Modeling Pedestrian Presence Probability on Signalized Crosswalks for the Safety Assessment Considering Crosswalk Length and Signal Timing

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Abstract: Quantifying effects of crosswalk length and signal timing on pedestrians’ presence position and timing is an important requirement for evaluating the probability of conflict. It can be utilized to provide a rational safety assessment and improve existing operational policies at signalized intersections. This study investigates the effects of crosswalk length and pedestrian green time on the spatiotemporal probability of pedestrian presence. It was found that the longer pedestrian green time and crosswalk length leads to the wider distribution of pedestrian presence probability. In addition, a surrogate safety measure for assessing pedestrian safety is proposed by utilizing the pedestrian presence probability model.

Keywords: Pedestrians, Crosswalk Length, Pedestrian Signal Timing, Surrogate Safety Measure

1. INTRODUCTION

Crosswalks are designated portions on a roadway to assist pedestrians desiring to cross it. They play an important role in the safety and mobility performance at signalized intersections. Although crosswalks are operated to give priority to pedestrians over vehicles, according to the report of National Police Agency in Japan (2013), more than one-third of the total traffic accident fatalities in Japan are pedestrians at signalized and unsignalized crosswalks. One reason is that pedestrians and turning vehicles usually share the same signal phase in Japan. Therefore, pedestrian-vehicle conflict is considered as one of the most common safety problems at signalized crosswalks.

Surrogate safety measure (SSM) is typically utilized to measure the severity and frequency of traffic conflict events as an alternative for safety assessment. Chen et al. (2014) found that high turning speed, in conjunction with higher frequency of short Post Encroachment Time (PET) result in higher crash rates. With regard to turning vehicle maneuver (Alhajyaseen et al., 2012), pedestrian maneuver is assumed to be another critical factor that may cause safety problems. In reality, road users behave by anticipating the behavior of other road users to avoid collisions. The variations of pedestrian positions may lead to widely distributed conflict points with left-turning vehicles (left-hand traffic system) and have an impact on gap acceptance behavior of vehicles. Therefore, it is quite important to consider not only vehicle’s maneuver but also pedestrian’s maneuver and its variation which are affected by the geometric layout of intersections, signal timing and surrounding conditions.

Essentially, presence position and speed profile compose the basic pedestrian behavior. Zhang et al. (2013) analyzed and modeled pedestrian walking speeds on first and second halves of crosswalk at signalized intersections and found that the walking speeds increases as
PG proceeds. In existing methods, most of the studies on pedestrian safety analysis focused on pedestrian speed and pedestrian position has not been sufficiently investigated. Since timings and positions where pedestrians are present have significant impacts on the probability and risk of conflict, spatiotemporal pedestrian distributions should be investigated.

This paper aims to analyze the impacts of crosswalk length and signal timing on pedestrian presence probability at signalized crosswalks. Based on the results, a model is developed to represent pedestrian presence probability on crosswalks. Applications of the model for the safety assessment at signalized crosswalks are discussed at the end of this paper.

2. METHODOLOGY

2.1 Definitions of position analysis

During pedestrian signal phase, pedestrian position is affected by various factors such as signal timing, crosswalk geometry, and presence of other crossing pedestrians and/or turning vehicles. For simplification, the following assumptions are made to analyze the pedestrian present position by time on the signalized crosswalk. Note that Japan has a left-hand traffic system. All of the following analysis and discussions are for the left-hand traffic.

Pedestrian crossing direction at the crosswalk is an important factor for pedestrian position. Here it is defined as pedestrian approaching side based on two categories; near-side and far-side of crosswalk. Near-side means the side where pedestrians and exiting turning vehicles have conflict and far-side is the opposite side as shown in Figure 1. Since the pedestrian position is strongly dependent on approaching side, it is better to analyze them separately. In this study, only near-side pedestrians are analyzed as an example.

