GAP ACCEPTANCE MODELS FOR LEFT-TURNING VEHICLES FACING PEDESTRIANS AT SIGNALIZED CROSSWALKS

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ABSTRACT

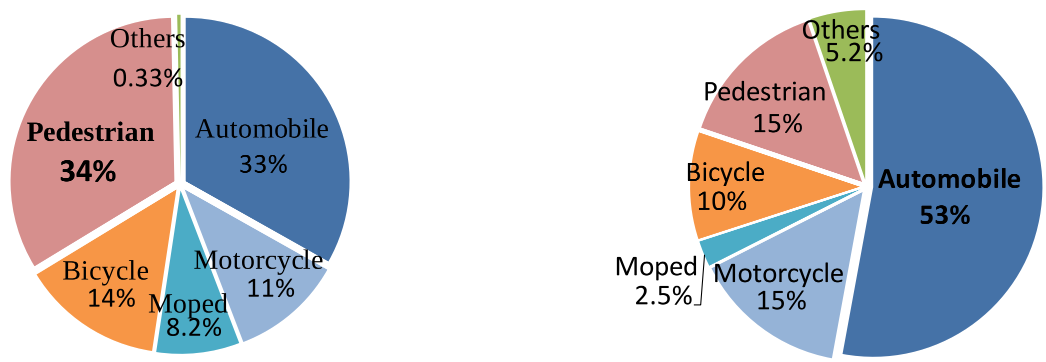
Pedestrian-vehicle conflicts are considered as one of the most common safety problems at signalized intersections. The threat to pedestrian safety is mainly related to the interaction with turning vehicles, especially left-turners (left-hand traffic). This paper aims at analyzing the lag/gap acceptance behavior of left-turning vehicles considering pedestrian movement at signalized crosswalks. Furthermore, this paper addresses the severity of pedestrian-vehicle conflicts by analyzing vehicle speeds at the conflict points. User behavior at several signalized intersections with different geometric characteristics and traffic conditions in Japan are observed by using video cameras. It is assumed that pedestrian movements have their origin at either the near-side or far-side of the crosswalk. Accepted/rejected lags and gaps are extracted and classified depending on the direction of pedestrian movement. Cumulative Weibull distribution function is utilized to fit the observed lag/gap acceptance probabilities. It is concluded that drivers tend to accept shorter lags/gaps between pedestrians coming from the near-side of the crosswalk. Furthermore, it is concluded that drivers tend to accept short lags while being conservative about short gaps between several pedestrians. Simultaneously vehicles clear the conflict area with significantly higher speeds when accepting a lag with a single pedestrian. This indicates that such conflicts are more severe than those when facing several pedestrians.

Keywords: left-turning vehicles, gap acceptance, pedestrian safety, signalized crosswalk

INTRODUCTION

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

Although signalized crosswalks are operated to give pedestrians prioritized right of way, more than one-third of the total traffic accident fatalities in Japan are pedestrians at signalized and unsignalized crosswalks (Japan National Police Agency, 2010) while 15% in Germany (German Institute for Economic Research, 2010) as shown in Figure 1. There are many reasons behind such kind of collisions for instance visibility, intersection geometric layout, traffic signal control policy, and behavior of turning vehicles and pedestrians.



a) Japan b) Germany

Figure 1 Traffic accident fatalities in Japan and Germany in 2009

Generally, in the safety assessment, before and after studies using crash data and conflict analysis are the most common approaches. Before and after studies have a lot of limitations since they are based on accident records. Traffic conflict analyses evaluate the safety conditions using empirical data without the need of accident records. This approach requires collecting sufficient empirical data which is usually not available and costly as well. Therefore, a tool assigned for the quantitative ex-ante evaluation of various operational policies and geometric layouts on the safety performance of signalized intersections, is internationally required. In order to develop such a reliable tool, variations in the maneuver of various users inside signalized intersections considering the effects of geometric and operational parameters need to be realistically modeled.

Microscopic simulation models are often used in practice as an alternative analysis tool to overcome the limitations of existing procedures, as simulation approaches are more flexible and promising. Existing simulation software, however, aimed at mobility assessment thus it simplifies the traffic flow inside of intersections to an extent that safety assessments are not reliable. The models described in this paper are one part of a comprehensive research project aimed at closing this gap. By incorporating them into simulation, a realistic representation of vehicles' maneuver can be achieved which can be used for the safety assessments of pedestrian-vehicle and vehicle-vehicle conflicts at signalized intersections.

Pedestrian-vehicle interactions significantly vary from one country to another dependent on traffic conditions and the compliance of users to traffic rules. Generally, drivers must yield to crossing pedestrians at signalized crosswalks however due to the geometric layout of the intersection, the surrounding environment and pedestrian direction of movement, drivers might take risky decisions by accepting short gaps or not yielding to pedestrians which might threaten pedestrian's safety.

In Japan, vehicles drive in the left-side of the road (left-hand traffic) while in Germany (and U.S.) vehicles drive in the right-side (right-hand traffic). In both cases, the position of the driver relative to road curb is similar. Therefore, it is expected that under the same intersection geometry, operation, and driver characteristics, the traffic systems (left-hand or right-hand) do not leave significant impacts on pedestrian-vehicle conflicts.

Since left turning traffic (left-hand traffic) has more frequent conflicts with pedestrians in common signal phasing plans, this research focuses on their maneuver and decision making which can be presented as a combination of driver lag/gap acceptance and yielding behavior. The yielding behavior presents how drivers adjust their speed after accepting or rejecting a specific lag/gap. It defines the speed of the vehicle when clearing the conflict area which is necessary for assessing the severity of pedestrian-vehicle conflicts.

