ANALYSIS ON PEDESTRIAN SPEEDS AT INTERSECTIONS CONSIDERING SIGNAL TIMING AND CROSSWALK LENGTH

Wael K.M. ALHAJYASEEN
Dr. Eng., Research Fellow
Department of Civil Engineering
Nagoya University
Furo-cho, Chikusa-ku, Nagoya
464-8603, JAPAN
FAX: +81 (52) 789-3837
Email: wael@genv.nagoya-u.ac.jp

Xin ZHANG
Graduate Student
Department of Civil Engineering
Nagoya University
Email: zhang@genv.nagoya-u.ac.jp

Abstract:
Quantifying the effects of signal timing and crosswalk geometry on pedestrian speed is an important requirement for improving existing operational policies and for providing a rational safety assessment at signalized intersections.
The objective of this paper is to macroscopically investigate the effects of signal timing, crosswalk length and pedestrian origin-destination on pedestrian speed at signalized crosswalks. Three signalized crosswalks in Nagoya City are videotaped. A pre-developed data processing program is utilized to extract speed data. Pedestrian signal timing is divided into six intervals. Depending on the entering time, each pedestrian is assigned to one of the intervals. Then the speed distributions in different time interval are estimated and compared.
Generally, it is concluded the entering speeds of pedestrians increase as pedestrian green interval proceeds. Moreover, pedestrians show higher travel speeds at long crosswalks.

Key Words: Pedestrian speed, Crosswalk length, Signal timing, Turning vehicles

1. INTRODUCTION

The operational efficiency of vehicular traffic and pedestrian flow are considered as important concerns especially at signalized crosswalks where both of them have to share the same space. Crosswalks are designated portions on a road, employed to assist pedestrians desiring to cross the street, and play a significant role in the mobility and safety performance of signalized intersections.

Although signalized crosswalks are operated in a way to give pedestrians prioritized right of way, more than one-third of the total traffic accident fatalities are pedestrians (Japan National Police Agency, 2010). There are many reasons behind such kind of collisions for instance visibility, geometric layout of the intersection, driver behavior while turning and pedestrian behavior. Most of the existing studies which try to analyze the mechanism of such collisions, concentrate on driver behavior assuming that it is the most critical factor in determining pedestrian-vehicle collisions. In reality, road users behave by anticipating other users’
behavior in order to avoid any collisions with them. Widely varying road user behavior and trajectories may lead to misunderstanding of other users’ decisions which might result in safety problems. Therefore, it is quite important to consider not only vehicles’ maneuver but also pedestrians’ maneuver and its variation which are affected by the geometric layout of intersections, signal timing and the existence of turning vehicles.

In another dimension, pedestrian crossing time is a very important requirement in the design of signal control at intersections to ensure that pedestrians will receive sufficient time to complete their crossing before releasing the next conflicting vehicular traffic. Most of the existing crossing time estimations assume a constant pedestrian crossing speed without considering the effects of crosswalk geometry, signal timing and the interaction with turning vehicles. Thus it is necessary to investigate how significantly the geometric and operational factors affect pedestrian crossing speed at signalized intersections.

The objective of this paper is to macroscopically analyze the effects of pedestrian signal timing, pedestrian origin-destination, and crosswalk length on pedestrian crossing speed at signalized intersections. The structure of this paper is as follows: after introduction and the literature review, the methodology of analyzing pedestrian speed is explained. This is followed by data collection and processing. Then a comprehensive discussion about the effects of signal timing, crosswalk length and pedestrian origin-destination on pedestrian speed is presented. Finally, the paper ends up with summary of the results and future works.

2. LITERATURE REVIEW

The walking speed and/or walking time of pedestrians are of prime importance in studying the operation and design of pedestrian facilities. Generally, macroscopic pedestrian speed analysis was first started by Navin and Wheeler (1969) and Fruin (1971) followed by many researchers and have been adopted by Highway Capacity Manual (2000). Few studies addressed the issue of pedestrian walking speed at signalized crosswalks. Most of the existing works in this respect attempted to investigate the variations in walking speed at other pedestrian facilities such as walkways and sidewalks. However the operational and surrounding conditions at crosswalks are different from other pedestrian facilities.

