Modeling Pedestrian Trajectory for Safety Assessment at Signalized Crosswalks

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Abstract: Pedestrian-vehicle conflict has been recognized as a common safety issue at signalized intersections. In addition to vehicle maneuver, pedestrian maneuver is assumed to be another critical factor that may result in safety problems. This study, as part of intensive efforts to develop a microscopic simulation model for safety assessment, aims to build a model to reproduce pedestrian trajectories at signalized crosswalk. Empirical analysis shows that pedestrian trajectories are influenced by intersection geometry, origin-destination, previous passing position, and densities of other road users. To represent the stochastic characteristics of pedestrian trajectory, pedestrian passing positions at near-side, middle and far-side cross-sections are modeled by Weibull distribution. Then, the models are incorporated into simulation and the validation is conducted in terms of cross-section passing positions and pedestrian-vehicle conflict points. The validation results demonstrate that the developed models can reasonably reflect pedestrian trajectories, which offer a good basis for pedestrian safety assessment at signalized crosswalks.

Keywords: Pedestrian Behavior, Trajectory Modeling, Microscopic Traffic Simulation, Safety Assessment, Signalized Crosswalk

1. INTRODUCTION

One of the common conflicts at signalized intersections is the interaction between left-turing vehicles and pedestrians in the left-hand traffic system. According to 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. Many reasons exist behind such statistics, such as intersection geometry, traffic signal control, and stochastic user behavior. Accordingly, to identify the safety problem prior to accident occurrence is of top importance for traffic safety management. However, a reliable tool which can conduct proactive safety assessment before facility implementation has yet to be developed. This study is part of intensive efforts to develop a microscopic simulation model for proactive safety assessment at signalized intersection. In order to develop such a simulation model, pedestrian and vehicle maneuvers must be reasonably reflected.

In addition to vehicle maneuver (Asano et al., 2011), pedestrian maneuver is assumed to be another critical factor that may result in safety problems. In reality, road users behave by anticipating the behavior of other road users to avoid collisions. The variations of pedestrian trajectories may lead to widely distributed conflict points with left-turning vehicles (left-hand traffic system) and confuse the decisions of drivers. Essentially, trajectory and speed profile compose the basic pedestrian behavior. However, most of the studies upon pedestrian safety analysis had focused on pedestrian speed with minimal attention paid on pedestrian trajectory (Waizman et al., 2013). At signalized crosswalk, pedestrian trajectories are under the interaction between pedestrian flow, conflicting vehicles and surrounding environment (Archer, 2005). They are closely related to the positions of conflict point and surrogate safety measures (SSMs). For the purpose of safety assessment, a reasonable pedestrian trajectory model is required to be incorporated into simulation program.

Therefore, the objective of this paper is to develop a model to reproduce the pedestrian trajectories at signalized crosswalk. Toward this end, a model considering intersection geometry, pedestrian origin-destination (OD) movements, previous passing position, and the densities of other road users is built to represent the distributions of pedestrian passing position at near-side, middle and far-side cross-sections of crosswalk. In addition, after incorporating the model into simulation, validation is conducted to confirm the model performance in terms of cross-section passing positions and pedestrian-vehicle conflict points. Finally, conclusions are drawn and recommendations are provided for future work.

2. LITERATURE REVIEW

Papadimitriou et al. (2009) conducted an exhaustive review of the existing research on pedestrian behavior in urban area focusing on route choice and crossing behavior. They found that in order to model pedestrian movement, it is necessary to incorporate the interactions between pedestrians and their environment (roadway, traffic and crowd).

A general framework for pedestrian behavior is proposed by Daamen (2004). Individuals make different decisions by following a hierarchical scheme: strategical, tactical and operational. Based on this scheme, Antonini et al. (2006) proposed a discrete choice framework for pedestrian dynamics, which regards short-term behavior of individuals as a response to the presence of other pedestrians. They used a dynamic and individual-based spatial discretization representing the physical space. Within the similar framework, Robin et al. (2009) improved the discrete choice model and calibrated it by tracking pedestrian trajectories in different datasets. They found that pedestrians have a strong preference of keeping their current direction as they move toward their goal destination.

Teknomo (2002) developed a microscopic pedestrian simulation model based on a multi-agent tool of basic kinematics and physical forces. He found that pedestrians prefer to follow other pedestrians rather than make their own paths. This microscopic behavior happens because the pedestrians tend to reduce their interaction effects, especially with pedestrians from different directions. Another micro-simulation tool for bi-directional flows in cellular automation by Blue and Adler (2001) reflects the similar phenomena. Weifeng et al. (2003) considered the following evolution for simulation: pedestrians keep a freely-moving state when density is low but several pedestrian paths are formed when density increases. Although these studies focused on the mechanism of path generation, they did not shed light on the characteristics of pedestrian trajectory and how to appropriately model the trajectory at signalized crosswalk.

When pedestrians realize a collision with another pedestrian, they generally decide a course of action. The most common choices are to change their trajectory or to change their speed (Usher and Strawderman, 2010). Pedestrians have a tendency to choose paths to their destination that minimize the need for angular displacements (Turner and Penn, 2002). Bierlaire et al. (2003) have demonstrated that pedestrians prefer a smooth non-linear path as opposed to a linear acute path. The changes in trajectory are more gradual and smooth. As for crossing behavior on roadway related to pedestrian safety, recent studies primarily based the decision making of pedestrians on gap acceptance theory (Ishaque and Noland, 2007; Yang et al., 2006) or utility theory (Sun et al., 2003; Lassarre et al., 2007). However, the pedestrian trajectory and the position of conflict point in this situation have not been analyzed intensively.

Ellis et al. (2009) proposed a non-parametric model for pedestrian motion based on Gaussian Process regression. Trajectory data were modelled by regressing relative motion against current position. They found that the trajectories of pedestrians are inherently stochastic, with varying degrees of uncertainty depending on the factors such as physical scene structure, the presence of other people and the time of day. The use of Gaussian Processe is able to be explicit about such uncertainties and to adapt to the various complexities of different scenes and situations online. Brogan and Johnson (2003) developed a pedestrian behavior model of path planning based on the laboratory observations of five experimental conditions. Each path was found to trace a smooth, circular path with a non-zero minimum turning radius constraint. However, people do not always follow the straight route to a goal. Their trajectories are stochastic and get influenced by the goal and their environment.

Although several studies analyzed and/or modeled the behavior of pedestrians, the variation of pedestrian trajectories at signalized crosswalk has not been well understood, especially under the influence of intersection geometric characteristics and pedestrian OD movements. To fill the gap, this study proposes an empirical model to address this issue.

