A STOCHASTIC APPROACH FOR MODELING PEDESTRIAN CROSSING BEHAVIOR AFTER THE ONSET OF PEDESTRIAN FLASHING GREEN SIGNAL INDICATION

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ABSTRACT

Pedestrian-vehicle conflicts are considered as one of the most common safety problems at signalized intersections. In Japan, pedestrian flashing green (PFG) is considered as a clearance time interval for pedestrians to safely finish crossing at crosswalks. Although pedestrians should not enter the crosswalk during PFG by law, many of them rush into the crosswalks without taking care of approaching turning vehicles, which causes higher probability to get severe conflicts with the vehicles. The objective of this paper is to analyze and model probabilistic behavior of pedestrians after the onset of PFG, which contains whether pedestrians give up crossing or not and pedestrian speed distributions. The empirical data analysis showed that longer crosswalks give significantly higher pedestrian stop probabilities and there is a significant difference between pedestrians' first and second half speed at crosswalks. Results of a Monte-Carlo simulation showed that the estimated models appropriately represent overall stochastic pedestrian behavior from the onset of PFG until they finish crossing.

Keywords: pedestrian behavior, signalized crosswalk, clearance time

INTRODUCTION

Pedestrian-vehicle conflicts are considered as one of the most common safety problems at signalized intersections. More than one-third of the total traffic accident fatalities in Japan are pedestrians (National Police Agency in Japan, 2012). Although signalized crosswalks are operated to give pedestrians prioritized right of way, 41% out of total pedestrian fatalities are due to illegal crossing behavior.

Pedestrian clearance time is an important design parameter to provide pedestrians with safer crossing. It is defined as the necessary time for pedestrians who are in the crosswalk at the end of the green indication to finish crossing. This clearance time is indicated by flashing green light in Japan and DON'T WALK in US. The main concern about how to determine the length of the clearance time is to provide sufficient time for slow walkers (elderly or pupils) who start crossing during green phase until they complete crossing (LaPlante and Kaesar, 2007). On the other hand, giving longer clearance time may encourage pedestrians to enter crosswalks even after the onset of the clearance time, which causes a safety problem. Those who enter crosswalk at the last moment of clearance time tend to have higher speed with less care to surrounding vehicles. These pedestrians may have higher risk of severe conflicts with vehicles. Especially in Japan, since the length of the clearance time is set to be smaller than US and other countries as discussed later, remaining pedestrians at the end of pedestrian phase are observed quite frequently. Therefore, there is a need to analyze such illegal behavior of pedestrians to propose safer design of the signalized crosswalks.

This paper aims to analyze and model the behavior of individual pedestrians who are approaching the crosswalks and may enter after the onset of flashing green. It contains the stop or go (cross) decision at the onset of PFG and speed distribution of pedestrians during the clearance time.

This study is a part of a project which develops a simulation model dedicated for safety assessment (Dang et al; 2012, Alhajyaseen et al; 2012). Safety evaluation and assessment using simulations based on conflict analysis technique is one of the most flexible and promising methods. However, existing simulation models are mainly developed for operational performance evaluation purposes. The objective of the project is to represent user behavior as functions of intersection layouts and signal control parameter. Since the simulation only contains vehicle maneuver models, the proposed model in this paper will be combined to the simulation to evaluate vehicle-pedestrian conflicts.

Some of the crucial characteristics of pedestrian behavior, such as stochasticity and sensitivity to the layout of intersection, contribute to hazardous condition. Therefore, the proposed model is a stochastic model as functions of intersection layouts and surrounding conditions of pedestrians to represent variation of their maneuvers. The model can be utilized to estimate the frequency of illegal crossing, entering time and speed distribution for safety evaluation.

In the literature review, definitions of clearance time in Japan and other countries as well as existing research on pedestrian behavior at clearance time are introduced. Then the methodology section describes components of pedestrian models to represent the entire behavior during clearance interval. After the empirical observations and analyses, pedestrian stop/go decision and speed distribution models are developed. Finally, Monte-Carlo simulation is applied to demonstrate pedestrian behavior, followed by discussions and conclusions.

LITERATURE REVIEW

Settings of Pedestrian Clearance Time in Different Countries

In US, pedestrians are allowed to pass through crosswalks during WALK and FLASHING DON'T WALK signal phase (FHWA, 2009). The former indication is given for pedestrians to start crossing. The latter is provided for them to finish crossing, and thus this duration is regarded as the clearance time for pedestrians. The clearance time is defined as the necessary time that pedestrians on the crosswalk can finish crossing in US and many other countries such as UK or Germany, although the signal indications are different in different countries.
In case of Japan, pedestrian green (PG) and pedestrian flashing green (PFG) indications seem to correspond to WALK and FLASHING DON'T WALK. However, according to Japanese Road Traffic Act, pedestrians must not start to cross and have to get out from crosswalk as soon as possible at PFG. Because of this rule, PFG is provided as much as pedestrian can walk half length of crosswalk by assuming pedestrians who started to cross just before PFG indication will return to their origin side (Japanese Society of Traffic Engineering, 2006). Even with this definition, pedestrians rarely return to their origin during PFG. Furthermore, there is a duration that red phase for pedestrians and green phase for vehicles parallel to the pedestrian phase are shown just after PFG. This time might also be substantially used as pedestrian clearance time.
Although clearance time in Japan is quite short as shown above, quite many pedestrians rush into crosswalks even after the onset of PFG (Suzuki et al. 2004). As a result, many pedestrians remain on crosswalks at the end of the phase. Moreover, their speed to enter crosswalk is higher than ordinary condition, and thus the probability to have hazardous conflict with vehicles increases.

Analysis on Pedestrian Clearing Behavior

Many works have been done on analyzing pedestrian behavior during clearance time and illegal crossing at signalized intersections. Hatfield et al. (2007) stated that one-third of both pedestrians and drivers misunderstand that the pedestrians may not have right-of-way during FLASHING DON'T WALK. This indicates pedestrians in the clearance time may often have hazardous condition as drivers do not always give the right of way. King et al. (2009) also supports this fact that the risk of illegal crossing is larger than that of legal crossing. Although these statistics include many types of illegal crossing scenarios, crossing in the PFG interval is also expected to have higher risk than the crossing in the pedestrian green interval.
Pedestrians' decision making factors whether they chose illegal crossing or not, is also analyzed by several researchers. Guo et al. (2012) modeled pedestrian stop-go decision as a function of waiting time at curb. Their subjects are not only the pedestrians who come

during clearance time but also those who cross during red phase. The stop-go choice is modeled considering the condition when pedestrians arrive at the curb. However, pedestrians may make decision in advance as they can see the traffic signals from the upstream. Furthermore, they do not tangle the issues related to pedestrian crossing speed and how severe the conflict they might have.