Tarawneh (2001) analyzed pedestrian crossing speed at various pedestrian facilities in Jordan. He recommended single constant pedestrian design speed values for various facilities including crosswalks. It is found that pedestrian walking speeds at walkways, sidewalks and crosswalks are significantly different. Furthermore, he concluded that age, gender, group size and street width are very important factors in defining average pedestrian walking speed. However, the effects of signal control parameters, pedestrian origin-destination and crosswalk geometry on pedestrian speeds at signalized crosswalks were not considered.

Montufar, et al. (2007) analyzed the difference in pedestrian speed between sidewalks (defined as normal speed) and signalized crosswalks (defined as crossing speed). They also analyzed the effect of seasonality (winter and summer) in the walking speed of pedestrians, taking into account age and gender. It is concluded that pedestrian walking speeds at crosswalks are significantly different from that at sidewalks at 95% confidence level. In general, pedestrians walk faster when they cross a crosswalk compared to walking along a sidewalk or walkway. Since authors wanted to compare pedestrian speeds between crosswalks and sidewalks, they did not analyze the effects of signal timing and crosswalk geometry on pedestrian speeds at crosswalks.
Pedestrians who walk faster in order to clear theonds

<table>
<thead>
<tr>
<th>Phasing plan at observed intersections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near-side</td>
</tr>
<tr>
<td>Far-side</td>
</tr>
<tr>
<td>Position $(x_1, y_1)$</td>
</tr>
<tr>
<td>Timing $t_1$</td>
</tr>
<tr>
<td>Entering spot speed $v_{in}$</td>
</tr>
<tr>
<td>Exit spot speed $v_{out}$</td>
</tr>
<tr>
<td>Travel speed of the first half of the crosswalk $v_1$</td>
</tr>
<tr>
<td>$v_1 = \sqrt{(x_3-x_1)^2 + (y_3-y_1)^2}$</td>
</tr>
<tr>
<td>$t_1-t_2$</td>
</tr>
<tr>
<td>Travel speed of the second half of the crosswalk $v_2$</td>
</tr>
<tr>
<td>$v_2 = \sqrt{(x_3-x_2)^2 + (y_3-y_2)^2}$</td>
</tr>
<tr>
<td>$t_1-t_2$</td>
</tr>
<tr>
<td>Near-side</td>
</tr>
<tr>
<td>Far-side</td>
</tr>
<tr>
<td>Position $(x_1, y_1)$</td>
</tr>
<tr>
<td>Timing $t_1$</td>
</tr>
<tr>
<td>Entering spot speed $v_{in}$</td>
</tr>
<tr>
<td>Exit spot speed $v_{out}$</td>
</tr>
<tr>
<td>Travel speed of the first half of the crosswalk $v_1$</td>
</tr>
<tr>
<td>$v_1 = \sqrt{(x_3-x_1)^2 + (y_3-y_1)^2}$</td>
</tr>
<tr>
<td>$t_1-t_2$</td>
</tr>
<tr>
<td>Travel speed of the second half of the crosswalk $v_2$</td>
</tr>
<tr>
<td>$v_2 = \sqrt{(x_3-x_2)^2 + (y_3-y_2)^2}$</td>
</tr>
<tr>
<td>$t_1-t_2$</td>
</tr>
</tbody>
</table>

Figure 1 Definition of pedestrian spot speeds and travel speeds

Lam and Cheung (2000) studied pedestrian walking speed at different walking facilities. They found that pedestrian free-flow speed at outdoor walkways is lower than that of signalized crosswalks by 17%. They suggested that the surrounding conditions of signalized crosswalks such as the existence of turning vehicles make pedestrians walk faster in order to clear the crosswalk. However they did not go deeply to analyze the effects of pedestrian signal timing and crosswalk geometry on the crossing speed of pedestrians.

