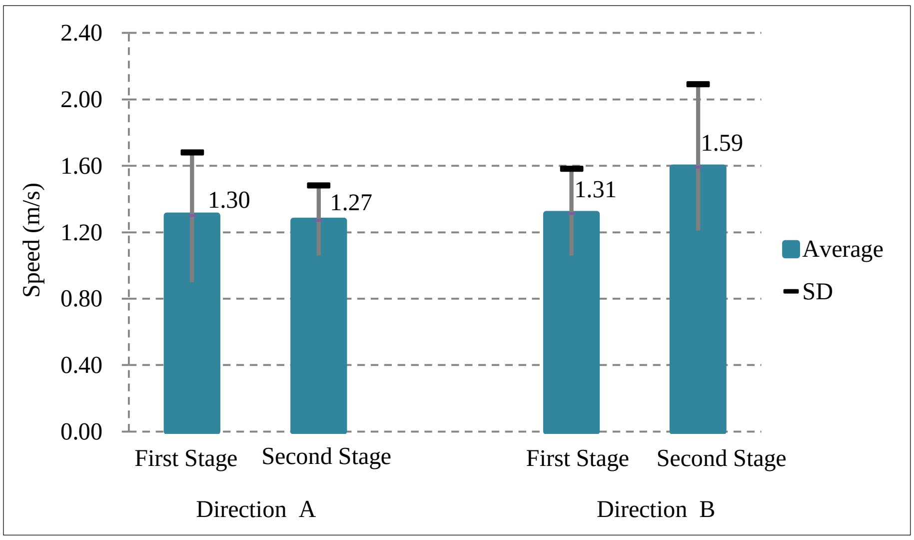

Figure 6. Pedestrians' average speeds of two-stage crossing in the two directions

4.2. Pedestrian Twice-Crossing Speed by Age Group

Pedestrian 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). The ANOVA analysis reveals that the young group is not statistically different with the middle-aged group in walking speed ($p = 0.127>0.05$), the old group is statistically different with the young group ($p = 0.029<0.05$) and with the middle-aged group ($p = 0.031<0.05$) in walking speed. Figure 7 shows the average speeds of different age groups in the two directions. In order to further investigate the impact of age on walking speed, pedestrian speed changes of the two stages for different age groups are shown in Figure 8.