Pedestrian speed is an important factor not only to determine their clearance time but also the conflict probability to turning vehicles. However, most of the existing works deal with the speed of elderly people in order to provide them with the necessary clearance (LaPlante and Kaesar, 2007). On the other hand, young pedestrians who can rush to the crosswalk may cross illegally. Although this may give hazardous condition with conflicting vehicles, characteristics of their speed are rarely discussed.

Dang et al. (2012) proposed a simulation model to represent turning vehicle and pedestrian conflicts for safety assessment. This model is a combination of detailed vehicle maneuvers including two-dimensional path of vehicles, reaction to signal indication and pedestrians. All these models consider the stochastic nature of user maneuver and they are functions of intersection geometries. This enables the assessment of conflict severity and probability by changing intersection geometry. However, the model only considers the drivers' reaction to pedestrian under the assumption that pedestrians walk in constant speed, without responding to traffic signals or vehicles.

This paper attempts to develop quantitative models for the estimation of pedestrian stop/go decision and speed around crosswalks, which can be utilized for the micro-simulator to assess how pedestrians conflict with vehicles. This model includes the behavior of approaching pedestrian at the sidewalk, since pedestrians can see the conditions of crosswalk from upstream and may make decision before their arrival.

METHODOLOGY

Components of Pedestrian Behavior Model

During PFG interval, pedestrian crossing behavior is very complicated since it is affected by many factors such as crosswalk geometry, presence of turning vehicles or other crossing pedestrians, weather conditions, and so on. For simplification, the following assumptions were made to develop a model which can stochastically represent pedestrian maneuver at signalized intersections during PFG interval.

Firstly, all pedestrians approaching crosswalks during PFG interval decide to go or to stop at the onset of PFG. This assumption considers that pedestrians do not make their decision when they reach the crosswalk edge but further upstream.

The pedestrians who chose to go adjust their speed, by time after the onset of PFG . Figure 1 shows examples of time-space diagram of a few pedestrians observed in Sasashima intersection in Nagoya City, Japan. Vertical axis shows the spacing from entering edge of the crosswalk (demonstrated in Figure 2). The slope of the trajectory represents the speed at each time and space. In this figure, one can see that pedestrians prefer to increase and then decrease their speed as they proceed. The reason to increase the speed in the beginning may be that pedestrians would like to make sure that they can finish crossing. However, they

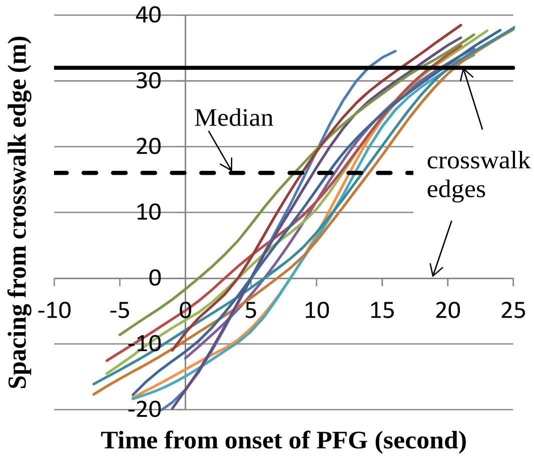


Figure 1 Examples of time-space diagram of pedestrians at Sasashima Intersection (west crosswalk), Nagoya

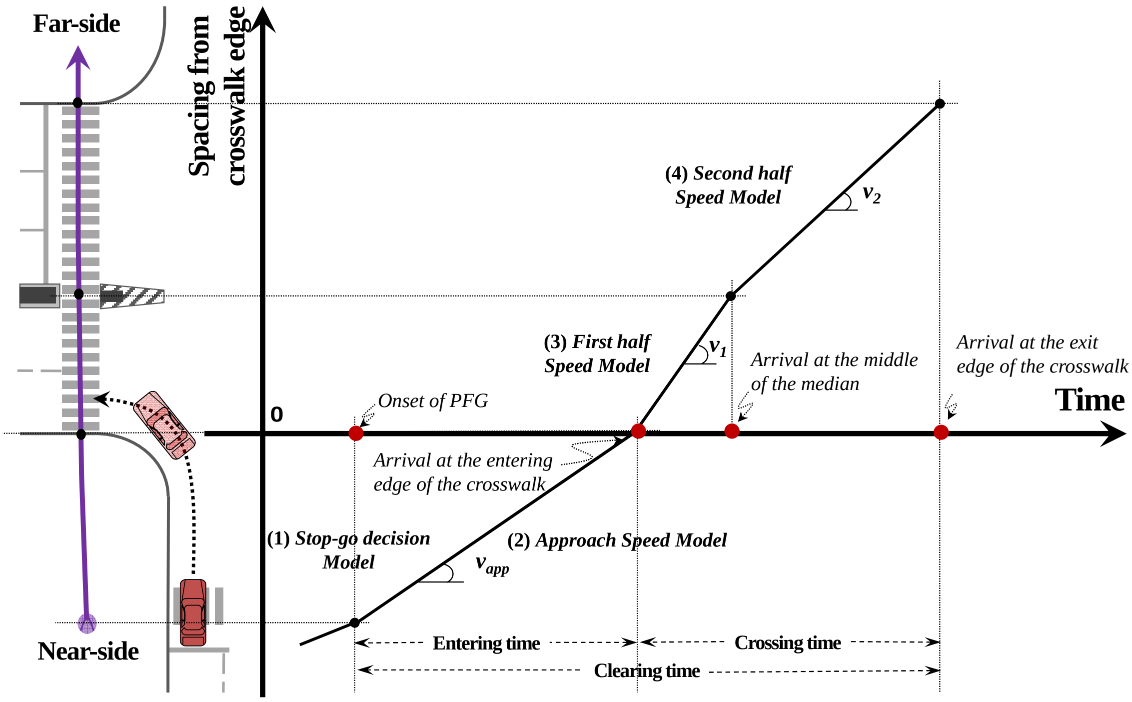


Figure 2 Definition of walking speed at different phases

become rather relaxed at the end of crossing as they can be easily seen by vehicles and may expect vehicles to give way.