3. DATA OBSERVATION AND ANALYSIS

3.1 Study Sites

In order to analyze the significance of various influencing factors on pedestrian maneuver, raw pedestrian trajectories were collected at seven signalized crosswalks with ranging traffic demands and geometric characteristics by video observation. Tables 1 and 2 present the geometric characteristics and sample size of pedestrians at the observed sites. All sites are located in Nagoya City, Japan. A pre-developed video image processing system was utilized to extract pedestrian positions every 0.5s (Suzuki and Nakamura, 2006). The large amount of trajectory data enable a thorough analysis of pedestrian maneuvers.

Table 1. Geometric characteristics of study sites

Objective crosswalk	Kanayama		Fushimi	Otsu	Ueda		Yamada
	North	East	South	West	East	South	East
Observation Time	8:20-8:40 9:30-13:00		10:00-11:00 14:00-15:00	10:00-11:00 14:00-15:00	7:30-10:00 14:30-6:30 (2 days)		7:00-10:00 14:30-7:30 (2 days)
The number of crashes^{*1}	1	0	1	2	1	0	1
Crosswalk width^{*2}[m]	5.8	5.8	6	6.3	6.3	5.2	5.7
Crosswalk length[m]	36.2	16.2	35.4	34.1	28.7	20.8	15.2
Crosswalk setback[m]	12.3	5.4	13.3	13.6	10.7	20.4	8.5
Intersection angle[deg]	81	95	90	90	66	118	120

*1: Crash records of pedestrians vs. left-turning vehicles from 2007 to 2010 are given by Nagoya National Highway Office

*2: Crosswalk width includes bicycle crossing path width

Table 2. Traffic volumes at study sites

Intersection name		Kanayama		Fushimi	Otsu	Ueda		Yamada
Objective crosswalk		North	East	South	West	East	South	East
Left-turn volume[veh/h]		124	148	122	94	46	176	50
Sample size of pedestrian OD movements*	N1→F1	5	24	29	65	9	7	7
	N1→F2	85	320	50	65	35	49	140
	N2→F1	35	20	54	74	65	44	23
	N2→F2	615	46	176	70	68	89	134
	F1→N1	6	48	9	54	6	21	12
	F1→N2	27	14	56	52	48	70	22
	F2→N1	129	187	71	85	43	33	56
	F2→N2	450	56	198	94	50	79	69
	Total	1352	715	643	559	324	392	463

*The definition of pedestrian OD movements is explained in section 3.2

3.2 Analysis Method and Definition

Generally, pedestrian trajectory can be described as a combination of the shortest-path criteria, perception of the environment and partly the occasional elements, such as pursuing behavior, halting to avoid collision and overtaking. Recording and analyzing the positions of each individual at each moment might be an ideal method to get comprehensive understanding of pedestrian trajectories. However, it is difficult to estimate the stochastic characteristics of pedestrian trajectory at each moment. Furthermore, related studies demonstrated that pedestrians prefer to keep their current directions toward their destination. Therefore, this study assumes that the changes in pedestrian trajectory are gradual and pedestrians change their walking directions only after passing near-side, middle, and far-side cross-sections 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.

There are several factors that might affect the variation of pedestrian trajectory. It is assumed that pedestrian positions are influenced by four types of factors; i.e. geometric characteristics, pedestrian OD movements, previous passing position, and densities of other road users. The detailed definitions are given as follows.

(1) Geometric characteristics of crosswalk

It includes crosswalk width, crosswalk length and setback distance of crosswalk, which are shown in Figure 1(a).

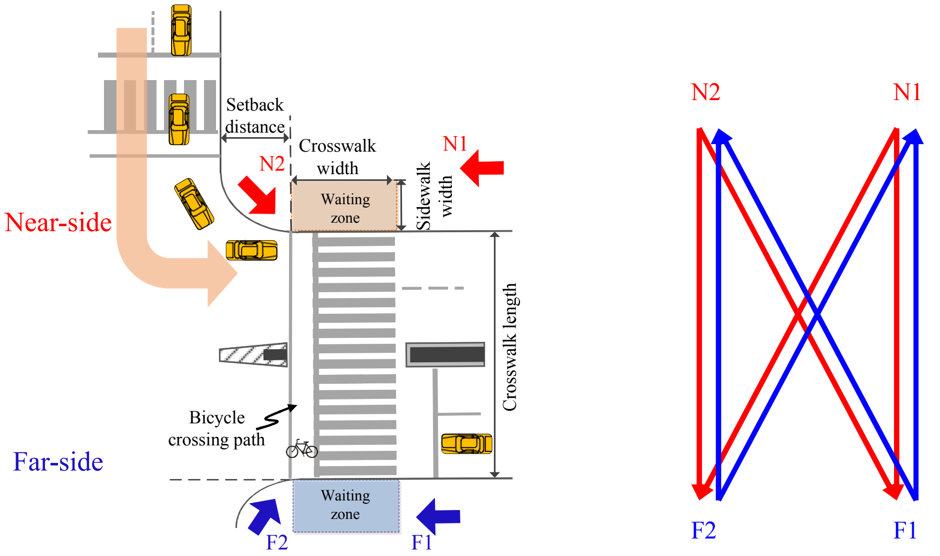
(2) Pedestrian OD movements

It is assumed that pedestrian movements have their origins and destinations at either the near-side or the far-side of the crosswalk. Altogether eight OD pairs exist, as shown in Figure 1(b). In this study, three dummy variables are defined to identify the OD pairs:

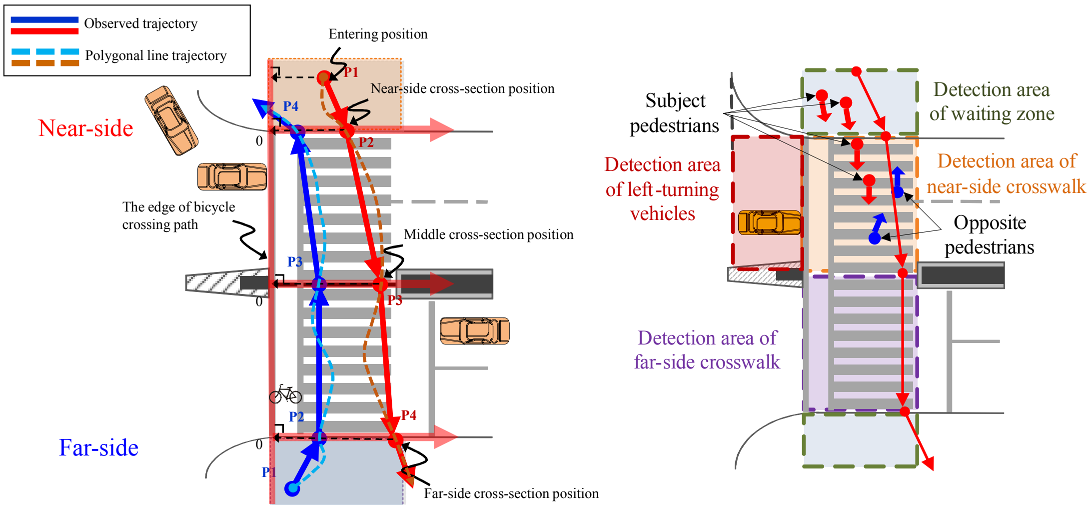
-*Near-side/Far-side dummy*: If origin is at the near-side (N1 or N2), dummy=1; 0 otherwise.