3. METHODOLOGY

In this paper four different speeds are estimated for each observed pedestrian. Figure 1 illustrates the estimated speeds which are defined as follows:

- Entering speed ($v_{in}$): The speed at the entering edge of the crosswalk (m/sec).
- Exit speed ($v_{out}$): The speed at the exit edge of the crosswalk (m/sec).
- First half travel speed ($v_1$): The travel speed in the first half of the crosswalk (m/sec).
- Second half travel speed ($v_2$): The travel speed in the second half of the crosswalk (m/sec).

Figure 1 shows how to estimate travel speeds ($v_1$ and $v_2$). Pedestrian origin-destination is defined as pedestrian movement direction which is divided into two categories; near-side or far-side. Near-side pedestrians are those who start crossing from the side of the vehicular traffic that is exiting the intersection while far-side pedestrians are those who start crossing from the side of the incoming vehicular traffic. One of the reasons behind dividing pedestrians into far-side and near-side is to macroscopically analyze the effect of turning vehicles on pedestrian speed. When comparing $v_1$ and $v_2$, it is important to remember that the first half of the crosswalk for near-side pedestrians is the second half for far-side pedestrians. In the analysis, pedestrians are also classified into two categories; pedestrians who faced a turning vehicle while crossing “with” and who did not face a turning vehicle “without”.

Pedestrian signal timing is divided into six intervals; $R_1$, $G_1$, $G_2$, $G_3$, $PFG$ and $R_2$ as shown in Figure 2. The first pedestrian green interval $G_1$ is assumed as 5 seconds assuming that this
time in average is enough for the waiting pedestrians to discharge at the edge of the crosswalk. The second interval $G_2$ is defined based on the time needed for one pedestrian to cross a half of the crosswalk by assuming a speed of 1 m/sec. $G_2$ is defined as mentioned above since we wanted to segregate the pedestrian who start crossing without the effect of the waiting pedestrian platoon at the beginning of pedestrian green $PG$. The rest of pedestrian green time $PG$ is defined as $G_3$. Pedestrians who start crossing before the beginning of pedestrian green $PG$ are classified as crossing during $R_1$ while those who start crossing after the end of pedestrian flash green $PFG$ are classified as crossing during $R_2$.

It is important to note that $v_1$, $v_2$ and $v_{out}$ for each pedestrian are categorized depending on the timing entered to the crosswalk. For example, if a pedestrian entered the crosswalk in $G_1$, then $v_1$, $v_2$ and $v_{out}$ for that pedestrian will also be classified as crossing during $G_1$.

4. DATA COLLECTION AND PROCESSING

4.1 Data Collection

In order to analyze the significance of various influencing factors on the speed of pedestrians, video data was collected at three signalized crosswalks. Table 1 presents the observation dates, the geometric and signal timing characteristics of the study sites. All these sites are located in Nagoya City, Japan. The observed crosswalks have significantly different geometric and operational characteristics such as crosswalk length and signal timing parameters. All the observed intersections are operated by 4-phase plan where shared through-left turning phase is followed by exclusive right turning phase (left-hand traffic) as shown in Figure 1.

4.2 Data Processing

The maneuver of pedestrians which include their positions and timings, are extracted from video data by using image processing system TrafficAnalyzer (Suzuki and Nakamura, 2006). The position of each pedestrian was extracted every 0.5 second and then the video coordinates are converted to the global coordinates by projective transformation. The point where the feet of the pedestrian are touching the ground is the reference observation point. All video observations were done from high buildings around the intersections, thus for all video tapes, the observation angle is large which enables tracking pedestrians without facing any obstacles.
It is important to note that all observed sites have high through traffic demand, thus most of the right turning vehicles turn in their exclusive phase which explains why most of the pedestrian involved in conflicts are with left turning vehicles. Table 2 presents the observed number of pedestrians who start crossing in various signal intervals and average left turning vehicle demand (L.T.V). Furthermore, numbers of pedestrians who faced “with” and did not face “without” turning vehicles at each site are also shown in Table 2. According to observations, number of pedestrians who start crossing after the end of pedestrian flash green is very small while those who start crossing before pedestrian green starts is higher, especially at Imaike Intersection where pedestrian demand is much higher compared to other sites.