Considering this fact, this paper divides the walking area into three sections for pedestrian speed analysis as in Figure 2. The first section is from the pedestrian positions at the onset of PFG to the crosswalk edge. The travel speed of pedestrians in this section is defined as approach speed v_{app}. (Note: since the regulation in Japan is left-hand traffic, following discussions are based on left-hand traffic.) The second and third sections are the first half and the second half of crosswalk. The travel speeds at these sections are defined as first half speed v_1 and second half speed v_2, respectively. It is important to mention that so far it is assumed that pedestrians do not react to each other or vehicles and do not avoid any conflict along their path. Pedestrians on the crosswalks have priority over vehicles. Therefore ideally, pedestrians are not necessary to react to vehicles for crash avoidance. Moreover, volume of

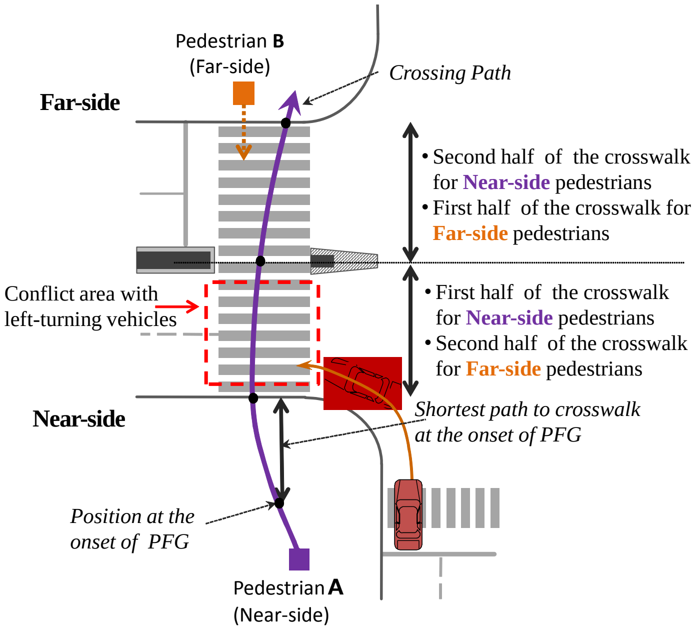


Figure 3 Definition of direction and measurement area

pedestrians crossing with PFG is quite low and thus avoidance behavior between pedestrians is almost negligible.

Since the maneuver of pedestrians who are about to enter the crosswalk is important for the safety evaluation, clearing time is defined as the time to clear the intersection plus the time it takes the pedestrian to get to the intersection (Figure 2). Meanwhile, entering time is defined as the time from the onset of PFG to the moment the pedestrian reaches the crosswalk.

In summary, the following sub-models are the main components to represent the whole crossing maneuver of pedestrians:

1. Stop-Go choice model,
2. Approaching speed model,
3. Crossing speed model for first and second half of crosswalk.

In this study, the terms ‘near-side’ and ‘far-side’ are defined based on the potential conflict area with turning vehicles as in Figure 3. Near-side means the side where pedestrians and exiting turning vehicles have conflict and far-side is the other side. It is also defined that pedestrians whose origin is near-side as near-side pedestrians and those who come from far-side as far-side pedestrians (corresponding to Pedestrians A and B in Figure 3, respectively).

Stop-Go Decision Model

Binomial logit model is applied to estimate the stop/go probability at the onset of PFG. In the binomial logit model, error term of utility to choose “go” is assumed to follow Gumbel distribution. The probability to go is explained in Equation 1.

$$\Pr(go) = \frac{\exp(V)}{1+\exp(V)} \tag{1}$$

where, V is the deterministic term of the utility to go which is a linear function of several influencing factors, such as distance to crosswalk, speed at the onset of PFG and direction of movement. The parameters of each variable are estimated using maximum likelihood method.

Speed Distribution Models

Approach speed v_{app} is defined as pedestrian travel speed at the sidewalk which is calculated by dividing the traveled distance from the position at the onset of PFG till entering the crosswalk, by the elapsed time from the onset of PFG till entering the crosswalk as shown in Figure 2. Observed approaching speeds are modeled using the cumulative Gamma distribution since the speed distributions during clearing time are skewed as shown in the latter sections. Probability to observe v_{app} = x of Gamma distribution is calculated by following function:

$$\Pr(v_{app} = x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \exp\left(-\frac{x-\gamma}{\beta}\right)(x-\gamma)^{\alpha-1}$$

$$\begin{aligned} \alpha &= f(y_{1,1}, y_{1,2} \sim y_{1,n}) = \alpha_{1,1}y_{1,1} + \alpha_{1,2}y_{1,2} \sim \alpha_{1,n}y_{1,n} + \alpha_{1,n+1} \\ \beta &= g(y_{2,1}, y_{2,2} \sim y_{2,n}) = \alpha_{2,1}y_{2,1} + \alpha_{2,2}y_{2,2} \sim \alpha_{2,n}y_{2,n} + \alpha_{2,n+1} \\ \gamma &= h(y_{3,1}, y_{3,2} \sim y_{3,n}) = \alpha_{3,1}y_{3,1} + \alpha_{3,2}y_{3,2} \sim \alpha_{3,n}y_{3,n} + \alpha_{3,n+1} \end{aligned}$$

((2)

where α is the shape parameter, β is the scale parameter, γ is the location parameter, $y_{i,1}$, …$y_{i,n}$ are independent variables, and $\alpha_{1,1}$, …, $\alpha_{1,n}$, $\alpha_{2,1}$, …, $\alpha_{2,n}$, $\alpha_{3,1}$, …, $\alpha_{3,n}$ are the model coefficients estimated by the maximum likelihood method. Γ(α) is Gamma function, which is given by the following equation.

$$\Gamma(\alpha) = \int_0^{\infty} t^{\alpha-1}\exp(-t)dt \tag{3}$$

Gamma distribution has a characteristic to represent various types of skewed distribution by changing parameters. The scale parameter represents skewness of the distribution. Larger the parameter is, smaller the skewness becomes. At the same time, large scale parameter leads to larger average value. The shape parameter determines the variation of the distribution. If the shape parameter is small, the distribution is more concentrated. The location parameter explains the domain of definition. The probability is equal to zero if $x < \gamma$.
It is obvious that the location parameter should be non-negative value as the pedestrian speed should take non-negative value.
In the same way the first half speed v_1 and second half speed v_2 are modeled. The definitions of v_1 and v_2 are shown in Figure 2. When estimating v_1 and v_2 from empirical data, the traveled distance in the first half of the crosswalk is used to estimate v_1 while the traveled distance in the second half of the crosswalk is used to estimate v_2.