A coordinate transformation of pedestrian position is done referring to the edge of crosswalk. The horizontal axis ($x$) is parallel to the edge of bicycle crossing path, then the vertical axis ($y$) is perpendicular to that as shown in Figure 1. Since the distance on horizontal axis ($x$) is more important for analyzing the conflict point between pedestrians and turning vehicles, in this paper for simplification, only the distance on $x$ axis will be considered and all the pedestrians are assumed to walk on this axis. In order to consider the position where pedestrians wait on the sidewalk for pedestrian green phase, a space between the beginning of crosswalk and 5m upstream from that is defined as waiting zone as indicated in Figure 1.
Thus, the origin of the horizontal axis is defined at the location 5m upstream from the beginning of near-side of the crosswalk.

The signal timing is an important factor for analyzing user behavior when pedestrians present on the crosswalk. In this paper, elapsed time of pedestrian green phase (PG) is considered and denoted by $t$ (sec).

Crossing pedestrians can be categorized into two categories depending on the timing when they start crossing; waiting pedestrian and arriving pedestrian. Waiting pedestrian means the pedestrian who arrived at the crosswalk before the pedestrian signal turns to PG. It is assumed that the first 5sec of PG is enough in average for the waiting pedestrians to discharge from the beginning of the crosswalk with a walking speed of 1m/sec. Thus, waiting pedestrian is defined as the pedestrians who enter the crosswalk before $t = 5$sec. Arriving pedestrian is the pedestrians arrive the crosswalk after PG starts, in brief, enter the crosswalk after $t = 5$sec. In order to spatiotemporally analyze the presence probability of pedestrian on the crosswalk, pedestrian presence probability which depends on pedestrian demand is defined as shown in Figure 2.

As Figure 2 indicated, left-turning and right-turning vehicles may also affect pedestrian around the crosswalk. However in Japan, pedestrians have absolute priority on the crosswalk during pedestrian green time. Also in reality, most of drivers are complying this rule and giving way to pedestrians. Thus, in this paper, the effect of turning vehicles for pedestrian presence probability distributions is considered as negligible.

2.2 Pedestrian presence probability distribution models during pedestrian phase

Pedestrian presence probability of position $x$ at time $t$ is estimated as shown in Figure 2. As defined already, the elapsed time $t$ (sec) is counted from the beginning of PG. Weibull distribution enables to approximate various types of distributions by adjusting the shape and scale parameters. Observed pedestrian presence probability are modeled by using the probability density function (PDF) of Weibull distribution shown by Equation (1). Here, the shape parameter $\alpha$ and scale parameter $\beta$ are functions of elapsed time $t$, crosswalk geometry and signal control. Since the shape of distributions are changed under different parameters, its density and cumulative distributions are shown in Figure 3.
\[ f(x; \alpha, \beta) = \frac{\alpha}{\beta} \left( \frac{x}{\beta} \right)^{\alpha-1} e^{-\left( \frac{x}{\beta} \right)^\alpha} \]  

(1)

Where,

- \( f \): probability density function (PDF) of Weibull distribution,
- \( \alpha \): shape parameter (\( \alpha > 0 \)), and
- \( \beta \): scale parameter (\( \beta > 0 \)).

3. DATA COLLECTION

3.1 Study sites

Four crosswalks at three signalized intersections located in Nagoya City, Japan, are selected as study sites. Table 1 summarizes the crosswalk geometry and signal settings at each site. All the study sites are four-leg intersection. They are operated by four-phase signal control with the protected right-turn phases. The crosswalk length \( L \) ranges from 16m to 36m. In this study, bicycle crossing path (2m wide as illustrated in Figure 1) is regarded as part of crosswalk width \( W \), since pedestrians are frequently observed to use this path for crossing. The cycle lengths and the pedestrian green time (PG) lengths at all sites are adjusted cycle by cycle, while pedestrian flashing green time (PFG) lengths are fixed. Pedestrian and vehicle volumes shown in the table are average hourly volumes during the observation period. Examples of detailed phase sequences and lengths are indicated in Table 2.