Therefore this paper aims at analyzing the acceptance of lags/gaps between pedestrians by left-turners at signalized crosswalks considering pedestrian direction of movement. Furthermore, in this study, the severity of pedestrian-vehicle conflicts is addressed by analyzing vehicle speeds at the conflict points. Concurrent models for probabilistically representing left-turners lag/gap acceptance behavior are developed. Based on empirical observations at signalized crossings in Japan and by applying Weibull regression approach, the lag/gap acceptance is described as a function of pedestrian movement direction. Finally this paper ends up with conclusions and future works.

LITERATURE REVIEW

In order to analyze the interaction between pedestrians and vehicles, it is important to gain better insight into both the behavior of pedestrians and vehicles. Since this research focuses on the left-turners maneuver, thus the literature review will concentrate on the yielding behavior and lag/gap acceptance behavior of vehicular traffic.

The likelihood of drivers to yield (give priority to pedestrians) in a macroscopic sense has been linked empirically to vehicle speeds and the relative positioning of the pedestrians to the curb (Geruschat and Hassan, 2005). In an attempt to analyze yielding patterns more closely, Sun et al. (2003) applied logit and probit modeling approach using empirical data from an unsignalized pedestrian crossing site. The authors used a discrete choice modeling approach and found that drivers are more likely to yield to a group of pedestrians, and drivers of heavy vehicles were more likely to yield than drivers of passenger cars. Schroeder and Rouphail (2010) developed a logistic-regression based model that predicts the driver yielding probability at unsignalized crossings as a function of vehicle speed and position relative to the crosswalk, pedestrian assertiveness, whether the vehicle is part of a platoon, and the presence of pedestrian crossing treatments. Previously mentioned yielding probability models focus on the decision whether or not driver yields to pedestrian under the given conditions. However, for safety assessment, it is quite important to evaluate how it is likely to have conflicts. For that, the arrival time at the conflict point of both individual vehicles and pedestrians need to be analyzed. Furthermore in general, most of the existing models are developed for unsignalized crosswalks where a mixed-priority situation exists between pedestrians and vehicles.

Traditionally, literature on vehicle gap acceptance has used a constant value of critical gap (CG hereafter) that is calibrated for local conditions (Troutbeck and Brilon, 2002). The CG is defined as the time between consecutive vehicles on the major road at which a vehicle waiting at the minor approach is equally likely to accept the gap or reject it. The critical gap can differ depending on the type of movement and the type of vehicle. These types of gap acceptance models are referred to as deterministic models which assume that drivers are homogeneous and consistent. In a homogeneous driver population, all drivers have the same critical gap while the consistency assumption means that the same gap acceptance situation will always cause a driver to make the same decision. In reality such assumptions are not likely, thus a probabilistic approach for gap acceptance is necessary to consider the variation in driver decisions.

Beside the deterministic gap acceptance models, probabilistic ones are also discussed in the literature. In a report by Federal Highway Administration (FHWA) in 2004 regarding the Next Generation Microsimulation (NGSIM) research effort, probabilistic gap acceptance models are proposed. Through a Probit or Logit approach, these models assume a mean CG with a random variance term depending on the specific coefficients defined for a driver and/or situation. This means that these models consider the inconsistency or randomness in the critical gap only. Such assumption might be sufficient for capacity analysis but definitely not for the safety assessment. Following the same approach, Logit gap acceptance models have been proposed by Ben-Akiva and Lerman (1985), and Cassidy et al. (1995), and Probit models were suggested by Mahmassani and Sheffi (1981) and Madanat et al. (1994). Conceptually, these models could represent inconsistent driver behavior and a heterogeneous population by using random distributions.

Most of the existing gap acceptance models of different concepts and types are developed to assess the capacity estimation of intersections. Furthermore, few of them are developed for the acceptance of gaps between crossing pedestrians by left-turning traffic (left-hand traffic). Viney and Pretty (1982) presented a model to calculate the saturation flow rate when vehicles have to yield to two-way pedestrian flow. Moreover, Chen et al. (2008) developed a gap acceptance model which was used for the capacity estimation of left-turning movements (left-hand traffic) at signalized intersections. These models are based on the deterministic critical gap approach, and they did not further investigate the effect of pedestrian direction of movement on driver decisions.

In a previous study, Asano et al. (2011) analyzed and modeled the variations in left-turning vehicle paths. They found significant variations in the paths of turning vehicles, which indicates that the conflict points with pedestrians at the downstream crosswalk are also significantly distributed. A sophisticated methodology to reproduce such variations in the paths of left-turners is developed considering vehicle speed, vehicle type and intersection layout parameters. However, a methodology to reproduce the trajectory of left-turners should consider not only the path but also the speed profile in which the effects of crossing pedestrians and intersection geometry are dominant.

This study is a continuation of Asano et al. (2011) analysis to incorporate the decision of drivers when facing pedestrians in reproducing the maneuver of left-turners.