-*Perpendicular/Diagona dummy*: If OD direction is perpendicular (N1→F1, F1→N1, N2→F2, F2→N2), dummy=1; 0 otherwise.

-*Bicycle crossing path side dummy*: If origin is near the side of bicycle crossing path (N2 and F2), dummy=1; 0 otherwise.



(a) Definition of crosswalk geometry (b) Definition of pedestrian OD movements



(c) Definition of cross-section passing positions (d) Definition of density detection areas

Figure 1. Definition of the four influencing factors on pedestrian trajectory

(3) Previous passing position

Figure 1(c) illustrates the passing positions along pedestrian trajectory, which include entering position, near-side cross-section position, middle cross-section position and far-side cross-section position. They are all measured as the perpendicular distances from the edge of bicycle crossing path. Note that the definition of entering position differs according to the pedestrian signal phase indicated. During pedestrian green (PG) or flashing green (PFG) phase, the entering position is defined as the first passing position when the pedestrian enters into the waiting zone. Whereas during pedestrian red (PR) phase, the entering position is defined as the initial stopping position at the waiting zone. If the pedestrian stops outside the waiting zone during PR, the definition of entering position is the same as that during PG.

It is assumed that the individual pedestrian determines his/her next cross-section position when passing the current cross-section. Take a pedestrian from near-side to far-side as shown in Figure 1(c) for example. Immediately after the pedestrian arrives at the near-side cross-section P2, he/she decides the next passing position, i.e. middle cross-section position P3, toward which he/she plans to go.

(4) Densities of other road users

Densities of left-turning vehicles and pedestrians are also significant factors influencing pedestrian trajectory. It is assumed that when the pedestrian arrives at a cross-section, his/her next cross-section position is influenced by the densities of left-turning vehicles and other pedestrians in corresponding detection areas at the moment. The detection areas are defined as shown in Figure 1(d). The density of left-turning vehicles or pedestrians is defined as the number of vehicles or pedestrians divided by the area size of detection area.

Similar to how the previous passing position influence on the current one, it is assumed that the density of left-turning vehicles and the density of pedestrians he/she faces at the current moment influence the determination of pedestrians on their next cross-section position. Take a pedestrian from near-side to far-side for example as shown in Figure 1(d). When he/she arrives at the near-side cross-section, he/she decides the passing position at middle cross-section according to the surrounding traffic densities, e.i. the density of left-turning vehicles, the density of subject and opposite pedestrians at near-side crosswalk.

3.3 Empirical Analysis of Pedestrian Trajectory

(1) Observed trajectories versus assumed polygonal line trajectories

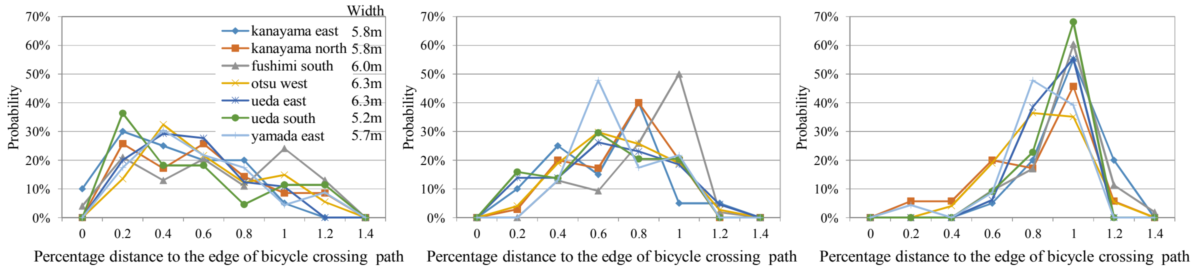
Figure 1(c) gives an illustration of the observed trajectory (dashed line) versus the assumed polygonal line trajectory. Seven crosswalks with different geometric characteristics and traffic demands are utilized to compare the difference between the real path length and the path length assumed by polygonal line. And t-test is applied to confirm their difference. According to the result of two sample t-test for difference of the means (unequal variances), the statistics presented in Table 3 shows that the difference between two path lengths is not significant. It demonstrates that pedestrians tend to pass the crosswalk by keeping their directions toward their destinations at near-side, middle and far-side cross-sections. Thus, the performed trajectories are approximated to polygonal lines. Longer walking distance is caused by the evasion behavior or interaction with vehicles or other pedestrians.

Table 3. Comparison between observed walking path length and polygonal line path length

Intersection name	Kanayama East	Kanayama North	Ueda East	Ueda South	Yamada East	Fushimi South	Otsu West
Average difference(m)	0.15	0.18	0.26	0.19	0.23	0.19	0.25
Standard Deviation(m)	0.26	0.14	0.21	0.22	0.21	0.26	0.24
Maximum Difference(m)	5.56	1.12	1.10	2.05	1.51	1.85	2.02
T-test value	1.57	1.85	0.92	1.71	0.85	1.29	1.48
Sample Size	715	1352	324	392	463	643	559

(2) Observed raw distributions of pedestrian passing positions at three cross-sections

Figure 2 shows the raw distributions of pedestrian positions at three cross-sections from N2 to F1 at seven observed crosswalks. It shows that the distributions of passing positions at three cross-sections are closely related to pedestrian OD movements. In this case of near-side passing position, pedestrians with the origin N2 tend to enter the crosswalk close to the side of bicycle crossing path. The peaks of the histograms at middle cross-section shift to the right side, indicating pedestrians are appealed by the destination direction. Finally, the peaks of the histograms at far-side cross-section further approach the right side when finishing the crossing at F1. The shapes of these distributions are of different characteristics. Therefore, it is necessary to develop a model which can flexibly represent the distribution of pedestrian passing positions.