Table 3 shows the observation periods and the number of data samples. Only the waiting pedestrians of near-side are analyzed for this paper. All of these intersections are located in urban district and most of road users are ordinary adults. The elderly and pupils are rarely observed.

The positions of pedestrians at every 1sec are manually extracted from observation videos by using the image processing system TrafficAnalyzer (Suzuki and Nakamura, 2006). Then, the coordinates in these images are converted to global coordinates through the projective transformation. Kalman smoothing method is applied to estimate trajectories and speeds of pedestrians at each time interval.
Table 1. Geometric characteristics and traffic conditions of observed sites

<table>
<thead>
<tr>
<th>Intersection name</th>
<th>Subject crosswalk</th>
<th>Crosswalk geometry (m)</th>
<th>Phase length (sec)</th>
<th>Cycle length (sec)</th>
<th>Pedestrian volume (ped/h)</th>
<th>Left-turn (LT) vehicle volume (veh/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Length $L$</td>
<td>Width $W$</td>
<td>PG</td>
<td>PFG</td>
<td></td>
</tr>
<tr>
<td>Kanayama East</td>
<td>16.2</td>
<td>5.8</td>
<td>48-61</td>
<td>6</td>
<td>148-174</td>
<td>180</td>
</tr>
<tr>
<td>Kanayama North</td>
<td>36.2</td>
<td>5.8</td>
<td>36-48</td>
<td>9</td>
<td>144-176</td>
<td>335</td>
</tr>
<tr>
<td>Ueda South</td>
<td>20.8</td>
<td>5.2</td>
<td>38-47</td>
<td>8</td>
<td>144-176</td>
<td>90</td>
</tr>
<tr>
<td>Fushimi South</td>
<td>35.4</td>
<td>6.0</td>
<td>39-42</td>
<td>10</td>
<td>159-161</td>
<td>326</td>
</tr>
</tbody>
</table>

Table 2. Signal phase sequences and timings of the four-phase signal control at the study sites

<table>
<thead>
<tr>
<th>Intersection name</th>
<th>Mode</th>
<th>Signal phasing length (sec)</th>
<th>Cycle length (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\phi_1$</td>
<td>$\phi_2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Kanayama E-W</td>
<td>Vehicle</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Pedestrian (location S and N)</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Right-turning vehicle</td>
<td>Shared</td>
<td>[ ]</td>
</tr>
<tr>
<td>Kanayama S-N</td>
<td>Vehicle</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Pedestrian (location E and W)</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Right-turning vehicle</td>
<td>Shared</td>
<td>[ ]</td>
</tr>
<tr>
<td>Ueda S-N</td>
<td>39</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Fushimi S-N</td>
<td>54</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3. Observation periods and the number of samples

<table>
<thead>
<tr>
<th>Intersection name</th>
<th>Subject crosswalk</th>
<th>Observation period</th>
<th>Number of subject pedestrians</th>
<th>Total</th>
<th>Near-side</th>
<th>Waiting pedestrians of Near-side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanayama East</td>
<td>9:00-13:00, 10/19/2012</td>
<td>595</td>
<td>345</td>
<td>132</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kanayama North</td>
<td>9:30-13:00, 10/19/2012</td>
<td>1,228</td>
<td>650</td>
<td>439</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ueda South</td>
<td>7:00-10:00, 14:00-16:30, 11/29-30/2012</td>
<td>367</td>
<td>179</td>
<td>102</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fushimi South</td>
<td>10:00-11:00, 14:00-15:00, 11/5/2012</td>
<td>590</td>
<td>271</td>
<td>146</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. ANALYSIS ON PEDESTRIAN POSITIONS

Figures 4 and 5 show the density distributions of pedestrian presence probability for near-side waiting pedestrian at North and East crosswalks of Kanayama intersection. During the observation periods, the pedestrian volumes were commonly not high in each cycle. The average waiting pedestrian volumes were 5ped/cycle and 2ped/cycle on North and East crosswalks, respectively. Since the pedestrian volumes in one cycle are not enough for distribution analyses, distributions are produced based on the data from all cycles during the observation periods, 80 and 57 cycles on North and East crosswalks, respectively. In the figures, the distribution profiles are shown during the elapsed time of PG ($t$) from 0 to 25sec.
for North crosswalk ($L=36.2\text{m}$) and from 0 to 15sec for East crosswalk ($L=16.2\text{m}$).