METHODOLOGY

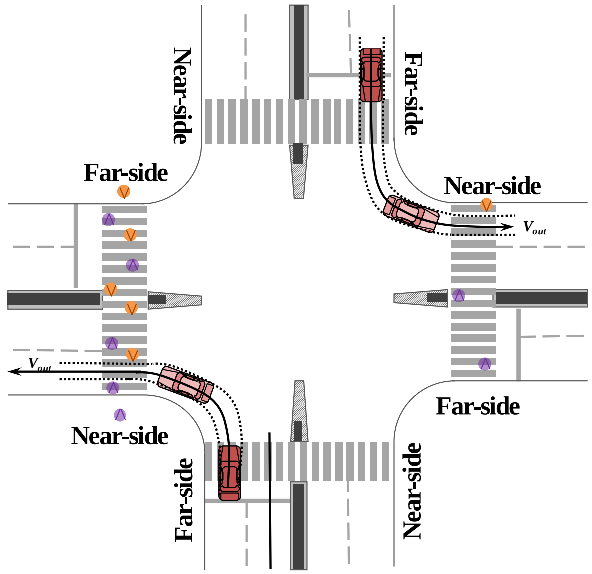
Generally, lag is the time that a subject needs to reach a specific position while gap is the time difference between two successive subjects arriving at the same position (Troutbeck and Brilon, 2002). In the vehicle-pedestrian conflicts, the available lags/gaps for drivers are defined in this study as follows; a lag is defined as the time needed for a single pedestrian to reach the conflict area while a gap is defined as the time difference between two successive pedestrians taken from the moment the first pedestrian has cleared the conflict area till the second one reaches the conflict area as shown in Figure 1b). These lags/gaps are opportunities for drivers to cross. If no suitable lag/gap is available when the vehicle approaches the crosswalk, the driver has to adjust the speed, if necessary to a full stop. The driver will then have to wait until an acceptable lag/gap appears or until all pedestrians have cleared the crosswalk. After excluding all external factors, whether available lags/gaps will be accepted or rejected is basically dependent on the stochastic behavior of drivers. The occurrence and characteristics of lags/gaps depends on pedestrian demand and pedestrian dynamics (movement direction and speed).

For the purpose of this study, it is assumed that pedestrian movements have their origin at either the near-side or the far-side of the crosswalk with reference to conflicting vehicles as shown in Figure 1a). Near-side pedestrians are those who start crossing from the side of the vehicular traffic that is exiting the intersection while far-side pedestrians are those who start crossing from the side of the incoming vehicular traffic as shown in Figure 1a).

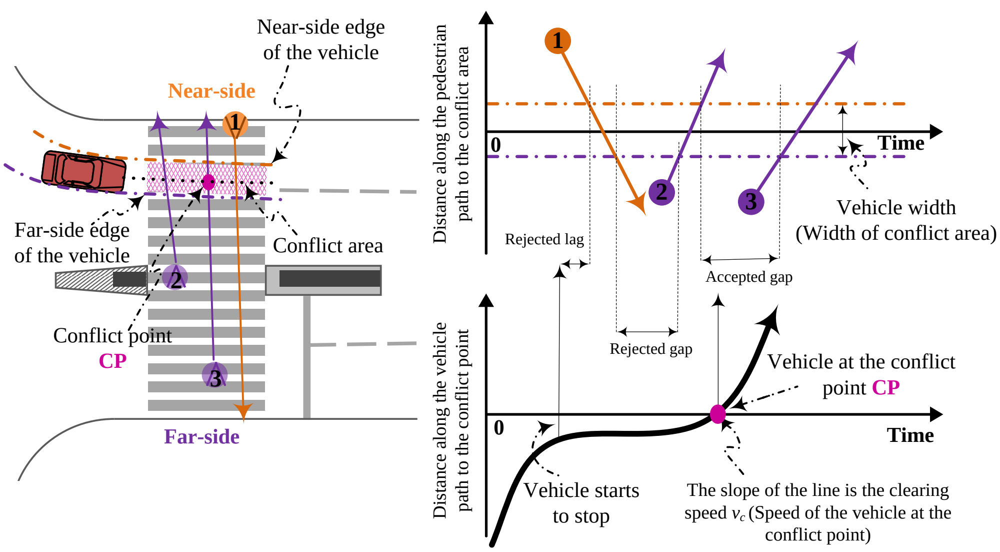
Furthermore, in this study the conflict area is defined as the area occupied by the body of the vehicle on the crosswalk. Since all potential conflicts with pedestrians occur within the conflict area, the calculated lags/gaps are precisely defined by excluding the time used by pedestrians to clear the area occupied by the vehicle body as shown in Figure 1b). It is important to note that lags/gaps are available time intervals for drivers which they can utilize without any conflicts with pedestrians. The edge of the vehicle which faces the pedestrians approaching from the near-side is defined as the near-side edge while the other edge is defined as the far-side edge (Figure 1b)).

Generally, driver reaction to various lags/gaps from different sides of the crosswalk might be different. To investigate the effect of pedestrian direction of movement on driver behavior near the crosswalks, lags/gaps are classified into five different types as shown in Figure 2.

Type A: lags of pedestrians approaching from the near-side of the crosswalk;
Type B: lags of pedestrians approaching from the far-side of the crosswalk;
Type C: gaps between two pedestrians approaching from the near-side of the crosswalk;
Type D: gaps between two pedestrians approaching from the far-side of the crosswalk;



a) The definition of near-side and far-side pedestrian origin-destination



b) Gap/lag definition

Figure1 Pedestrian origin-destination and gap/lag definition considering vehicle size

Type E: gaps between a pedestrian approaching from the near-side of the crosswalk and another approaching from the far-side.

In order to estimate the lag/gap acceptance probability distribution for each type of the defined lags/gaps, empirical data is necessary. After collecting the required data, gaps/lags of the same type are divided into several bins. Due to the limited sample size, the size of each bin is assumed as 1.0 *sec*. The gap/lag acceptance probability for bin *i* of Type *j* is calculated according to Equation (1).