DATA COLLECTION

Study Sites

Seven crosswalks at three signalized intersections located in Nagoya city, Japan, are selected as study sites. Table 1 shows the geometry characteristics and signal settings for each site. Imaike and Yagoto-Nisseki intersections are operated by four-phase signal control. Sasashima intersection is operated by fully-protected phases, which provides green phases to vehicles and pedestrians at different periods so that no conflicts occur between them. The detailed phase sequences are shown in Tables 2 and 3 and Figure 4.

These intersections are located in urban area and most of the users are ordinary adult people. Elderly people and pupils are rarely observed. Pedestrian and vehicle volumes are the observed average hourly volume during the observation period, which is explained in the following section.

These are large intersections whose crosswalk lengths are approx. 20m to more than 30m and cycle length are more than 130 seconds. Such intersection geometry is common in urban area in Japan where two-stage crossing is rarely applied. Crosswalk width include bicycle lane width (approximately 2m), since pedestrians and bicycles do not clearly run separately in Japan and the bicycle lane can be regarded as a part of the pedestrian crosswalk.

Table 1 Information of study sites

Intersection name	Approach	Crosswalk geometry (m)		Pedestrian volume (ped/h)		Left-turn vehicle volume (veh/h)
		length	width	Near-side	Far-side	
Sasashima	West	31	10	394	1631	270
	East	20.6	9	1058	180	56
	South	37	8	900	203	68
Imaike	West	22	9	158	202	101
	East	21	10	158	169	169
	North	22	9	68	79	158
Yagoto-Nisseki	North	18	6.7	28	222	28

Table 2 Signal phase sequence and timing at Sasashima Intersection

Direction	Mode	Signal phasing (second)															Cycle length (second)
		φ_1					φ_2			φ_3				φ_4			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
S-N	Through vehicle																
	Left-turning vehicle(S to N)																
	Left-turning vehicle(N to S)																
	Right-turning vehicle																
	Pedestrian																
E-W	Through vehicle (E to W)																
	Through vehicle (W to E)																
	Left-turning vehicle (E to W)																
	Left-turning vehicle (W to E)																
	Right-turning vehicle (W to E)																
	Pedestrian																
Intersection	Sasashima	30	6	1	3	5	17	3	5	40	7	3	6	24	2	8	160

Figure 4 Signal phase sequence at Sasashima Intersection

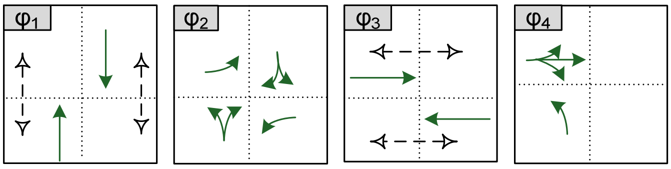


Table 3 Signal phase sequence and timing at Imaike and Yagoto-Nisseki Intersections

Direction	Mode	Signal Phasing (second)														Cycle length (second)
		φ1				φ2			φ3				φ4			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	
S-N	Vehicle															
	Pedestrian															
	Right-turning vehicle															
E-W	Vehicle															
	Pedestrian															
	Right-turning vehicle															
Intersection	Imaike	44	8	6	3	15	2	5	42	8	5	3	12	2	5	160
	Yagoto-Nisseki	38	7	1	3	7	2	5	44	4	2	3	7	2	5	130

Green Amber Red Pedestrian flashing green

Data Processing

Maneuver of pedestrians are videotaped at each study site using video cameras located at high buildings nearby the intersections. The angle of the camera is good enough to capture the detailed trajectories of individual pedestrians. Among observed pedestrians, those who were at upstream of the subject crosswalks and approaching toward them at the onset of PFG are collected as subjects. Total number of observed subject pedestrians and number of those who started to cross after the onset of PFG are shown in Table 4. The observation periods include both off-peak and peak hours. As in Table 4, significant number of pedestrians enters crosswalks even after PFG starts.
The positions of pedestrians at every second are manually extracted from video images. Then, the coordinates in these images are converted to global coordinates by projective transformation. By applying fixed-interval Kalman smoothing method, trajectory and speed of pedestrians at each time are obtained.

Table 4 Number of observed data samples

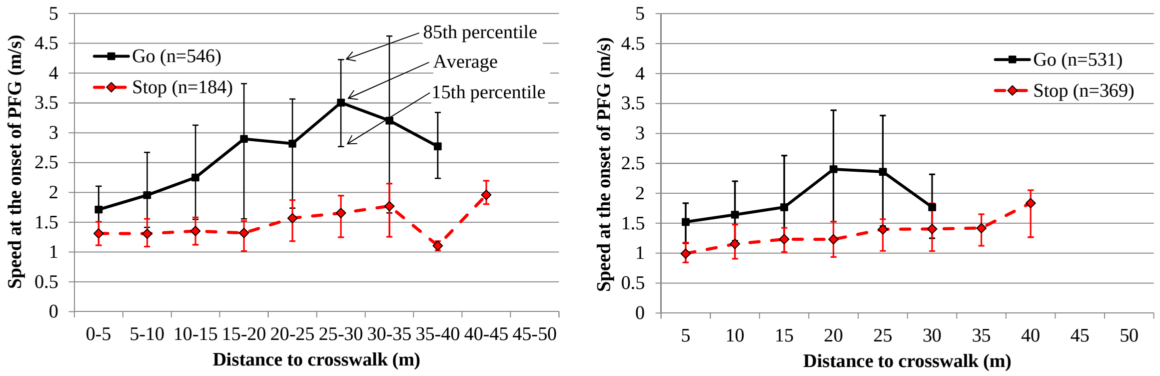
Intersection name	Approach	Observation period	Number of subject pedestrians*		
			Near-side	Far-side	Total
Sasashima	West	10/26/2011 8:00-17:00 10/28/2011 8:00-17:00	436 (242)	454 (289)	890 (531)
	East		275 (206)	454 (340)	730 (546)
	South		178 (90)	212 (124)	390 (214)
Imaike	West	9/6/2011 9:00-17:00 9/7/2011 9:00-17:00	266 (91)	160 (96)	426 (187)
	East		119 (65)	124 (78)	243 (143)
	North		44 (34)	65 (51)	109 (85)
Yagoto-Nisseki	North	7/22/2011 8:30-11:30 7/28/2011 8:30-11:30 7/29/2011 8:30-11:30	66 (61)	7 (4)	73 (65)

*Numbers in the parentheses are number of pedestrians who chose to go out of total number of observed subject pedestrians.