When the elapsed time of PG ($t$) increases, the pedestrian presence probability distributions shift to the moving direction, i.e. right side and their variations get wider. This is because of the variation in pedestrians’ walking speeds. Comparing the two crosswalks of Figures 4 and 5 at the same $t$, the pedestrian presence probability distributions of the shorter crosswalk (Figure 5) are more concentrated. It indicates that the shorter crosswalk is, the smaller a chance of variations in pedestrian behavior becomes. When $t=0$, most of pedestrians at East crosswalk are still in the waiting zone. This suggests that the number of samples was not enough for the analysis regarding the waiting zone. It is necessary to add trajectory data in the waiting zone as a future work.

5. MODEL ESTIMATION

5.1 Model estimation results

Based on the results of the empirical analysis, it was found that the shapes and characteristics of pedestrian presence probability distributions are left-right asymmetric, as presented in Figure 4 and 5. In this regard, Weibull distribution indicated by Equation (1) is employed to
model the pedestrian presence probability distributions. In order to verify the tendency of shape and scale parameters, the models of pedestrian presence probability distributions which have the constant parameters only are estimated for each crosswalk with different lengths $L$ and each $t$. The results shown in Figure 6 suggest that both of the shape parameter $\alpha$ and scale parameter $\beta$ are increasing functions of $t$. In addition, longer crosswalks show higher values of shape parameter $\alpha$. With regard to the scale parameters, the differences of four crosswalks are not large.

For generalization, both of the shape and scale parameters are here assumed to follow linear function of several independent variables. Considering the tendency of the result above, three influencing factors; elapsed time of PG ($t$), PG length and crosswalk length $L$ are considered. Accordingly, general models of the shape parameter $\alpha$ and scale parameter $\beta$ are estimated by linear functions of these factors shown by Equation (2).

$$\alpha = f(y_{1,1}, y_{1,2}, \ldots, y_{1,n}) = \alpha_{1,1}y_{1,1} + \alpha_{1,2}y_{1,2} + \ldots + \alpha_{1,n}y_{1,n} + \alpha_{1,n+1}$$

$$\beta = f(y_{2,1}, y_{2,2}, \ldots, y_{2,n}) = \alpha_{2,1}y_{2,1} + \alpha_{2,2}y_{2,2} + \ldots + \alpha_{2,n}y_{2,n} + \alpha_{2,n+1}$$  \hspace{1cm} (2)

Where,

- $y_{i,1}, \ldots, y_{i,n}$ : independent variables of influencing factors, and
- $\alpha_{1,1}, \ldots, \alpha_{1,n}$ and $\alpha_{2,1}, \ldots, \alpha_{2,n}$ : model coefficients estimated through the maximum likelihood method.

Table 3 shows the estimated coefficients for estimating $\alpha$ and $\beta$ of the pedestrian presence probability model. Elapsed time of PG has a positive impact to both the shape and scale parameters, suggesting that pedestrians widely distributed on the crosswalk and far from the origin when $t$ increases. PG length is a significant variable of shape parameter and the longer PG length results in the greater variation of the distribution. It indicates that when PG length is long, pedestrians have enough time for crossing and can walk in their desired walking speeds. Crosswalk length has a negative impact to the shape parameter, suggesting that there are wider distributions along the longer crosswalk.