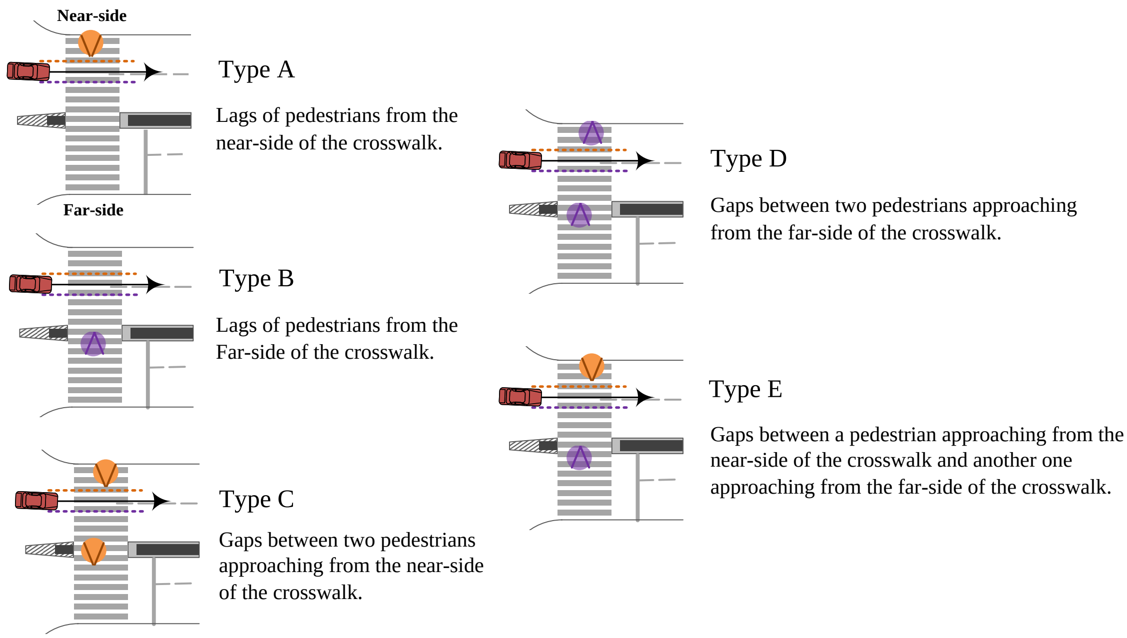


Figure 2 Assumed types of lags/gaps

$$P(x)_{i,j} = \frac{No.\ of\ observed\ accepted\ gaps/lags_{i,j}}{No.\ of\ observed\ accepted\ and\ rejected\ gaps/lags_{i,j}} \quad (in\ bin\ i\ of\ Type\ j) \tag{1}$$

Various functions are used in the literature to present different gap acceptance conditions such as Logistic (Agrestic, 2007) and Probit regression approaches. Mathematically, in Logit and Probit models, a positive value of acceptance probability can be estimated at zero second lag/gap. This is one of the main disadvantages of using this type of models. To overcome this problem, Cumulative Weibull distribution is used in this study to fit the observed lag/gap acceptance probability distributions. The Weibull distribution is a widely used lifetime distribution in reliability engineering (Abernethy, 2004). It is a versatile distribution that can take on the characteristics of other types of distributions based on the values of its parameters. Thus it can be used to model a variety of life behavior (Abernethy, 2004). Moreover, Weibull distribution is a widely used function to represent the breakdown probability in traffic flows on highways and expressways. Equation (2) presents the Cumulative Weibull distribution function with two parameters; the scale parameter α and the shape parameter β.

$$P(x) = 1 - e^{-(x/\alpha)^{\beta}} \tag{2}$$

Where $P(x)$ is the acceptance probability of lag/gap x; α and β are Weibull distribution parameters.

Table 1 Geometry characteristics of observation sites

Intersection	Left-turners entering approach	Corner Radius R_c (*m*)	Intersection corner angle θ (*deg*)	Downstream crosswalk setback distance D_s (*m*)	Downstream crosswalk Width(*m*) * Length(*m*)	No of exit (outflow) lanes N_o
Suemori-dori	East	9.7	88.3	6.5	7.3 * 18.5	2
	West	19.0	65.4	16.5	7.7 * 18.0	2
	North	17.0	117.0	11.0	6.7 * 25.4	3
Taiko-dori	West	17.0	94.1	16.0	6.7 * 15.4	3
Horita	East	14.0	94.1	5.0	5.3 * 37.5	3
	South	12.0	88.3	14.0	5.9 * 20.8	3
Hiroji-dori	West	5.0	95.0	2.0	6.7 * 9.4	2
Imaike	North	16.0	79.0	16.5	4.7 * 20.3	3
Nishiosu	East	17.0	76.9	17.0	4.6 * 35.1	3
Kawana	East	21.0	106	22.5	6.2 * 14.8	2
Aoyama	North	11.5	92.0	7.6	6.2 * 25.5	4
	West	12.0	90.0	7.8	6.3 * 18.0	3

STUDY SITES AND DATA OBSERVATION

Study Sites

Since empirical observation is essential to study the lag/gap acceptance behavior, video data was collected at several signalized intersections under various pedestrian and vehicle traffic conditions. Twelve approaches at eight signalized intersections were videotaped. All these sites are in Nagoya City except Aoyama Intersection which is located in Tokyo. Table 1 presents geometric characteristics of the observed sites. Definitions of the parameters in Table 1 are illustrated in Figure 3. The observation sites have significantly different geometric layouts such as curb radii, intersection corner angles and crosswalk setback distances. Furthermore, one shared left-through lane exists at each site. However due to the big size of the intersection, overtaking while turning or double turning is observed. All these cases are excluded in data processing.