5. **ANALYSIS ON PEDESTRIAN SPEEDS**

There are several factors that might affect the variations in pedestrian speeds. According to the conducted analysis, signal timing, crosswalk length and the existence of turning vehicles are the most significant factors that affect pedestrian speed profile while crossing.
Figure 3 shows the distribution of pedestrians’ entering speeds from the near-side and far-side of the crosswalk. It is clear that average entering speed increases as the time of pedestrian green proceeds. Therefore, the cumulative distributions of entering speeds in $G_2$ are shifted to the right compared to that of $G_3$ and $G_1$ at all observation sites. This tendency is understandable, since pedestrians who see the green indication early before reaching the crosswalk tend to hurry up so they can cross before the signal change. This phenomenon is affected by crosswalk length. It is found that both near-side and far-side average pedestrian entering speeds during $G_2$ at Nishiosu intersection are significantly higher (at 95% confidence level) than other sites. Due to the extremely long crosswalk at Nishiosu intersection, pedestrians hurry up when they approach the crosswalk during pedestrian green interval trying to secure as much time as possible for the long crossing distance. This also explains...
a) $v_1$ for near-side pedestrians, Imaike intersection

b) $v_2$ for near-side pedestrians, Imaike intersection

c) $v_1$ for near-side pedestrians, Nishiosu intersection
d) $v_2$ for near-side pedestrians, Nishiosu intersection

e) $v_1$ for near-side pedestrians, Suemori-Dori2 intersection
f) $v_2$ for near-side pedestrians, Suemori-Dori2 intersection

Figure 4 Histograms and cumulative distributions of travel speeds $v_1$ and $v_2$ of near-side pedestrians

why the differences between the entering speeds in $G_1$, $G_2$ and $G_3$ increase as crosswalk length increases. Simultaneously, it is clear that the average entering speeds of near-side pedestrians are higher than far-side pedestrians especially during $G_3$.

Figure 4 and 5 show the travel speed distributions ($v_1$ and $v_2$) for near-side and far-side pedestrians respectively. For near-side pedestrians, there were no significant differences (95% significance level) between $v_1$ distributions in $G_1$ and $G_2$ as shown in Figures 4a) and c). This also applies to $v_2$ distributions. However at Suemori-Dori2 intersection, $v_1$ and $v_2$ distributions
Figure 5 Histograms and cumulative distributions of travel speeds $v_1$ and $v_2$ of far-side pedestrians for near-side pedestrians in $G_1$ and $G_2$ are significantly different as shown in Figures 4e) and 4f). The inconsistent results at Suemori-Dori2 intersection might be due to the insufficient sample size. The travel speed distributions in $G_3$ are significantly different from those in $G_1$ and $G_2$ at all intersections. This can be explained that pedestrians predict how long time is available before the termination of pedestrian green interval, which makes them speed up.

Generally, it is concluded that the travel speeds of the pedestrians waiting at the beginning of green interval ($G_1$) from near-side and far-side are quite similar. The significant change occurs in the second half of pedestrian green interval ($G_3$). This phenomenon is very
important to be considered since most of the severe conflicts between pedestrians and turning vehicles occur during the second half of pedestrian green in which number of crossing pedestrians becomes smaller. Moreover, by comparing the travel speeds ($v_1$ and $v_2$) at Nishiosu Intersection with those at Imaike and Suemori-Dori2 intersections, it is clear that travel speeds at Nishiosu intersection is significantly higher (95% significance level) as shown in Figure 4c), 4d), 5c) and 5d), which can be referred to the extremely long crosswalk.

Figure 6 presents the distribution of the entering, exit and travel speeds during pedestrian flash green interval $PFG$. Since the observed number of pedestrian during $PFG$ at each site is very small, pedestrians at all sites are aggregated in Figure 6. The distributions of entering speeds for far-side and near-side pedestrians in PFG are similar as shown in Figure 6a). This somehow contradicts with the results shown in Figure 3 where near-side pedestrians have significantly higher entering speeds in $G_3$ compared to far-side pedestrians at all sites.