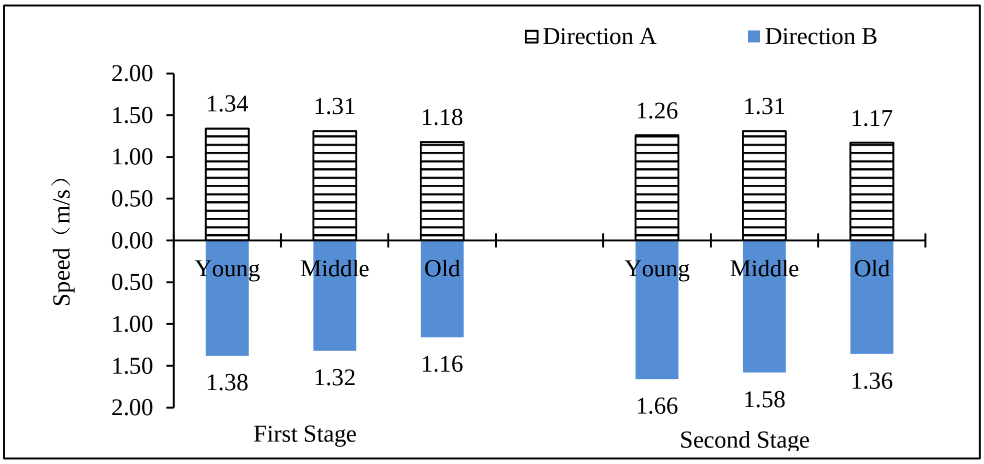

Figure 7. Pedestrians' average speeds by age group

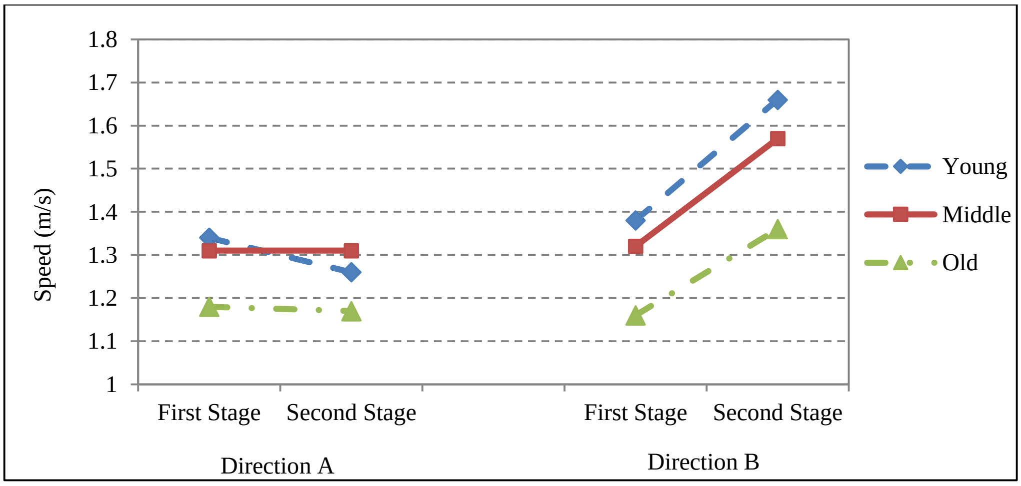

Figure 8. Pedestrian speed changes of the two stages by age group

Young Group: In direction A, the SS has a slightly slower speed than the FS. In the SS, young pedestrians (mostly university students) in direction A chose to voluntarily avoid conflicts with the opposite by slowing down, which could cause a reduction in walking speed. In direction B, young pedestrians also faced conflicts from the opposite side when they crossed the FS, but they were able to reach a higher speed. This was attributed to young pedestrians' route choice: they chose to detour near the lateral boundary lines of crosswalk to give way, which provides them more space to speed up. Even though young pedestrians in both directions voluntarily avoided conflicts with opposite pedestrians, different choices could lead to different speed performances.

Middle-aged Group: In direction A, the average speed remains unchanged in the two stages. The middle-aged group has a higher average speed than the young group in the SS. The results show that when conflicting with the opposite direction in a bi-direction stream, middle-aged pedestrians might not voluntarily give way as young pedestrians did. Thus, their walking speeds were less affected by the opposite conflicts. In direction B, the middle-aged group has a lower average speeds in the two stages than the young group, due to middle-age pedestrians' route choice. They preferred to walk along a straight path in the middle of the crosswalk. Despite involving in a relatively short walking distance, the crowded space made pedestrians difficult to increase their speeds.

Old Group*:* In direction A, the average speed remains unchanged in the two stages. In the SS, facing conflicts with the opposite side in a density flow, old pedestrians could keep their speeds unchanged. Because the opposite direction was more likely to voluntarily give way to elderly pedestrians, elderly pedestrians' speeds were less affected by the conflicts. In direction B, there is a large difference in walking speed between the elderly group with the young group, and with the middle-aged group. This might be contributed to physical frailty in elderly people.

4.3. Pedestrian Twice-Crossing Speed by Group Size

Figure 9 shows the average speeds of pedestrian two-stage crossing by group size in the two directions. The ANOVA analysis reveals that the team group is statistically different with the individual group in walking speed ($p = 0.027<0.05$). It was observed that the team group has a lower average speed than the individual group in the two stages in the both directions. Especially, the significant speed difference between the two groups was found, in the SS of direction A and the FS of direction B. Because the two segments appeared high-density bidirectional conflicts, which could result in a larger reduction on the team group.

When two or more pedestrians cross street in a group, they show similar behavior and hence can be considered as a whole. If each individual was considered to be a small elliptical force field, a team group could be regarded as a larger-size force field, as shown in Figure 10. In a high-density bi-directional stream, one team group exposed to more frequent conflicts than one individual did. To avoid the conflicts, the team groups generally spent more time to change their behavior, which would largely reduce their crossing speeds. For example, if one pedestrian in a team group decided to avoid the conflicts, he would have to tell his partners and then they make action together. This process took a longer time than one individual did.