Note that such other factors as pedestrian demand and number of waiting pedestrians, were also examined and found insignificant, thus they were excluded from the models.
Table 3. Pedestrian presence probability model

<table>
<thead>
<tr>
<th>Variables</th>
<th>Coefficients</th>
<th>t-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape parameter $\alpha$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elapsed time of PG $t$ (sec)</td>
<td>0.179</td>
<td>72.1</td>
</tr>
<tr>
<td>PG length (sec)</td>
<td>-0.0623</td>
<td>-8.12</td>
</tr>
<tr>
<td>Crosswalk length $L$ (m)</td>
<td>-0.102</td>
<td>-17.6</td>
</tr>
<tr>
<td>Constant</td>
<td>8.15</td>
<td>16.1</td>
</tr>
<tr>
<td>Scale parameter $\beta$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elapsed time of PG $t$ (sec)</td>
<td>1.29</td>
<td>367</td>
</tr>
<tr>
<td>Constant</td>
<td>4.21</td>
<td>80.1</td>
</tr>
</tbody>
</table>

Number of samples | 819
Log likelihood    | -66,120
Initial log likelihood | -187,967
$\chi^2$ value    | 243,694
Adjusted $R^2$     | 0.648

5.2 Model validation

According to the developed model of Table 3, it is still difficult to analyze the relationship between specific variables and presence probability distributions under different combinations of shape and scale parameters. In order to validate the model characteristics, a Monte-Carlo simulation is carried out for North and East crosswalks of Kanayama intersection. Fixed input values of crosswalk length $L$ and PG length are based on the observed data. Note that PG lengths of observed sites are adjusted cycle by cycle, therefore the norm PG lengths are input in simulation, 44sec for North crosswalk and 57sec for East crosswalk.

Figures 7 and 8 show the comparison of observed and estimated cumulative pedestrian presence probability distributions on the subject crosswalks. It is similar between these two curves for each $t$, the elapsed time of PG. However, the differences become smaller when $t$ increases. This can be considered because of the spatiotemporal change in pedestrian walking speeds which is not considered in the estimation model. Since Zhang et al. (2013) found pedestrians have different walking speeds influenced by crosswalk length, the position of crosswalk, and pedestrian signal timing, the change in pedestrian walking speed should also be considered in the model in the future work. The curves for $t=0$ of East crosswalk are not shown in Figure 8, due to the insufficient number of observed samples as mentioned in Section 4.

![Figure 7. Validation of Monte-Carlo simulation results versus observed data](image-url)  
(Near-side of North crosswalk, Kanayama intersection; PG=44sec)
The “two-sample Kolmogorov-Smirnov statistic test” (K-S test) was carried out for verifying the goodness of fit between the simulated and observed values, and their results confirmed good fitness at each elapsed time of PG of the two crosswalks with different crosswalk lengths.

6. DISCUSSION ON POTENTIAL APPLICATIONS

As one of the dominant example applications, the developed model can be utilized for estimating surrogate safety measures (SSMs) for the conflict assessment of pedestrian versus turning vehicle. Suzuki et al. (2004) proposed an index for evaluating the conflict risk between pedestrians and vehicles at signalized intersections. This index is calculated as a product of probability and severity of the conflict. Nakamura and Mabuchi (2006) improved this index through considering traffic volumes for assessing the conflict risk between entry and circulating vehicles at roundabouts. By referring to them, risk at a position \((x, y)\) of pedestrians versus turning vehicles in a cycle \(R_{con}(x, y)\) can be proposed as a SSM in this study. The cycle can be defined as a complete sequence of pedestrian signal indications and in this research it is counted from the onset of PG to the next one. The \(R_{con}(x, y)\) can be calculated by aggregating risk at a position \((x, y)\) at each moment \(r_{con}(t, x, y)\) which is composed by three factors; probability of conflict \(p_{con}\), severity of conflict \(i_{con}\) and arrival rates of pedestrians and turning vehicles \((\lambda_{ped}, \lambda_{LT} \text{ and } \lambda_{RT})\) as shown in Equation (3).

\[
R_{con}(x, y) = \int_{0}^{t_{cycle}} r_{con}(t, x, y) dt = g(p_{con}(t, x, y), i_{con}(t, x, y), \lambda_{ped}, \lambda_{LT}, \lambda_{RT})
\]