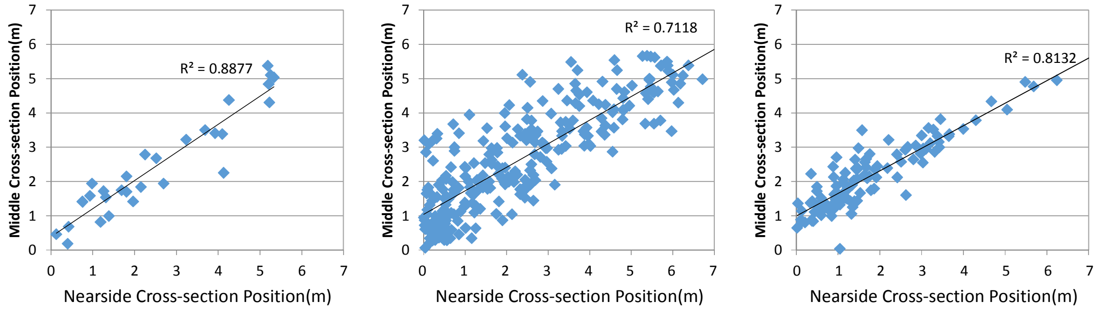


(a)Near-side cross-section (b)Middle cross-section (c)Far-side cross-section

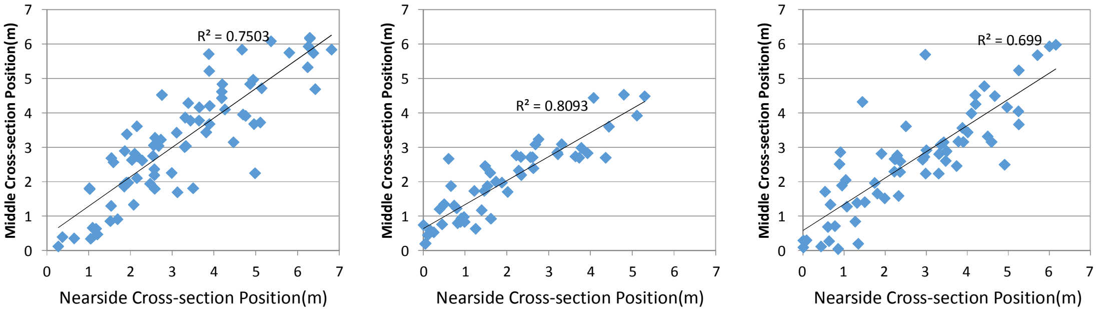
Figure 2. Pedestrian passing position distributions at each cross-section

(3) Current passing position versus previous passing position

Here, a simple linear relationship between current and previous position is assumed and Pearson correlation coeffiention is applied for testing their correlationship (the following ananlysis of crosswalk width and bi-directional pedestrian density on average passing position are also based on similar assumption). Figure 3 shows the pedestrian passing positions at near-side and middle cross-section in the case of N2→F2. According to R^2, the middle cross-section position significantly increases as the near-side cross-section position becomes further from the reference origin. It indicates that the pedestrian current passing positions are significantly related to their previous ones.



(a) Kanayama East (n=30) (b) Kanayama North (n=271) (c) Yamada East (n=76)

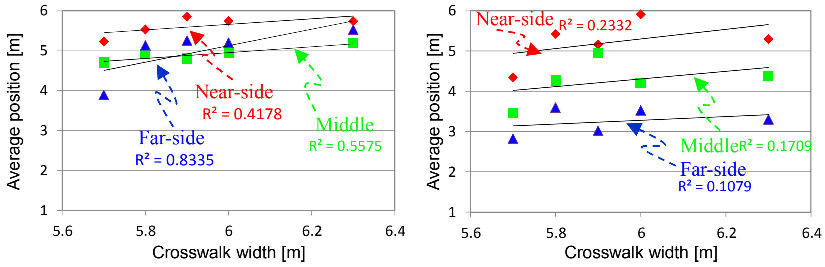


(d) Fushimi South (n=110) (e) Ueda South (n=51) (f) Ueda East (n=63)

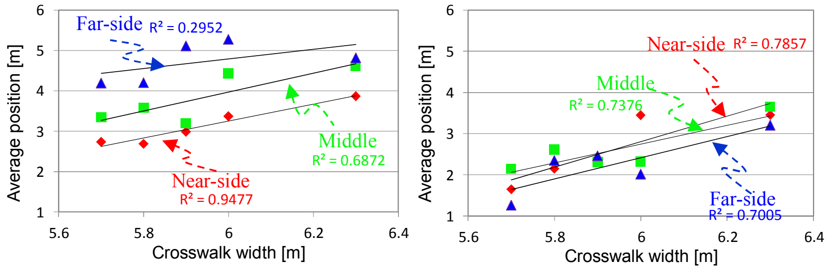
Figure 3. Middle cross-section position versus near-side cross-section position (OD: N2→F2)

(4) Crosswalk width versus average passing position at each cross-section

Figure 4 shows the relationship between average pedestrian passing positions and crosswalk widths at three cross-sections by referring to the four OD pairs. In most of the cases, R^2 is larger than 0.5, indicating a significant relationship between pedestrian passing position and crosswalk width. In addition, the positive signs of R^2 values show that the average passing positions at three cross-sections increase as crosswalk width becomes larger.



(a) Perpendicular direction: N1→F1 (b) Diagonal direction: N1→F2

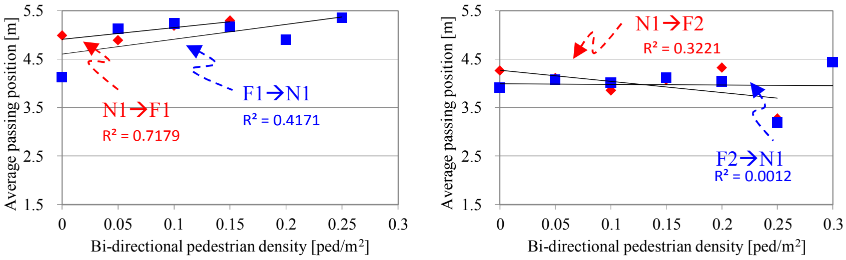


(c) Diagonal direction: N2→F1 (d) Perpendicular direction: N2→F2

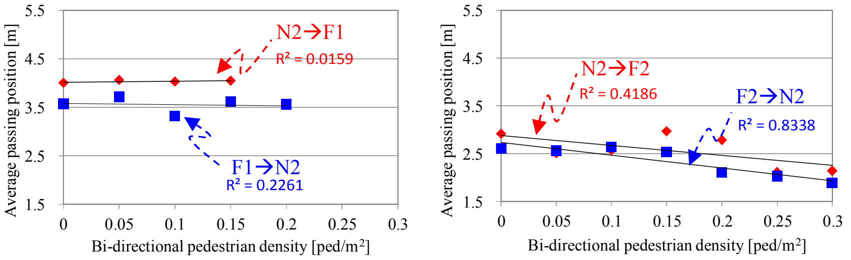
Figure 4. Crosswalk width versus passing position at each cross-section