EMPERICAL ANALYSIS

Stop-Go Decision of Approaching Pedestrians

Figure 5 shows the relationship between pedestrian instantaneous walking speed at the onset of PFG and distance from pedestrian position to the crosswalk. In the legend, 'Go' and 'Stop' indicates whether pedestrians chose to go or to stop. Pedestrians who chose to go tend to have significantly higher walking speed at the onset of PFG than those who chose to stop. This tendency becomes clearer for those who were at far upstream at the onset of PFG.



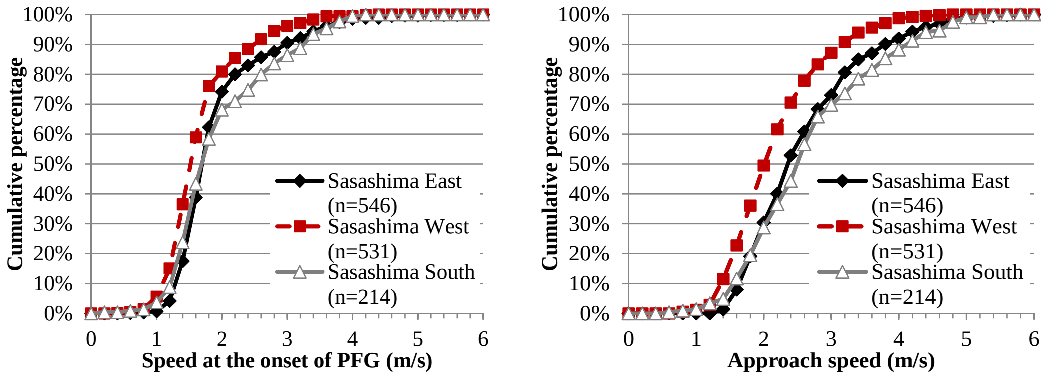
(a) Sasashima East crosswalk

(b) Sasashima West crosswalk

Figure 5 Relationship between distance to crosswalk, average walking speed at onset of PFG and stop/go decision

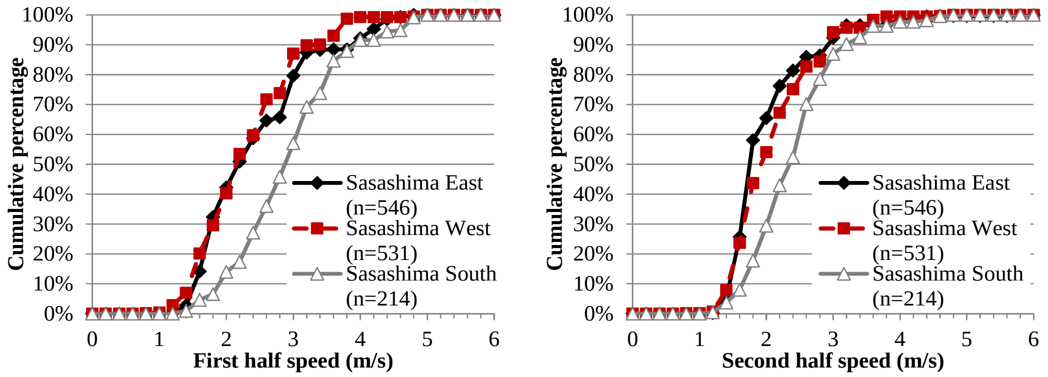
Speed Distributions

Cumulative distributions of instantaneous pedestrian speed at onset of PFG, approach speed and crossing speed at different crosswalks in Sasashima intersection are shown in Figure 6. These speed distributions do not tend to follow normal distribution but it is rather skewed.
Approach speed and first half speed distributions shift to the right compared to the distribution of the speed at the onset of PFG, and their variance becomes larger. This is reasonable since pedestrians who decide to go at the onset of PFG try to hurry up. The larger variation can be observed since the speeding of pedestrian depend on their distance to crosswalk and the their ability of going faster which is different from one person to another. Compared to the first half speed, the second half speed tends to be lower.
Regarding the difference between crosswalks, speed at Sasashima South crosswalk is higher than other crosswalks since it is longer than others. Pedestrians tend to hurry at long crosswalks so that they can finish crossing in the limited PFG time. Figure 7 presents the effects of pedestrians' entering time to the crosswalks on the first half and second half speed distribution. Entering time is the time when pedestrians enter the crosswalk after the onset of PFG as defined in Figure 2. As the entering time increases, the first half speed has significant increasing tendency, while the second half speed has no clear relationship with entering time. This is also explained that pedestrians try to go as fast as possible in the beginning of crossing, but they becomes rather relaxed in the latter half although they do not have enough time to finish crossing before the beginning of the green phase of conflicting traffic stream.