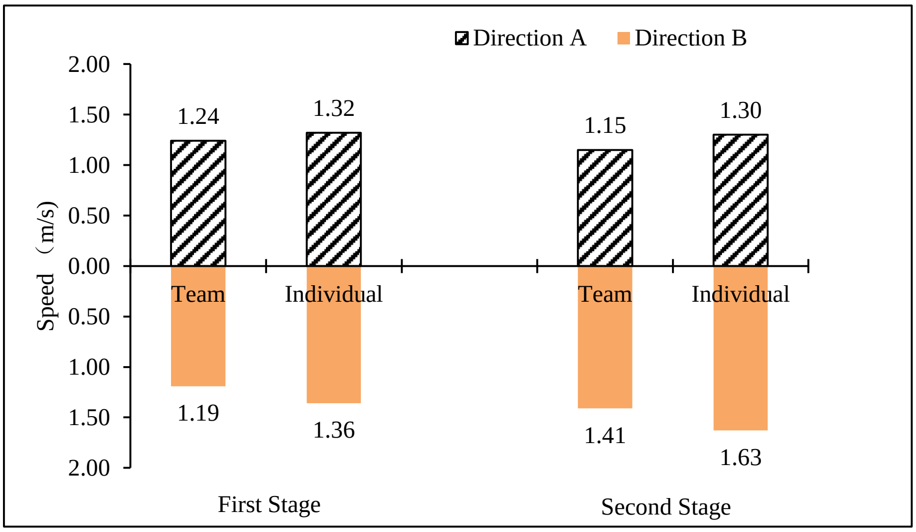

Figure 9. Pedestrians' average speeds by group size

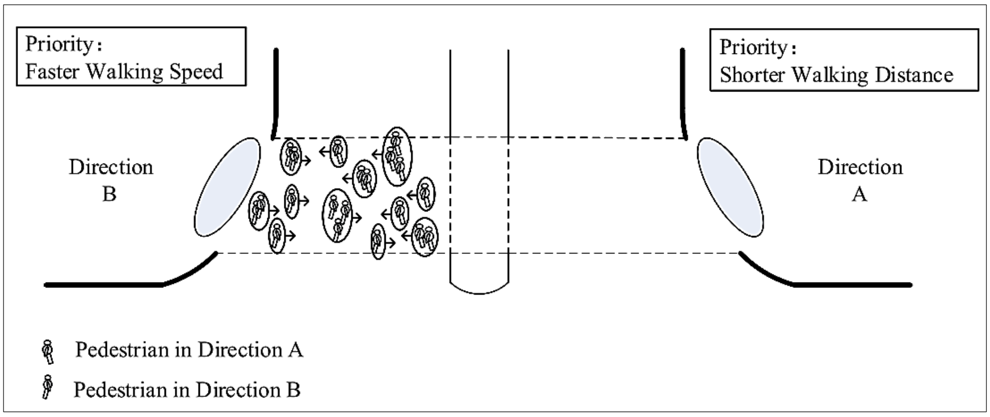

Figure 10. Force field demonstration of the individual and team groups

4.4. Pedestrian Twice-Crossing Speed by Gender Group

Figure 11 shows the average speeds of pedestrian two-stage crossing by gender group in the two directions. The ANOVA analysis reveals that the male group is statistically different with the female group in walking speed ($p = 0.044<0.05$). The results show that the female group has a lower average speed than the male group in the two stages in the both directions. This might be contributed to strong physical and aggressive personality of male pedestrians.

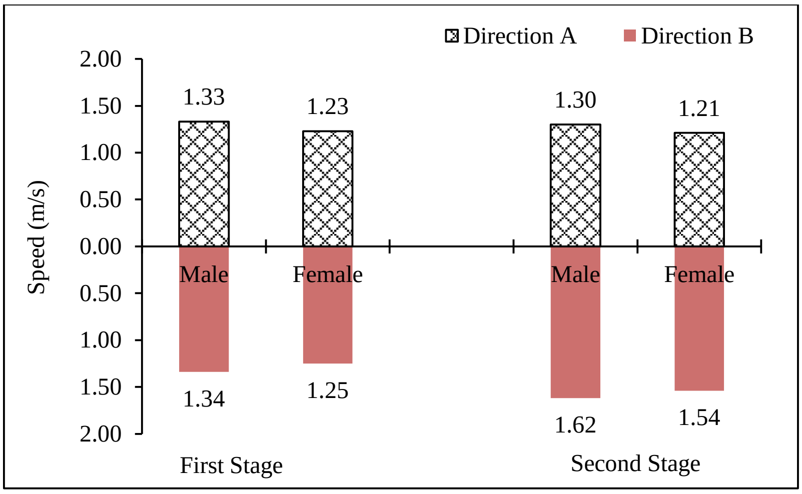

Figure 11. Pedestrians' average speeds by gender group

4.5. Effects of Gender and Group Size on Pedestrian Twice-Crossing Speed

In order to analyze the effects of gender and group size on pedestrian twice-crossing speed in different age groups, each age group was divided into five categories by gender and group size: a.) male individual; b.) male team; c.) female individual; d.) female team; e.) mixed-sex. The age attribute of the team group was determined according to the age of the oldest pedestrian in group. For each group, the changes in walking speed of the two stages are demonstrated for direction A in Figure 12 and for direction B in Figure 13. The detailed analysis by age group are demonstrated as follows.