(3)

Where,  
- \(R_{con}(x, y)\) : risk at a position \((x, y)\) between pedestrian and turning vehicle in a cycle,  
- \(r_{con}(t, x, y)\) : risk at a position \((x, y)\) between pedestrian and turning vehicle at time \(t\),  
- \(t_{cycle}\) : cycle length,  
- \(p_{con}(t, x, y)\) : probability of conflict between pedestrian and turning vehicle at \((t, x, y)\),  
- \(i_{con}(t, x, y)\) : severity of conflict between pedestrian and turning vehicle at \((t, x, y)\),  
- \(\lambda_{ped}\) : arrival rate of pedestrians,  
- \(\lambda_{LT}\) : arrival rate of left-turning vehicles, and  
- \(\lambda_{RT}\) : arrival rate of right-turning vehicles.
Risk at a position \((x, y)\) between pedestrian and turning vehicle in a cycle \(R_{con}(x, y) = \int_0^t r_{con}(t, x, y) \, dt\)

Risk at a position \((x, y)\) between pedestrian and turning vehicle at time \(t\) \(r_{con}(t, x, y)\)

Arrival rate

Probability of conflict \(p_{con}(t, x, y)\)

Severity of conflict \(i_{con}(t, x, y)\)

Pedestrian presence probability \(p_{ped}(t, x, y)\)

Turning-vehicle presence probability \(p_{veh}(t, x, y)\)

Probability on \(x\) axis of crosswalk \(p_x(t)\)

Probability on \(y\) axis of crosswalk \(p_y(t)\)

Left-turning vehicle \(p_{LT}(t, x, y)\)

Right-turning vehicle \(p_{RT}(t, x, y)\)

Influencing factors:
- Speed of turning vehicle

Near-side pedestrian \(p_{nw}(t)\)

Far-side pedestrian \(p_{fx}(t)\)

Waiting pedestrian \(p_{nw}(t)\)

Arriving pedestrian \(p_{unx}(t)\)

Waiting pedestrian \(p_{wfx}(t)\)

Arriving pedestrian \(p_{afx}(t)\)

Influencing factors:
- Crosswalk length \(L\)
- Pediatric green time \(PG\)
- Elapsed time of \(PG\) \(t\)

Figure 9. Framework of Surrogate Safety Measure calculation

The framework of the \(R_{con}(x, y)\) calculation is shown as Figure 9. At each time \(t\), the probability of conflict \(p_{con}(t, x, y)\) is determined by the pedestrian presence probability \(p_{ped}(t)\) and the turning-vehicle presence probability \(p_{veh}(t, x, y)\).

In order to estimate \(p_{ped}(t, x, y)\), direction of crosswalk \((x\) and \(y\) axes), pedestrian approaching side (near-side and far-side) and state of pedestrians (waiting and arriving) should be considered and presence probability models are necessary for each of them. In this paper, the pedestrian presence probability on \(x\) axis of crosswalk for near-side waiting pedestrians \(p_{nw}(t)\) was analyzed and modeled. For the proposed probability \(p_{nw}(t)\), the impacts of pedestrian volume and interactions from opposing (far-side) pedestrian need to be explored through further research.

Other presence probabilities are potentially to be considered as follows. Firstly, with regard to pedestrian presence probability on \(y\) axis \(p_y(t)\) of crosswalk, Zeng et al. (2013) developed a model considering crosswalk geometry, pedestrian walking direction and road users’ density for each cross-section of the beginning, middle and end of crosswalk. Secondly, for the far-side pedestrian, the presence probability \(p_{fx}(t)\) is expected to be modeled by the same methodology of near-side pedestrian in this paper. Then, presence probability of arriving pedestrians can be estimated considering the impacts of pedestrian arrival rate and upstream intersections.

As previously mentioned, the presence probabilities of left-turning and right-turning vehicles \((p_{LT}(t, x, y)\) and \(p_{RT}(t, x, y)\)) approaching the crosswalk should also be analyzed as a future work.