(a) Instantaneous speed at the onset of PFG

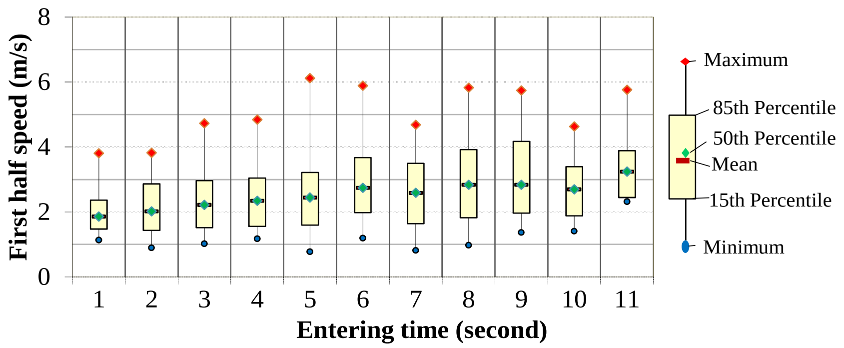
(b) Approach speed



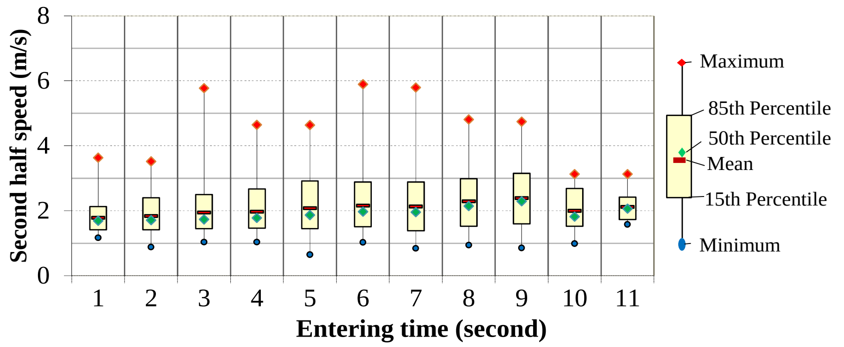
(c) First half speed

(d) Second half speed

Figure 6 Cumulative speed distributions at Sasashima intersection (pedestrians who chose to go only)



(a) First half speed



(b) Second half speed

Figure 7 Relationship between entering time and crossing speeds (All crosswalks)

Table 5 Estimated results of stop/go decision model

Variables	Coefficients	t-value
Distance to crosswalk (m)	-0.261	574
Speed at the onset of PFG (m/s)	3.73	327
Crosswalk length (m)	-0.0570	29.0
Constant	-0.164	0.178
Number of samples	2621	
-2 Log likelihood	1522	
R^2 (Cox & Snell)	0.516	
Percentage correct	88.2	

MODEL ESTIMATION RESULTS

Stop-Go Decision Model

Table 5 describes the parameter estimation results of the stop-go decision model which was defined as Equation (1). The definition of distance to crosswalk is the shortest distance to crosswalk from pedestrian position at the onset of PFG. This parameter is very influential factor in pedestrian decision whether to go or to stop. The distance to crosswalk and the crosswalk length have negative coefficients. This is logical since the longer the remaining distance to walk is, the less motivation pedestrians have to start crossing. Speed at the onset of PFG has positive impact, which also reflects the empirical analysis discussed in Figure 5.

Speed Distribution Model

Table 6 shows the estimated parameters of approach speed, first half speed and second half speed distributions. Although brief discussions are shown below, it is not easy to imagine combined effect of parameters to the shape of distribution. In order to clearly illustrate the sensitivity of parameters, the next chapter presents an analysis which demonstrates speed distribution using Monte-Carlo simulation.

Regarding the approach speed, distance to crosswalk has positive impact to the shape parameter. This means that if pedestrians are far from the crosswalk at the onset of PFG, the approach speed becomes larger. Positive coefficient of the speed at the onset of PFG means that the variation of the speed will be large if this variable is higher. These results are logical since pedestrians who are far from the crosswalk need to increase their speed to catch up the clearance time. If pedestrians have high speed at the onset of PFG, they may possibly keep their speed after that or they might reduce the speed if they are sure that they can finish crossing during the available time. These different behaviors may lead to larger variance to the approach speed. The location parameter of the approach speed was set to be zero since no variables have significant influence to it and the constant value was neither.

Results of the first half speed model are shown in Table 6(b). Approach speed is a strong influencing factor. Longer crosswalk also has positive influence to the shape parameter and entering time to crosswalk has positive influence to the scale parameter. These can be explained that pedestrians have to hurry at longer crosswalks to finish crossing.

Table 6 Estimated results of speed distribution model

(a) Approach speed

	Variables	Coefficients	t-value
Shape parameter α	Distance to crosswalk (m)	0.256	10.2
	Constant	24.1	27.2
Scale parameter β	Speed at the onset of PFG (m/s)	0.0379	24.0
	Constant	0.0218	14.7
Number of samples		1521	
Log likelihood		-886	
Initial log likelihood		-1871	
χ^2 value		104.1	

(b) First half speed

	Variables	Coefficients	t-value
Shape parameter α	Approach speed (m/s)	3.88	16.4
	Crosswalk length (m)	0.129	8.24
	Constant	-3.51	-7.22
Scale parameter β	Approach speed (m/s)	-0.0144	-6.20
	Entering time to crosswalk (s)	0.0158	12.2
	Constant	0.170	17.4
Location parameter γ	Pedestrinan demand (ped/h)	-0.000055	-2.77
	Constant	0.777	21.4
Number of samples		1608	
Log likelihood		-1284	
Initial log likelihood		-1851	
χ^2 value		272.0	

(c) Second half speed

	Variables	Coefficients	t-value
Shape parameter α	First half speed (m/s)	0.580	-4.62
	Constant	6.67	11.4
Scale parameter β	First half speed (m/s)	0.0862	11.8
	Constant	-0.00333	-0.29
Location parameter γ	First half speed (m/s)	0.218	8.84
	Direction dummy (Near-side:1, Far-side:0)	-0.0597	-3.79
	Constant	0.499	15.8
Number of samples		1608	
Log likelihood		-871	
Initial log likelihood		-1432	
χ^2 value		1122	

If pedestrian enter the crosswalk around the end of PFG, they are also hurried to go. However, as it is difficult to correctly detect the remaining time rather than the remaining distance to finish crossing, not all the pedestrians increase the speed and as a result the variance becomes larger.

Pedestrian demand on the crosswalk has negative impact upon the location parameter, which determines minimum speed. As the demand increases, probability to avoid other pedestrians becomes high which pushes pedestrians to decelerate.

The second half speed in Table 6(c) strongly depends on the first half speed. The direction dummy of the location parameter indicates the second half speed of pedestrians who come from near-side is slower than those from far-side. The possible reason is that far-side pedestrians have conflicts to the turning vehicles at the second half. Therefore, they might feel the danger from vehicles which make them hurry up as compared to near-side pedestrians who don't have conflict with vehicles at the second half.
Other factors, such as the differences between behaviors in peak and off-peak periods and the impact of existence of conflicting turning vehicles, were also analyzed. However, these factors were not significant thus they were excluded from the models.