It is important to mention that all sites have a shared left turn-through phase while turn left on red is prohibited. At all observed sites pedestrians share the same signal phase with the through and left turning traffic of the same direction. Thus left-turning traffic has frequent conflicts with crossing pedestrians depending on the demand and the arrival pattern of each of them.

The average demands of left-turning vehicles, pedestrians and cyclists during the observation periods are presented in Table 2. Pedestrian and left-turning vehicle demands are quite high at Suemori-dori and Nishiosu Intersections. Furthermore, according to observations, the share of heavy vehicles is low at all sites. Imaike Intersection has the heaviest pedestrian and cyclist demand while most of the other sites have low to medium pedestrian and cyclist demands.

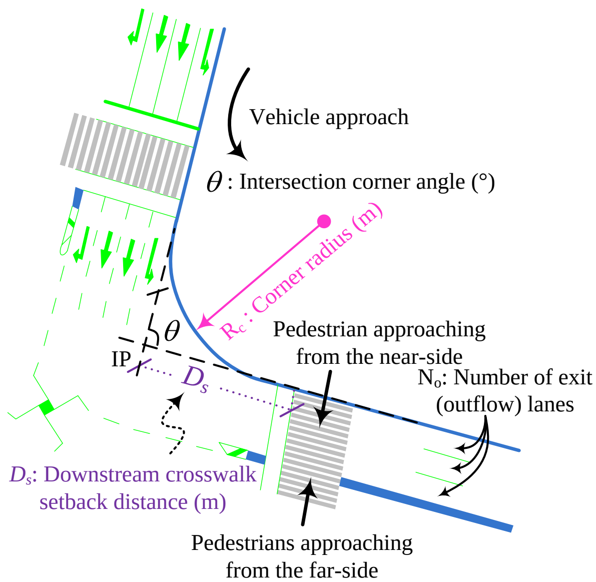


Figure 3 Definition of the parameters related to intersection layout

Table 2 Traffic conditions at observation sites

Intersection	Left-turners entering approach	Survey time	Average left-turning vehicle demand (*veh/hr*)		Average pedestrian/Cyclist demand (*ped.* or *cyc./hr*)			
					Near-side		Far-side	
			PC*	HV*	Ped.	Cyc.	Ped.	Cyc.
Suemori-dori	East	9:00-12:00	312	6	28	60	28	28
	West		204	8	16	32	64	52
	North		304	9	8	32	12	36
Taiko-dori	West	7:30-10:30	84	–	73	20	50	19
Horita	East	9:00-10:30	84	11	20	64	172	76
	South		28	5	20	36	128	36
Hiroji-dori	West	7:00-10:00	156	10	81	146	60	90
Imaike	North	13:00-15:00	146	7	145	120	104	81
Nishiosu	East	9:00-12:00	344	14	20	76	20	44
Kawana	East	7:30-10:30	208	2	20	52	108	28
Aoyama	North	9:00-12:00	124	6	50	32	29	11
	West		142	11	60	75	20	15

* PC means passenger car while HV means heavy vehicle.

Trajectory Tracking

Trajectories of left-turning vehicles as well as pedestrians including the positions and timings are extracted from video data by using video image processing system *TrafficAnalyzer* (Suzuki and Nakamura, 2006). The positions were extracted every 0.5 second and then their video coordinates are converted to the global coordinates by projective transformation. The point