Young group in direction A*:* The average speed is reduced from the FS to the SS for each sub-group, but the rates of speed change appear to be different. Specifically, a larger speed reduction appears in the team sub-groups than in the individual sub-groups. In the SS with a high-density bi-directional flow, either young individual or young team could voluntarily avoid the conflicts with the opposite. The young team spent more time to change their behavior, resulting in a bigger drop in speed.

Middle-aged group in direction A*:* It was found that the walking speed decreases in the individual groups and remains unchanged in the team groups. It indicates that when facing conflicts with the opposite pedestrians in the SS, the middle-aged pedestrians in the team sub-groups might not voluntarily give way (as young pedestrians do), but the middle-aged pedestrians in the individual sub-groups are more likely to do it. It was also found that the changes in walking speed include increase, decrease and keeping unchanged. It shows the behavioural diversity of middle-aged pedestrians crossing the two stages. In the mixed-sex sub-group, female pedestrians had to catch up with her male partner, resulting in an increase on female pedestrian speed. This situation is not common in the young and old groups.

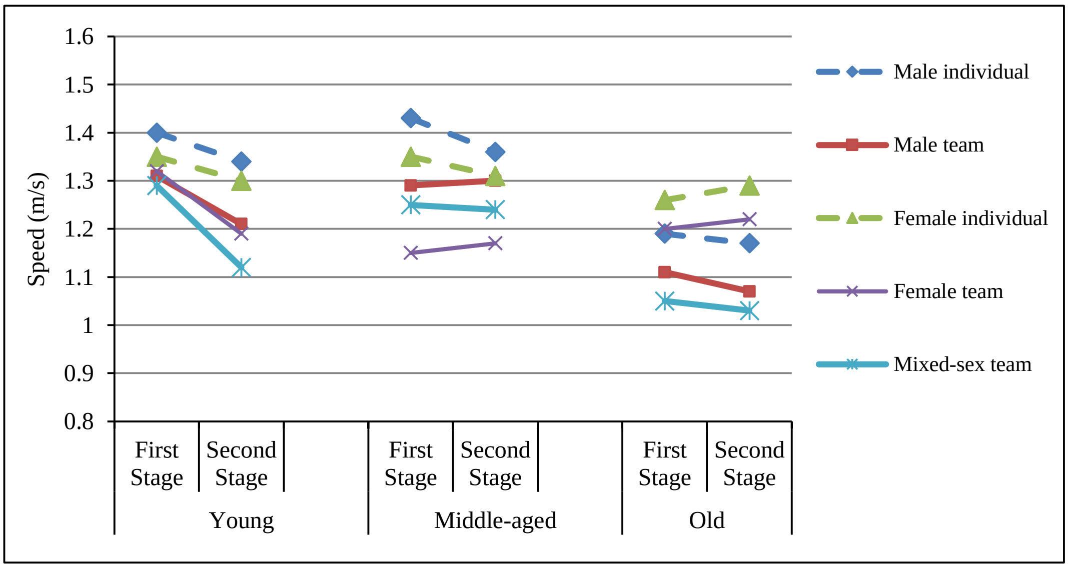

Figure 12. Pedestrian speed changes of the two stages by group in direction A

Old group in direction A*:* In general, there is very little change in walking speed for each sub-group in the two stages. This might be that when facing conflicts with the opposite pedestrians in the SS, the opposite pedestrians usually voluntarily gave way for elderly people. Therefore, the bi-directional conflicts put a small impact on walking speed of elderly pedestrian. Moreover, the female sub-groups have a greater average speed than the male ones, either individual or team. This phenomenon does not appear in the young and middle-aged groups. It might to be related to old people's physical and mental characteristics.

***Young group in direction B**:* When facing high-density conflicts with the opposite in the FS, young pedestrians were able to reach a higher speed. This might be due to young pedestrians' route choice: they chose to walk along the edges of crosswalk to avoid conflicts with the opposite, which provides them more space to move quickly. In the FS, the individual sub-groups have a higher average speed than the team ones. It indicates that young individuals can find space more easily to avoid conflicts than young pedestrians in group. Moreover, the magnitude of acceleration for the male sub-groups is greater than the female ones, either individual or team. This might be that young men have greater physical strength than young women.