MONTE-CARLO SIMULATION FOR MODEL VALIDATION

Structure of Monte-Carlo Simulation

The models in the previous chapter are estimated by using maximum likelihood method and the goodness of fit cannot be directly calculated. It is also difficult to correctly understand the relationship between variables and the behavior of the function itself. In order to validate and check the model characteristics, Monte-Carlo simulation is applied. The Monte-Carlo simulation starts at the onset of PFG. The speed and position of each pedestrian at the onset of PFG are randomly generated. Each pedestrian decide whether he/she stop/go according to the stop/go decision model. Those who decide to "go" will determine their approach speed and crossing speed following the speed distribution models. As all of the models are probabilistic functions, pedestrians choose their speed according to these probabilities. Input parameters of the Monte-Carlo simulation are as follows:

1. Intersection condition
   - Crosswalk length.
2. Parameters on individual pedestrian characteristics
   - Distance to crosswalk at the onset of PFG,
   - Speed at the onset of PFG,
   - Walking direction (Near-side / Far-side).

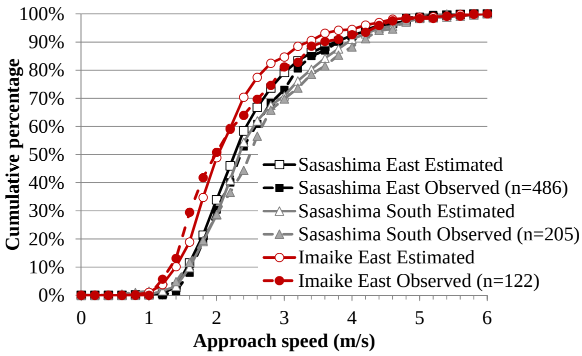
Distribution of distance to crosswalk is dependent on offset between adjacent intersections, frequency of public transport which usually stops near the intersection and several other factors which determine pedestrian arrival pattern to the crosswalk. In this study, observed distribution is utilized for the following Monte-Carlo simulation.

Validation of Estimated Clearance Time Distribution

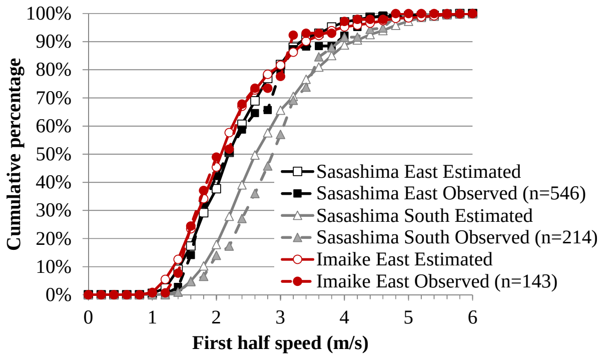
The Monte-Carlo simulation was applied to Sasashima East and South crosswalks as well as Imaike East crosswalk. In the simulation, 1000 pedestrians are generated at each intersection. The distance and speed of each pedestrian at the onset of PFG were randomly generated by following the observed probability distribution. Walking direction of pedestrians was determined by the proportion of the directional demand.

Figure 8 shows the comparison of speed distributions between observed data and results of Monte-Carlo simulation at subject crosswalks. Probabilities of pedestrian choosing to go at Sasashima East, Sasashima South and Imaike East crosswalks in the simulation are estimated as 71.8%, 52.8% and 60.5% respectively, while the observed values were 74.9%, 54.9% and 58.8%, respectively.

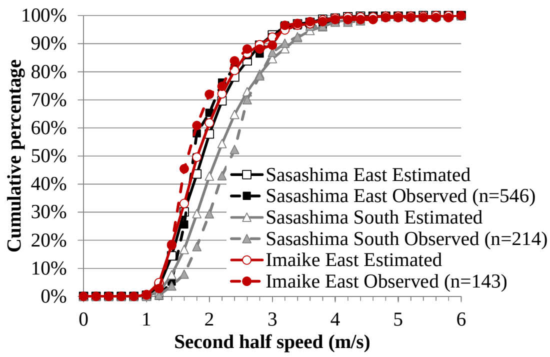
Speed distributions of estimated and observed curves are found not to have significant difference by statistical test in 5% significance level, which means the models successfully represent the speed distribution at each phase.



(a) Approach speed distribution



(b) First half speed distribution



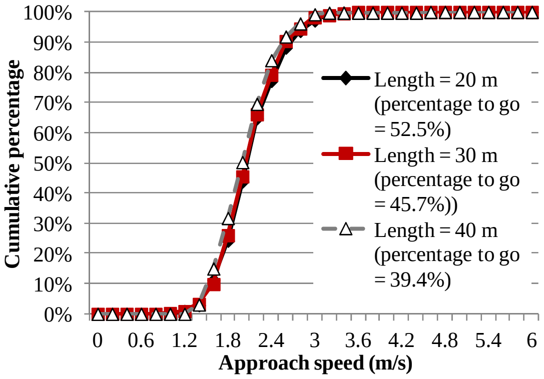
(c) Second half speed distribution

Figure 8 Validation of Monte-Carlo simulation comparing to the field observation data

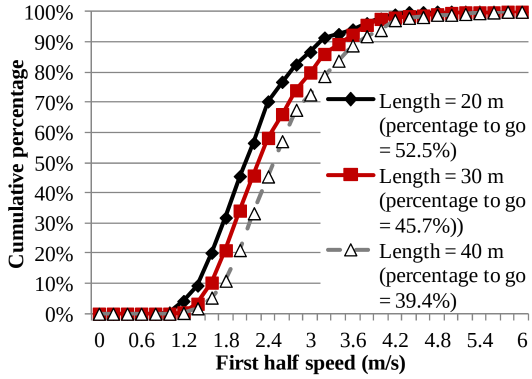
Sensitivity Analysis of Speed Distribution Models

As the speed distribution models use Gamma distribution, it is not easy to discuss the characteristics of the models by parameters. Sensitivity analysis helps to understand how these models behave dependent on change of each variable.