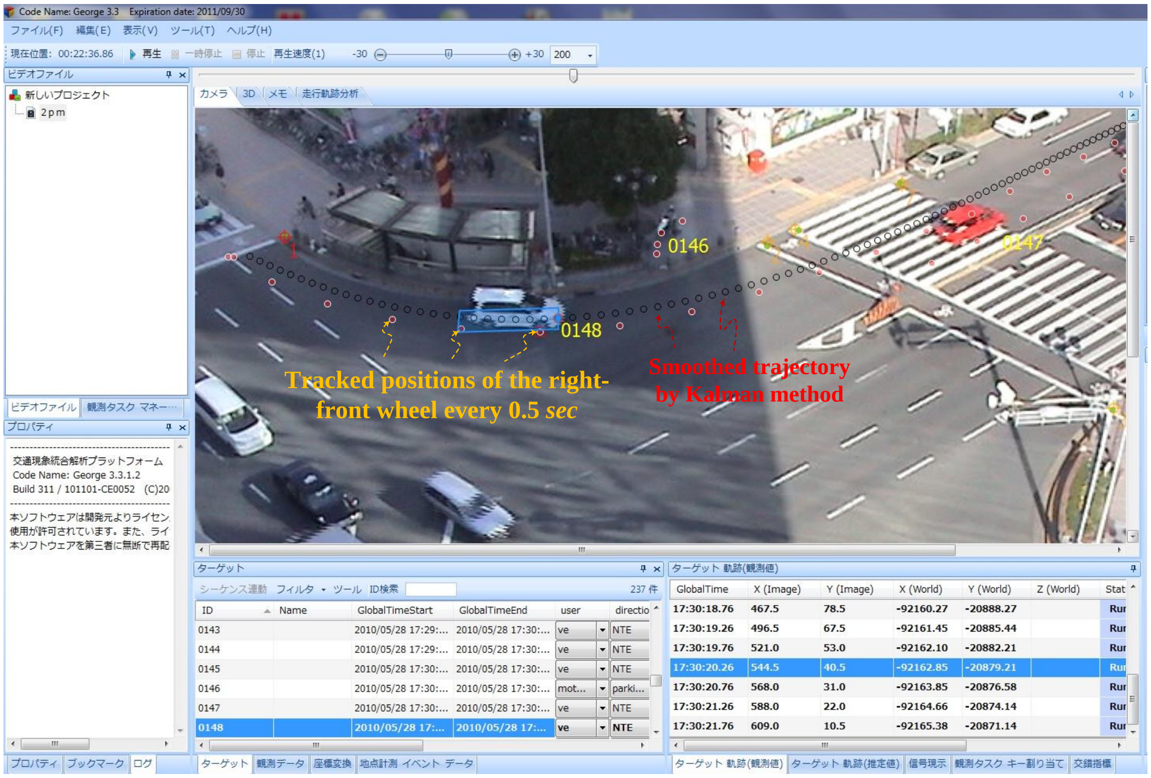


Figure 4 A picture of the image processing system TrafficAnalyzer

where the right-front wheel is touching the ground is the reference observation point for all left-turning vehicles as shown in Figure 4. All video observations were done from high buildings around the intersections, thus for all video tapes, the observation angle is large enough to allow us to track the right-front wheel of turning vehicles without facing any problems. By considering the dimension of each turning vehicle, the observed trajectories based on the right-front wheel are transformed to the trajectories which correspond to the center-front of the vehicles. The transformed trajectories may contain measurement errors due to manual tracking, oscillation of installed camera and so on. Kalman filter technique is used for correcting these measurement errors. This method simultaneously estimates the optimal values of position, velocity and acceleration of the vehicles, while taking into account the physical relationship among these variables and the accuracy of the measurement.

Figure 4 is a picture of the image processing system *TrafficAnalyzer* where the tracked and smoothed trajectories are shown. Regarding pedestrians, the center point of their body is considered as the reference observation point. Furthermore, pedestrians are tracked from the sidewalk when they are approaching to the crosswalk till they finish the whole crossing process.

Data Processing

In order to extract accepted and rejected lags/gaps, there is a very important question; where or when left-turners decide to accept or to reject an available lag/gap. Such a decision point is not

Table 3 Extracted data for each type of lag/gap

Intersection	Approach	Type A		Type B		Type C		Type D		Type E	
		A*	R**	A*	R**	A*	R**	A*	R**	A*	R**
Suemori-dori	East	5	0	10	4	0	0	0	1	0	0
	North	16	14	18	12	13	8	11	13	12	7
	West	15	20	10	18	12	10	14	19	8	5
Taikodori	West	4	20	6	12	4	6	5	2	5	7
Horita	East	9	2	20	4	0	2	6	1	5	0
	South	0	0	4	3	0	0	0	1	0	0
Hirojidori	West	1	4	3	17	0	0	1	3	0	3
Imaike	North	2	14	8	17	5	46	5	58	10	66
Nishiosu	West	6	4	25	18	4	20	5	37	8	30
Kawana	West	0	2	0	0	2	0	2	6	4	6
Aoyama	North	1	0	15	16	0	0	1	13	0	0
	West	5	0	12	16	0	0	3	11	0	0
Total		64	80	131	137	40	92	53	165	52	124

* Accepted lags/gaps. ** Rejected lags/gaps.

fixed but it is distributed depending on driver behavior, visibility, pedestrian direction of movement and speed. Since a precise determination of this decision point is very difficult, it is assumed that the decision point is when the drivers reach the crosswalk. For a yielding vehicle that faces pedestrians but does not encounter any stop, an accepted gap or lag is extracted when the vehicle reaches the conflict area. On the other hand, if the yielding vehicle stops because of the crossing pedestrians, accepted and rejected lags/gaps are extracted after the vehicle stops near the crosswalk as shown in Figure 1a). Authors are aware that this procedure neglects possible rejected lags/gaps by yielding vehicles who adjusted their speed to avoid the rejected lags/gaps so they can meet the accepted ones without stopping. However for such cases it is very difficult to define a rational decision point where can be said that at that point drivers decide to reject existing lags/gaps and adjust their speed.

Furthermore, following left-turning vehicles are not considered in the data processing. Leading left-turning vehicles are defined as the vehicles that did not face any other vehicles while turning from the stop line of the entering approach to the downstream crosswalk at the exit approach. Moreover since the demand of heavy vehicles is very low at all observation sites, it is not possible to consider the effect of vehicle type in the lag/gap acceptance analysis. Although, this factor is an important issue which needs to be considered in the future. Table 3 shows the number of extracted lags/gaps for each type from each observation site. Lags/gaps are measured as a continuous parameter with a precision of 0.1 *sec*.

LAG/GAP ACCEPTANCE PROBABILITY DISTRIBUTIONS

As mentioned in the methodology, observed lags/gaps of each type are divided into several bins of 1.0 *sec* size. By using the number of observed accepted and rejected lags/gaps (Table 3), the acceptance probability can be calculated through Equation (1). The plots of the observed acceptance probabilities in these bins are shown in Figure 5. The number of plots in Figure 5