By comparing Figures 3 and 6a the average entering speed during $PFG$ is significantly higher than that for $G_1$, $G_2$ and $G_3$. It is interesting to see that the exit speed $v_{out}$ distribution during $PFG$ of far-side pedestrians is significantly higher compared to that of near-side pedestrians as shown in Figure 6b). This can be referred to the effect of turning vehicles since far-side pedestrians exit from the side where they have conflict with turning traffic. This explains why far-side pedestrians hurry up when they reach the second half of the crosswalk which is
Simply to clear the conflict area as fast as possible. Meanwhile, near side pedestrians exit from the side where they don’t have conflict with turning traffic, thus they feel safer which make them slow down. This is the same reason why $v_2$ of far side pedestrians is significantly higher (95% significance level) than that of near-side pedestrians as shown in Figure 6d. Such behavior is very critical since drivers might not be able to predict such change in pedestrian speeds which might lead to misjudgments and wrong decisions.

In order to analyze the effect of turning vehicles in pedestrian speeds, Figure 7 is presented. However, due to the high demand of L.T.V. at Nishiosu and Suemori-Dori2 intersections (Table 2), there was insufficient number of pedestrians who did not face turning vehicles for the comparison analysis. Thus, Figure 7 only includes the observed pedestrians during pedestrian green interval $PG$ at Imaike intersection. The travel speed distributions ($v_1$ and $v_2$) for far-side pedestrians who faced (with) and did not face (without) turning vehicles are significantly different at 95% confidence level while no significant difference can be found for near-side pedestrians. Basically, the effect of turning vehicles on pedestrian speed is totally dependent on the circumstances when they meet, such as vehicle speed, vehicle type, pedestrian signal timing, etc. Therefore, it is difficult to reasonably assess the effects of turning vehicles in macroscopic analysis level.
6. CONCLUSIONS

In this paper, pedestrian entering, exit and travel speeds at signalized crosswalks are analyzed and compared considering the effects of pedestrian signal timing, crosswalk length and pedestrian origin-destination.

It is concluded that pedestrian behavior is significantly affected by pedestrian signal timing, crosswalk length and pedestrian origin-destination. The entering speeds of pedestrians increase as pedestrian green interval proceeds. The entering speed during pedestrian flash green interval is significantly higher (95% confidence level) than that during green interval. Furthermore, near-side pedestrians tend to have higher entering speeds during the second half of pedestrian green interval compared to far-side pedestrians. This can be referred to the conflicts with turning vehicles, since near-side pedestrians start crossing from the side of the exiting vehicular traffic. Moreover, it is concluded that long crosswalks has higher entering pedestrian speeds.

Generally, it is found that travel speeds ($v_1$ and $v_2$) during $G_3$ are significantly different from those during $G_1$ and $G_2$. Furthermore, travel speeds during pedestrian flash green interval $PFG$ are significantly higher than those during pedestrian green $PG$. Simultaneously, it is concluded that longer crosswalks have significantly higher travel speeds.

It is concluded that pedestrians hurry up when they cross the part of the crosswalk where the turning vehicular traffic uses to exit the intersection. This can be explained that pedestrians are threatened by the probability of facing a turning vehicle which encourages them to speed up. Such behavior might be critical in analyzing the interaction between pedestrians and turning vehicular traffic for the safety assessment of signalized intersections. Therefore, it is very vital to develop a rational methodology which can quantify the changes in pedestrian speeds as a function of signal timing, crosswalk geometry and the interaction with turning vehicles.

In this paper, the effects of age, gender and trip purpose are not considered. This might leave some bias in the analysis and conclusions which should be rationally investigated.

ACKNOWLEDGEMENTS

The authors express their gratitude to Mr. Tien Dung CHU for his help in video observation. Furthermore, authors are very grateful to Takata foundation and Japan Society for the Promotion of Science for supporting this research.

REFERENCES