(5) Bi-directional pedestrian density versus average passing position

Figure 5 shows the relationship between average pedestrian passing position and bi-directional flow pedestrian density at middle cross-section. According to R^2 values, the average pedestrian passing positions at middle cross-section are found to be significantly influenced by bi-directional pedestrian density as illustrated in Figures 5(a) and 5(d). The average passing position at middle cross-section increases as the bi-directional flow pedestrian density becomes larger as shown in Figure 5(a), whereas it decreases as in Figure 5(d). It indicates that pedestrians have to keep their directions under the influence of denser bi-directional pedestrian flow. However, the correlation is not significant as shown in Figures 5(b) and 5(c). It suggests that the impact of bi-directional pedestrian density on diagonal pedestrian OD pairs is less significant than perpendicular ones.



(a) Perpendicular direction: N1→F1 & F1→N1 (b) Diagonal direction: N1→F2 & F2→N1



(c) Diagonal direction :N2→F1 & F1→N2 (d) Perpendicular direction :N2 →F2 & F2 →N2

Figure 5. Bi-directional pedestrian density versus passing position at middle cross-section

4. PEDESTRIAN TRAJECTORY MODELING

According to the analyses above, a consecutive random distribution model is required to reflect the distributions of pedestrian passing position in simulation. Previous study (Walck, 2007) have verified that Weibull distribution is able to approximate various distributions by adjusting the shape and scale parameter shown in Figure 6. Therefore in this study, Weibull distribution is employed to establish the pedestrian trajectory model. The density probability function of Weibull distribution is shown in Equation (1).

$$f\left(x;\alpha,\beta\right)=\frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1}e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \tag{1}$$

where

f : probability function (PDF) of Weibull distribution;
α : shape parameter which controls the shape of the distribution, and
β : scale parameter which controls the mean value and standard deviation of the distribution.

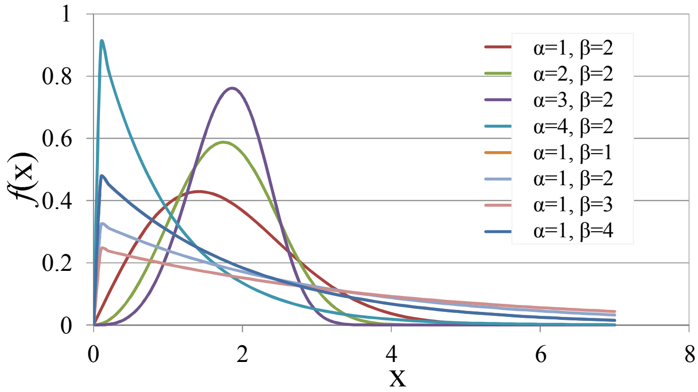


Figure 6 Probability density functions of Weibull distribution

The pedestrian trajectory model is based on the following assumptions. (1) Pedestrians change their directions only when they pass the near-side, middle and far-side cross-section. In addition, pedestrians keep their direction when they are walking between near-side and middle cross-section or between middle and far-side cross-section. (2) The next passing positions are influenced by crosswalk geometry, pedestrian OD movements, previous passing position and the densities of other road users. (3) The distribution of pedestrian cross-section passing positions can be represented by Weibull distribution.

Based on the assumptions above, four types of influencing factors listed above are considered. Accordingly, the shape and scale parameters are modeled as the functions of these factors, as shown in Equation (2). The coefficients are estimated by the maximum likelihood method.

$$\begin{aligned}\alpha &= f(y_{1,1}, y_{1,2}, \ldots, y_{1,n}) = \lambda_{1,1}y_{1,1} + \lambda_{1,2}y_{1,2} + \ldots + \lambda_{1,n}y_{1,n} + \lambda_{1,n+1}\\ \beta &= f(y_{2,1}, y_{2,2}, \ldots, y_{2,n}) = \lambda_{2,1}y_{2,1} + \lambda_{2,2}y_{2,2} + \ldots + \lambda_{2,n}y_{2,n} + \lambda_{2,n+1}\end{aligned} \tag{2}$$

where

$y_{1,1},\ldots,y_{1,n}$ and $y_{2,1},\ldots,y_{2,n}$: independent variables of influencing factors, and
$\lambda_{1,1},\ldots,\lambda_{1,n}$ and $\lambda_{2,1},\ldots,\lambda_{2,n}$: model coefficients.

A commonly used method for parameter selection of regression model is to modify the parameters and components of the model until the significance of t-test for each parameter is achieved at a setting confidence level. The parameter estimates at three cross-sections and the goodness of fit results are presented in Table 4. Note that several parameters were excluded from model estimation because they were found not significant in the model at a 95% confidence level. For example, the density of left-turning vehicle is not considered for far-side cross-section because left-turing vehicles do not have significant impact on pedestrian trajectory when the pedestrian is walking at the area of far-side crosswalk as shown in Figure 1(d).

Table 4. Parameter estimation results of pedestrian trajectory model

Weibull	Variables		Parameters (t-value)		
			Near	Middle	Far
Shape (α)	Geometry	Crosswalk width(m)	0.210(3.03)	-0.540(-6.61)	0.450(5.38)
		Setback distance(m)	-0.0200(-4.02)	-	0.0200(2.71)
	OD	Near-side/Far-side(dummy)	-0.220(-6.15)	-	0.150(3.47)
		Perpendicular/Diagonal(dummy)	-1.03(-16.8)	-0.390(-5.87)	-0.660(-11.9)
		Bicycle crossing path side(dummy)	-1.06(-13.8)	0.440(4.71)	-0.220(-3.59)
	Previous passing position(m)		0.100(8.75)	0.830(45.1)	0.200(13.8)
	Road user Density	Density of left-turning vehicle(veh/m^2)	-6.36 (-6.16)	0.110 (2.16)	-
		Density of opposite pedestrian(ped/m^2)	-	2.16 (2.10)	-
	Constant		2.11(4.31)	3.51(7.10)	-1.19(-2.20)
Scale (β)	Geometry	Crosswalk length(m)	-0.0400(-9.05)	-	-
		Crosswalk width(m)	-	1.13(5.45)	1.00(4.88)
		Density of opposite pedestrian(ped/m^2)	-	-	6.93(5.56)
		Density of bi-directional pedestrian(ped/m^2)	-0.660 (-5.57)	-0.950 (-2.31)	-1.69 (-2.40)
	Constant		2.31(9.44)	1.86(7.95)	-1.94(2.20)
Number of samples			4448		
Log likelihood			-9034	-7195	-8302
Initial log likelihood			-9727	-8435	-8666
χ^2 value			1098	2765	538
Adjusted R^2			0.0694	0.145	0.0398