***Middle-aged group in direction B**:* In the two stages, a lower speed was observed for the team sub-groups than the individual ones. In the SS, middle-aged pedestrians in group seemed not to present a strong desire to cross the street quickly, despite they had a very limited green time left. It indicates that middle-aged pedestrians in team have a low awareness about traffic rules, and thus they are more likely to involve in red-light violations. A significant difference in speed was found among different sub-groups, which reflects the behavioural diversity of middle-aged pedestrians crossing the two stages.

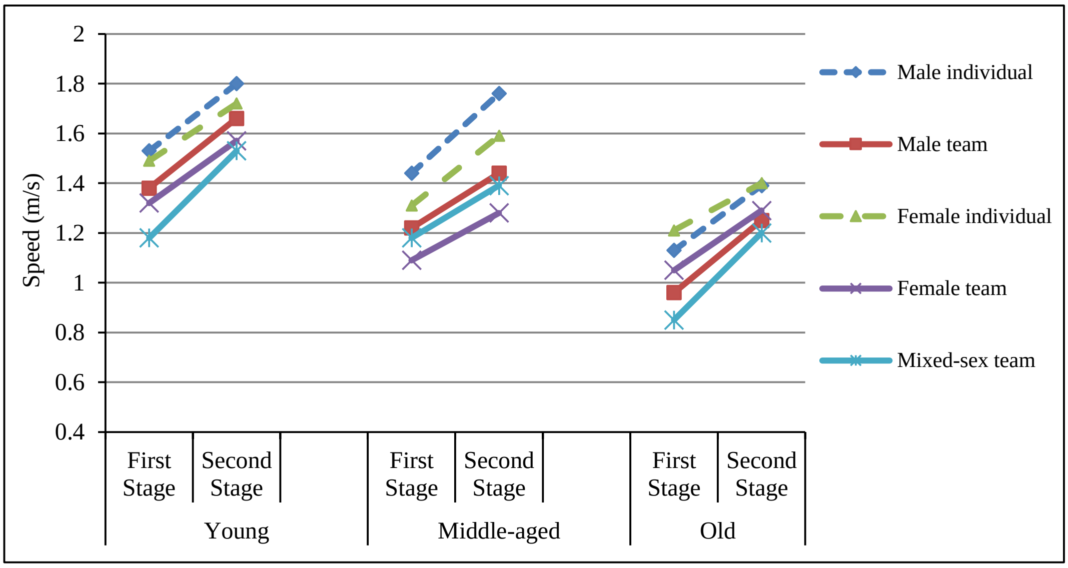

Figure 13. Pedestrian speed changes of the two stages by group in direction B

***Old group in direction B**:* The female sub-groups have a greater average speed than the male, either individual or team. This phenomenon is quite opposite in the young and middle-aged sub-groups. In the FS with a high-density bi-directional stream, the team sub-groups have a lower average speed than the individual ones. The main reason might be that although the opposite pedestrians (in direction A) could voluntarily slow down to avoid conflicts with elderly pedestrians, they might not give way to elderly pedestrians. Thus, elderly pedestrians still had to change their routes to cross the street. This causes a reduction on walking speed for seniors, especially for the elderly in the team sub-groups.

Table 1. The main factor affecting the speed change for each age group

	Direction A			**Direction B**		
	Young	Middle-aged	Old	Young	Middle-aged	Old
Main Factor	*Group size*	*Group size*	*Gender*	*Gender*	*Group size*	*Gender*

In Figures 12 and 13, the magnitude of the slope shows the effect size of gender and group size on walking speed. The greater the magnitude of the slope, the larger the effect size. By analyzing the magnitude of the slope, the main factor affecting the speed change for each age group was determined as shown in Table 1. For example, for the old group in direction A, it was observed an increase in speed for female sub-groups and a decrease in speed for male sub-groups. This reflects that gender has a remarkable effect on speed change for the old group in direction A. For the middle-aged group in direction B, a steeper slope appears in the individual sub-groups than the team. This indicates that group size has an important effect on speed change for the middle-aged group in direction B.

5. Conclusion

This paper presents pedestrians' speed behavior for twice crossing at a signalized intersection, focusing on pedestrian speed change in the two stages by age, gender and group size, as well as the main factors affecting speed-changing for each group. The results show significant differences in walking speed on different gender and age groups, as well as on different group size. The young group has different factors affecting the speed change in the two directions, and the middle-aged and old groups have same factors affecting the speed change in the two directions. A goal-oriented and time-driven model was proposed to analyze pedestrians' twice-crossing speed behavior at signalized intersections, where the two directions have different pedestrian signal timing. The results also show that the proposed model is effective in simulating pedestrian speed 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.

6. Funding

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7. Conflicts of Interest

The authors declare no conflict of interest.

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