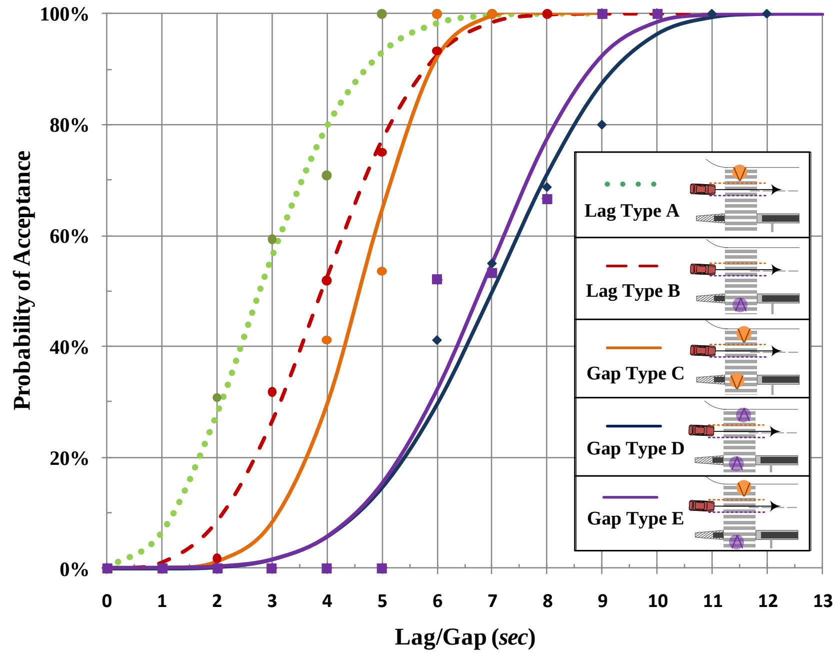


Figure 5 Observed gaps/lags acceptance probabilities and fitted Cumulative Weibull distributions

Table 4 Parameters of the fitted lag/gap acceptance probability distributions

Lag/Gap Type	Weibull Distribution Parameters α (scale) & β (shape)	Estimate	Standard Error	Adjusted R^2	Sample Size
A	α	3.269	0.169	0.977	144
	β	2.292	0.391		
B	α	4.405	0.092	0.993	268
	β	3.076	0.269		
C	α	4.966	0.183	0.959	132
	β	4.884	1.147		
D	α	7.615	0.200	0.968	218
	β	4.388	0.667		
E	α	7.346	0.268	0.934	176
	β	4.683	1.057		

does not represent the sample size for each distribution. Each point is estimated using Equation (1), where the number of observed accepted lags/gaps within the bin range of that point is divided by the total number of observed accepted and rejected lags/gaps within the same bin range. Cumulative Weibull distribution function is used to fit these plots using non-linear least-squares estimation. The parameters of the fitted distributions are listed in Table 4. The sample size of each distribution in Figure 5 is presented in Table 4.

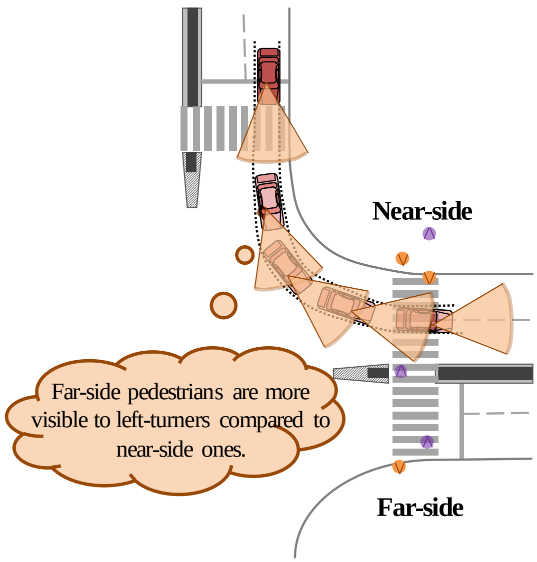


Figure 6 Illustration of the visibility of near-side and far-side pedestrians to left-turning vehicles

As shown in Figure 5, lags/gaps between pedestrians from the near-side have significantly higher (t-test) acceptance probability compared to the corresponding lags/gaps between far-side pedestrians (95% confidence level). This can be referred to the lower visibility of the pedestrians coming from the near-side as shown in Figure 6, therefore drivers may notice the approaching pedestrians in a late stage where they prefer to accelerate and cross before the approaching pedestrian reaches the conflict area rather than stopping with a high deceleration rate. Moreover, due to vehicle body and the position of near-side pedestrians in relative to the driver's line of sight (Figure 6), it is difficult for drivers to estimate the size of the available lag/gap which may make drivers take risky decisions by accepting short lags/gaps. One of the possible reasons could also be that drivers give attention mainly to pedestrians who are in the crosswalk. Since the part of the crosswalk to the left-side of the vehicle is generally shorter in left-hand traffic, it is likely that in short gaps or lags pedestrians are very close to the crosswalk but still did not start crossing. In this case drivers may not be sure if those pedestrians will cross or just stay in the sidewalk which encourages them to accept short lags/gaps.

For the same reasons mentioned before, gaps between near-side pedestrians (Type C) have significantly higher acceptance probability compared to gaps of Type D and E as shown in Figure 5.

As shown in Figure 5, lags (Type A and B) have always significantly higher (t-test) acceptance probability compared to gaps (Type C, D, and E) at 95% confidence level. Basically, as pedestrian demand increases the probability that a left-turner will face a lag with individual pedestrian reduces while the probability of facing gaps between pedestrians increases. As shown in Table 2 and Table 3, most of the observed lags are at the intersections with relatively low pedestrian demand (such as the north and west approaches of Suemori-dori Intersection and the west approach of Nishi-Osu Intersection). In such condition, drivers pay less attention to the