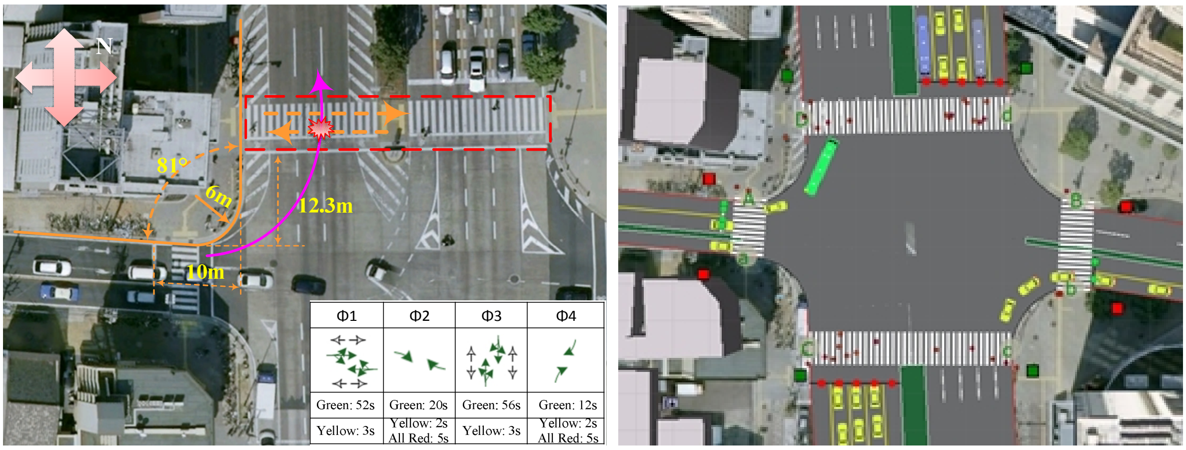
5. MODEL VALIDATION

The developed models of Table 4 are then incorporated into a simulation platform (Dang et al., 2012) for traffic safety assessment. For the purpose of pedestrian trajectory validation, other road user behavior models such as vehicle trajectory model (Alhajyaseen et al., 2012), car-following model (Treiber et al., 2000), left-turning vehicle gap acceptance model (Alhajyaseen et al., 2012), vehicle speed profile model (Wolfermann et al., 2011) and pedestrian speed model (Zhang et al., 2011; Asano et al., 2013) are also incorporated into the simulation. Traffic parameters such as pedestrian/vehicle speed and discharge headway were calibrated by using the observed vehicle and pedestrian data.

The validation is conducted to confirm whether the developed model can well represent pedestrian trajectories at signalized crosswalks. The common method for simulation validation is to test the “fit” between field observations of pedestrian passing position and the estimation results by simulation. Considering that the simulation to be developed is intended to be used for safety assessment, the validation is also focused on inspecting the aspect of safety performance, e.g., comparing the positions of conflict point. In the following section, simulation validation is conducted at a representative signalized crosswalk by referring to the distribution of pedestrian positions at three cross-sections and the distribution of conflict points.

5.1 Simulation Scenario Description

The North crosswalk of Kanayama intersection with longer crosswalk length and larger traffic volumes is chosen for validation. The characteristics of the site are shown in Tables 1 and 2. The corner radius is mild whereas the setback distance of the crosswalk is large. Besides, traffic volumes of left-turning movement were high during the survey periods. The concerned conflict is between left-turning vehicles from the west approach and pedestrians at the north crosswalk as shown in Figure 7. For validation purpose, the pedestrian trajectory data from N2 to F2 at this crosswalk were utilized. Note that the data were not adopted for the parameter estimation shown in Table 4.



(a) Aerial photo (Source: Google Earth)   (b) Simulation scenario

Figure 7. Kanayama intersection in reality and in the simulation program

5.2 Pedestrian trajectory validation

Figure 8 shows the distribution of observed and simulated pedestrian trajectories from N2 to F2 at Kanayama North crosswalk. No significant difference is found of passing positions at the three representative cross-sections according to two sample t-test for difference of their means (unequal variances) at a 95% confidence level. However, the distributions of simulated trajectories agree with the observed ones better at the middle and far-side cross-sections than that at near-side cross-section. The deviations at near-side cross-sections are due to no consideration of pedestrian waiting behavior in the modeling. In reality, pedestrian may walk randomly around the waiting zone during PR. For example, the near-side (N2) incoming pedestrians may walk a certain distance from the edge of bicycle crossing path or walk around in waiting zone during PR and then enter the crosswalk during PG. However, such behavior has not been fully considered in the simulation.