On the other hand, the severity of conflict \(i_{con}(t, x, y)\) is also an essential element for the risk calculation. Chen et al. (2014) found that high turning speed, in conjunction with a higher frequency of short Post Encroachment Time (PET) result in higher crash rates. Rosén and
Sander (2009) found that pedestrian fatality risk is strongly dependent on impact speed and showed the importance of keeping the impact speeds as low as possible in city areas where most pedestrian accidents occur. Considering these findings, the speed of turning vehicles can be used for estimating $i_{con}(t, x, y)$.

The hazard map is one of the useful expression method by using surrogate safety measure on safety evaluation. This can spatiotemporally show the level of conflict risk for any specific event, location and time, then makes it visible. Furthermore, it is produced not only for individual event, location and time but also can aggregate them at each mesh by a period of time for some events. Based on the framework above, the risk is calculated by presence probabilities that mean the probability density functions of pedestrians and vehicles, and this risk can be mainly used for general safety evaluation. Thus, a hazard map of the aggregated risk $R_{con}(x, y)$ on the crosswalk during a cycle is expected as illustrated in Figure 10 as an example. The estimated risk levels can be visibly defined by different colors. The total risks at specific location meshes are shown in the hazard map, then the hazardous area and its level can be clearly indicated. Moreover, the differences under various signal plan and crosswalk geometry may also be discussed.

In brief, this methodology has a potential to utilize for assessing alternative measures of operational policies, pedestrian timing strategies and crosswalk geometry. Evaluations can be done by comparing the existing situation with some alternative policies, such as two-stage crossing, leading pedestrian interval (LPI) and/or protected pedestrian phase. Especially, LPI (Saneinejad and Lo, 2015) which is to provide pedestrians with the opportunity to begin crossing the street before the green time of the conflicting turning vehicles, can be utilized to reduce the joint probability between pedestrian and vehicle.

7. CONCLUSIONS

In this paper, pedestrian presence probabilities of near-side waiting pedestrian on signalized crosswalk during PG were analyzed and modeled. It was concluded that pedestrian presence probability is significantly affected by crosswalk length, PG length and elapsed time of PG.

In the empirical analysis, it was found that the distributions of pedestrian presence probabilities move on to the downstream of crosswalk following the moving direction, and variations become greater during $t$ elapses as PG proceeds. Longer crosswalk and longer PG
length correspond to greater variations of the presence probabilities. In order to quantify the effects of various influencing factors of presence probability at crosswalks, Weibull distribution was selected for modeling it. Elapsed time of PG is the most significant influencing factor, whereas crosswalk length and PG length affects the variations of presence probability. Through comparing the observed and estimated data at different elapsed time of PG, it was found that the most of distributions are similar among them. However, the differences become greater when elapsed time of PG increases. This is considered due to the fact that change in pedestrian walking speed is not considered in the model, and it should be solved in the future work. In addition, only the near-side waiting pedestrians were analyzed in the analysis. As the next step, presence probability of arriving pedestrian will be estimated by assuming a uniform arrival pattern. With regard to far-side pedestrians, the same methodology can be used as the near-side pedestrian, however interactions and conflicts between the two opposing pedestrian flows should also be investigated for considering its impact. Moreover, the effect of turning vehicles was not analyzed in this paper and it should be done in the future work.

A surrogate safety measure of pedestrian safety was proposed by applying the presence probability model. Pedestrian presence probability can be utilized to apply the risk of conflict between pedestrian and vehicle. Then, a hazard map of conflict risk can be produced with severity of conflict and arrival rates of pedestrian and left/right turning vehicle. This method can be used for comparison of pedestrian safety under alternative geometry layouts and signal plans, and then improvement of pedestrian safety on the signalized crosswalk.

ACKNOWLEDGEMENT

The contents of this paper are a part of research supported by National Institute for Land and Infrastructure Management (NILIM).

REFERENCES