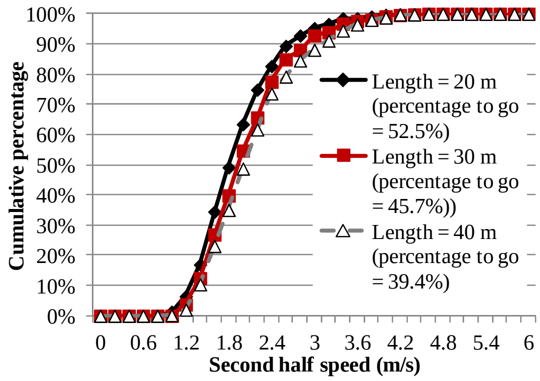
Considering the influence of crosswalk length, three scenarios with crosswalk lengths of 20, 30 and 40 m respectively are applied. Other input parameters are set as follows; speed at the onset of PFG as 1.5 m/s, pedestrian demand at the crosswalk as 1500 people/h, walking direction as from near-side, and the uniform distribution from 0 m to 40 m is assumed for the distance to crosswalk. Figure 9 show the estimated speed distributions under the different crosswalk length settings. Approach speed does not change even though the crosswalk length becomes longer, while first half speed increases significantly. Even on the 40m crosswalk length, almost 40% of pedestrians start crossing after the onset of PFG. These



(a) Approach speed distribution



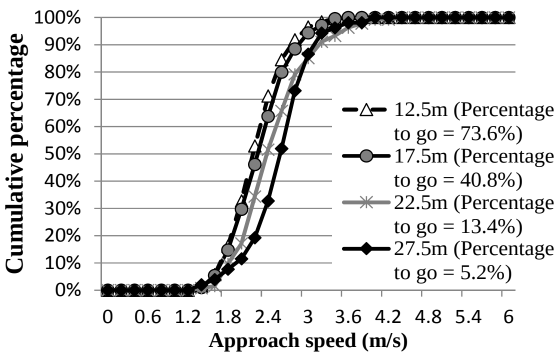
(b) First half speed distribution



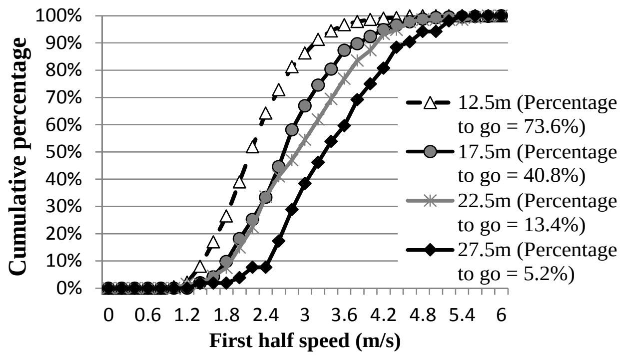
(c) Second half speed distribution

Figure 9 Sensitivity analyses of speed distribution models (by changing crosswalk length)

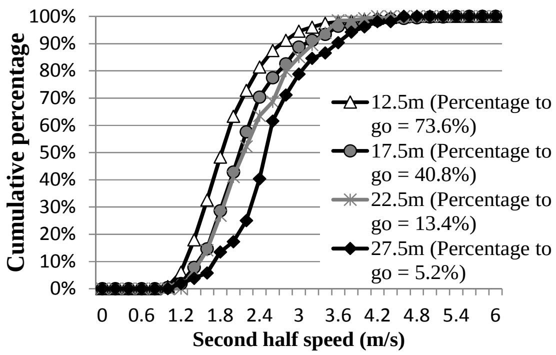
results indicate that the longer the crosswalk, the higher possibility to have pedestrians running in high speed on the crosswalk. As vehicles can hardly detect the existence of pedestrians with high speed, this may give more opportunity of severe conflicts with vehicles.
Considering the influence of pedestrian positions at the onset of PFG, four scenarios are tested. In these scenarios, all the pedestrians are assumed to be at the same position at the onset of PFG. The distances from those positions to the crosswalk edge were set to be 12.5m, 17.5m, 22.5m and 27.5m respectively. The crosswalk length was set as 30m. 1000 pedestrians were generated again for each scenarios in the Monte-Carlo simulation.
Figure 10 shows the results under the scenarios with different pedestrian initial positions at the onset of PFG. It is clearly shown that pedestrian speed significantly increases as the position becomes further. Accordingly pedestrians tend to have much higher speed at the first half of the crosswalk. It is important to mention that the percentage of pedestrians who chose to cross drastically decreases when pedestrians are at far upstream of the crosswalk. However if pedestrians at far upstream decide to go (percentage of these pedestrians is not high), they will have high possibility of hazardous conflict to turning vehicles who may not recognize the rushing pedestrians or may not be able to react immediately.
In the same methodology, sensitivities of other variables such as speed at the onset of PFG, walking direction and pedestrian demand are also discussed. Higher speeds at the onset of PFG result in higher speeds at downstream and it also leads higher probability of pedestrians start crossing after the onset of PFG.



(a) Approach speed distribution



(b) First half speed distribution



(c) Second half speed distribution

Figure 10 Sensitivity analyses of speed distribution models
(by changing pedestrian position at the onset of PFG)

Regarding walking direction and pedestrian demand, their impacts upon speed distribution are much smaller than the other variables. It is important to mention that the range of analyzed pedestrian demand in the subject crosswalks is not high and there is enough spaces for pedestrian to avoid others during PFG.

Overall, the major factors of pedestrian speed during PFG are crosswalk length, position and speed at the onset of PFG. Since pedestrians have limited time to cross, longer distances to crosswalk and longer crosswalks result in pedestrian speeding up for crossing. Otherwise, if pedestrians had low speeds at the onset of PFG, long distances to crosswalk and long crosswalk, they would have low possibility to cross.

DISCUSSIONS AND CONCLUSIONS

This study analyzes and models the stop/go maneuver as well as speed distributions of pedestrians who haven't yet started crossing at the onset of PFG. The empirical analysis revealed that there is a significant number of illegal crossings who rush to the crosswalk after the onset of PFG. It is also showed that the walking speeds are significantly different between those who decided to go and to stop. Furthermore, approach speed of pedestrians who choose to go is significantly higher as compared to the speed at the onset of PFG. This implies that pedestrians decide to go and adjust their speed even before they reach the curb.
The proposed model successfully represented the percentage of illegal crossing as well as speed of pedestrians at different crosswalks. The crosswalk length and the distance to

crosswalk from pedestrian position at the onset of PFG have positive impact to pedestrian speed. The sensitivity analysis suggested that longer crosswalks make pedestrian speed up, although the probability to start crossing becomes less. The proposed models provide quantitative evaluation of the impact of different geometric and traffic conditions on pedestrian behaviour at the onset of PFG. By combining these models with existing vehicle maneuver models (Dang et al; 2012, Alhajyaseen et al; 2012), it is expected to simulate probability and severity of conflicts between vehicles and pedestrians for safety assessment.

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