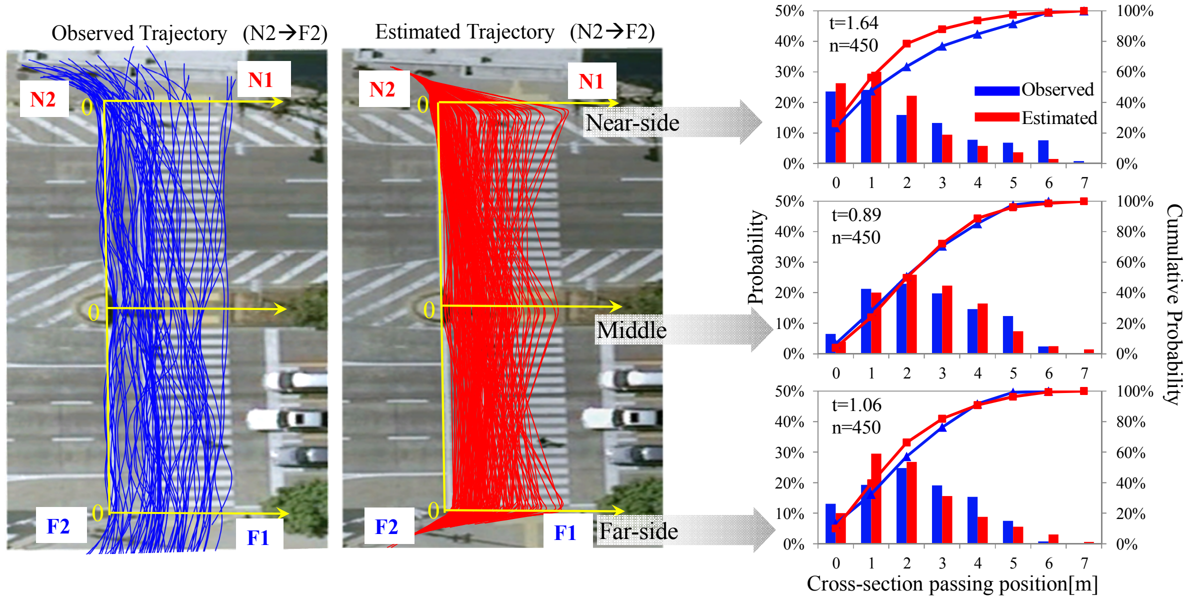
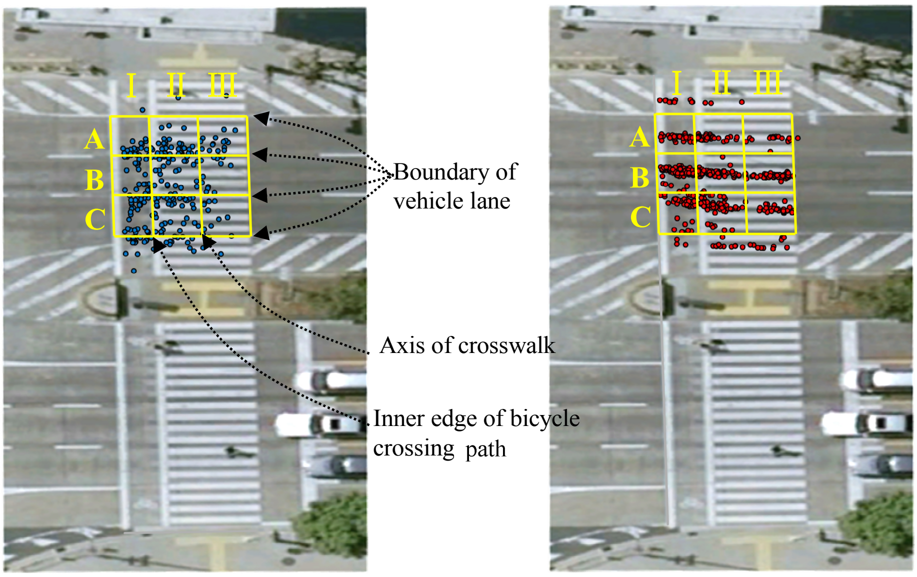


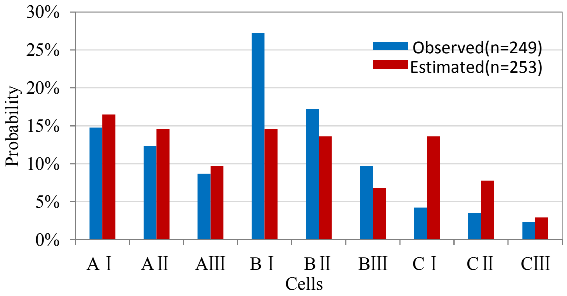
Figure 8. Comparison of observed and estimated pedestrian trajectories

5.3 Validation of conflict point

The pedestrian-vehicle conflict points are selected for validation when the absolute post-encroachment time (PET) is less than 6.4s according to the average walking time between near-side and middle cross-sections. In order to validate the distribution of conflict points, the crosswalk to be analyzed is divided into nine cells as illustrated in Figure 9. Surrounded horizontally by near-side edge of the crosswalk, boundary lines of each lane and middle cross-section, and vertically by edges of crosswalk and the axis of the crosswalk, fifteen conflict areas are generally related. Considering the fact that fewer left-turning vehicles cut the zebra marking when exiting, nine conflict cells in light of A, B, C horizontally and I, II and III vertically are further classified for analysis. It is found that in general the simulation model can well represent the distribution of conflict points. Note that the areas BI and CI show a slight difference. It indicates that pedestrian maneuver on the real bicycle crossing path needs further attention, especially when interactions with bicycles. In this study, the bicycle crossing path is regarded as part of crosswalk for pedestrian to use whereas in reality pedestrian behavior may be influenced by bicycles when walking on bicycle crossing path. On the other hand, the observed conflict points are widely distributed in each cell as shown in Figure 9(a) whereas the estimated conflict points tend to be concentrated in the middle of the lane as shown in Figure 9(b). It is primarily related to the vehicle trajectory model with simplified assumption that most of left-turning vehicles run along the middle line of lane when exiting intersection (Asano et al., 2011). Thus, the influence of bicycles on pedestrian trajectory in addition to the improvements of vehicle trajectory model are supposed to be incorporated into future updates of the simulation.



(a) Observed conflict points (b) Estimated conflict points



(c) Observed conflict points vs. estimated conflict points

Figure 9. Comparison between observed conflict point and estimated conflict point

6. SENSITIVITY ANALYSIS

Sensitivity analysis helps understand how the developed models behave with the change of each variable. Here, sensitivities of previous passing position, crosswalk width, the density of bi-directional pedestrians and the density of left-turning vehicles are examined. When the objective variable changes, other variables are set to default values as shown in Table 5.

Table 5. Default settings for sensitivity analysis

Variable	Value	Note
Near-side/Far-side dummy	1	
Perpendicular/Diagonal dummy	1	
Bicycle crossing path side dummy	1	
Crosswalk length	35 [m]	
Crosswalk width	6.0 [m]	Walking direction: N2→F2
Previous passing position	3.0 [m]	
Setback distance	5.0 [m]	
Density of left-turning vehicle	0 [veh/m^2]	
Density of opposite pedestrian	0.2 [ped/m^2]	
Density of bi-directional pedestrian	0.3 [ped/m^2]	

(1) Sensitivity of previous passing position on current passing position

For previous passing position, four scenarios at middle cross-section are applied in sensitivity analysis, i.e. near-side passing position are set to be 2m, 3m, 4m, and 5m, respectively. Figure 10 shows the estimation results. As the positions at near-side cross-section becomes farther to the edge of bicycle crossing path, the positions at middle cross-section become more concentrated. It indicates that pedestrians adjust their directions when passing middle cross-section to make up the bias from destination. In addition, if the pedestrians pass the positions at near-side cross-section close to the edge of bicycle crossing path, they simply have more choices of passing position at middle cross-section, which pose less impact on the destination.

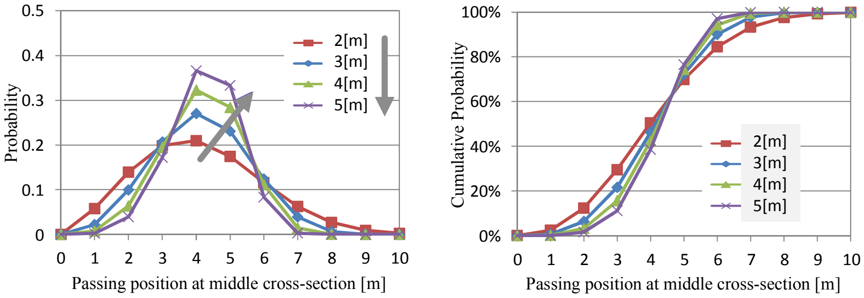


Figure 10. The sensitivity of previous passing position on current passing position

(2) Sensitivity of crosswalk width on current passing position

Crosswalk widths are set to be 5.5m, 5.7m, 5.9m and 6m, and positions at middle cross-section are selected for analysis shown in Figure 11. It implies that pedestrians tend to walk farther from the edge of bicycle crossing path as the crosswalk width becomes larger. Apparently, pedestrians have more choices to decide their positions at middle cross-section at a wider crosswalk.

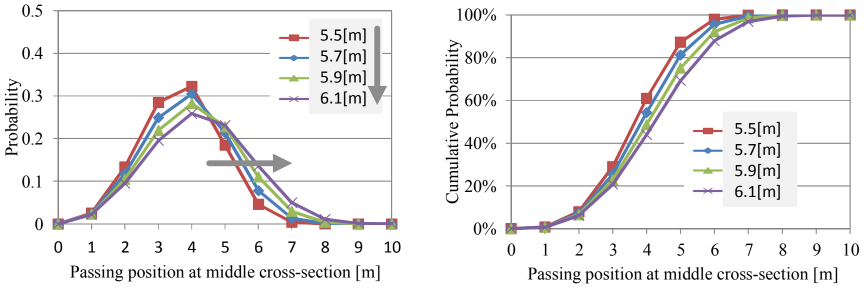


Figure 11. The sensitivity of crosswalk width on current passing position

(3) Sensitivity of bi-directional pedestrian density on current passing position

The densities of bi-directional pedestrian are set to be 0 ped/m^2, 0.15 ped/m^2, 0.30 ped/m^2 and 0.45 ped/m^2 for analysis. Figure 12 shows the estimation results at middle cross-section. It indicates that pedestrians tend to walk closer to the edge of bicycle crossing path as the density of bi-directional pedestrian becomes larger. In such a case, pedestrians have limited choices of their positions under the interaction of denser pedestrian flow.

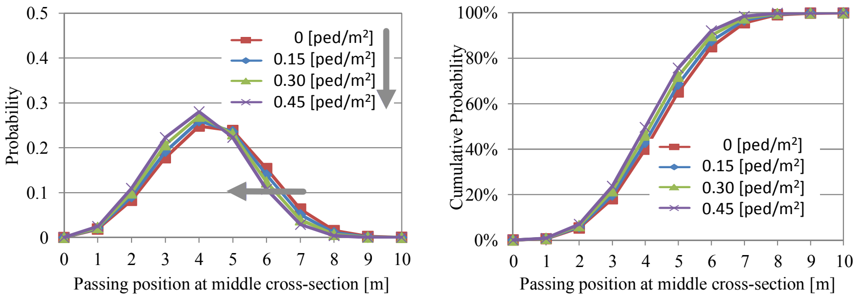


Figure 12. The sensitivity of bi-directional pedestrian density on current passing position

(4) Sensitivity of left-turning vehicle density on current passing position

Passing positions at near-side cross-section are applied for analysis because they are most probably influenced by left-turning vehicles when entering the crosswalk. Densities of left-turning vehicles are set to be 0veh/m^2, 0.02veh/m^2, 0.04veh /m^2 and 0.06veh/m^2, respectively. Figure 13 shows the estimation results. As the density of left-turning vehicles increases, the distribution of positions at near-side cross-section becomes more dispersive. It indicates that near-side pedestrians tend to keep a certain distance from conflicting turning vehicles when they entering the crosswalk at near-side cross-section.

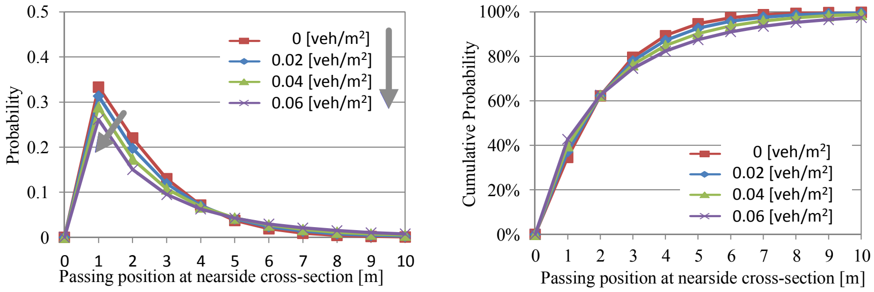


Figure 13 The sensitivity of left-turning vehicle density on current passing position

7. CONCLUSIONS AND DISCUSSIONS

The pedestrian trajectories at signalized crosswalks were analyzed and modeled as a function of intersection geometry, pedestrian OD movements, previous passing position, and the densities of other road users. Comparison with the empirical data showed that the developed model can reasonably reflect the effects of various influencing factors not only on pedestrian passing positions but also on their conflict points with left-turning vehicles. The quantitative representation of pedestrian trajectory enables to estimate the changes in pedestrian maneuver as a result of the improvements of intersection layout or the surrounding environment. Furthermore, the proposed model offers a good basis for intersection safety assessment considering stochastic pedestrian behavior.

However, the developed model still has several limitations. The influences of signal phase, bicycle behavior, and the time of day (peak/off-peak) are not considered. For example, as shown in Figure 8, one of the reasons for the estimation deviation is due to no consideration on pedestrian waiting behavior in the modeling during red phase. Moreover, in this study, the bicycle crossing path is regarded as part of crosswalk for pedestrian to use. However in reality, pedestrian behavior can be influenced by bicycles at crosswalk. Therefore, pedestrian green phase and red phase should be separately considered and the effect of bicycle behavior and peak period also need to be included in the future development of model.

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