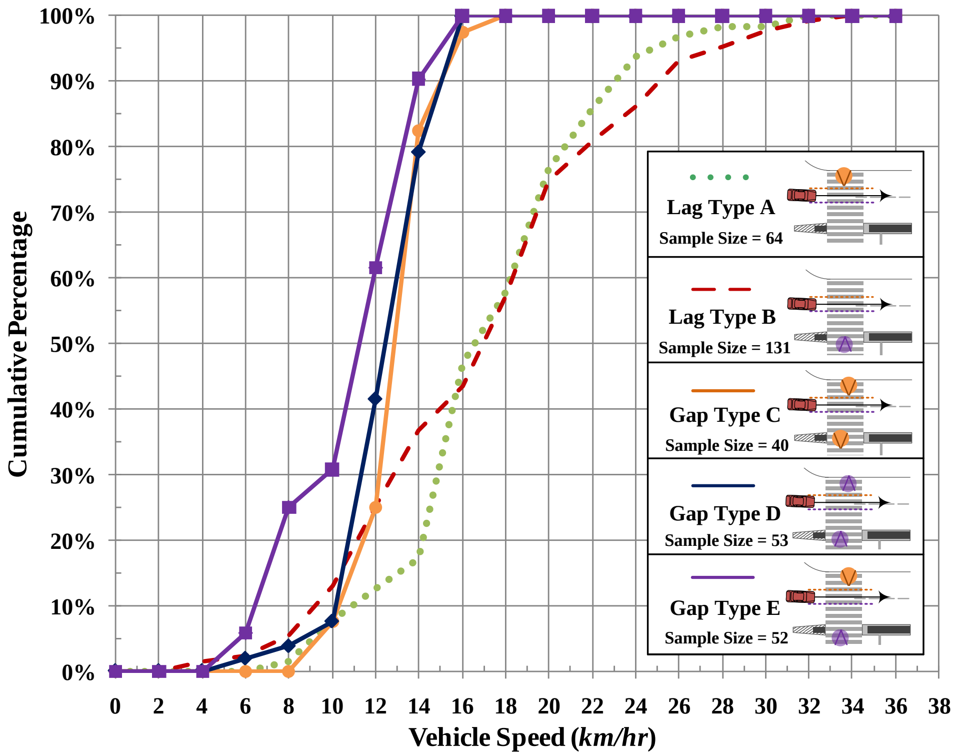


Figure 7 Cumulative distributions of observed vehicle clearing speeds v_c at the conflict points for different types of accepted lags/gaps

crossing pedestrians which explains why they tend to take risky decisions by accepting short lags. However if the number of crossing pedestrians increases, drivers become more conservative in accepting short gaps in order to avoid collision risk, since the prediction of pedestrian movements becomes much more difficult.

Vehicle Speeds at the Conflict Points

Several previous studies found that vehicle speed when a crash occurs (crash speed) significantly contributes to the severity of that crash. Kloeden et al. (2001) concluded that the risk of involvement in a casualty crash increases more than exponentially with increasing free travelling speed above the mean traffic speed in rural roads. It is reasonable to use the speed of the vehicle at the conflict point (clearing speed) as an indicator for the severity of the conflict, assuming that the clearing speed would be very close to the crash speed if the conflict becomes a real crash.

The cumulative distributions of observed vehicle clearing speeds v_c for the five types of lags/gaps are shown in Figure 7. The clearing speed is defined as the measured vehicle speed at the conflict point (Figure 1b) after accepting a specific lag/gap, thus the sample sizes of observed speeds are equal to the number of observed accepted lags/gaps shown in Table 3. Vehicle clearing speed is measured as a continuous parameter with a precision of 0.1 *km/hr*. The cumulative distributions shown in Figure 7 are developed by dividing the clearing speeds into bins of 2.0 *km/hr* size due to the limited sample size. Each plot in Figure 7 is estimated by dividing the number of observed clearing speeds of the accepted lags/gaps within the bin range of that point to the total number of observed clearing speeds of the same type of lag/gap.

Keeping in mind that vehicles tend to accept shorter lags of Type A and B compare to gaps of Type C, D and E, Figure 7 shows clearly that clearing speeds v_c are significantly higher (t-test) when vehicles accept lags with individual pedestrians (Type A and B) at 95% confidence level. Since most of the observed lags are at intersections with low pedestrian demand, it is reasonable to conclude that conflicts with individual pedestrians are more severe, or in other words pedestrian-vehicle conflicts are more severe when pedestrian demand is low. In such condition, drivers might not expect to meet pedestrians while clearing the intersection, thus they do not give sufficient attention to pedestrians and they tend to keep higher speeds while turning.

The clearing speed v_c distributions for accepted lags of Type A and Type B are not significantly different at 95% confidence level while the clearing speed distribution for gaps of Type E is significantly different (shifted to the left) from all other distributions. This indicated that drivers are most careful when they meet pedestrians coming from both sides of the crosswalk (Type E), therefore they tend to accept long gaps (Figure 5) and they tend to significantly reduce their speeds which result in lower clearing speeds v_c (Figure 7).

CONCLUSIONS

Through this study, the acceptance of lags/gaps between pedestrians by left-turners (left-hand traffic) considering the direction of pedestrian movement at signalized crosswalks was analyzed. Generally, it is concluded that the direction of pedestrian movement significantly affects the lag/gap acceptance behavior of left-turners. Empirical lag/gap acceptance models that consider pedestrian direction of movement were proposed. Lags/gaps between crossing pedestrians were classified into five types depending on the direction of pedestrian movement. Cumulative Weibull distribution was used to fit the observed lag/gap acceptance probability distributions. It is concluded that lags/gaps between near-side pedestrians have significantly higher (t-test, 95% confidence level) acceptance probability compared to those between far-side pedestrians. This might be referred to the lower visibility of near-side pedestrians and their relative position to the driver's line of sight while turning, whereas far-side pedestrians can be easily seen by left-turners.

Moreover, through this study it is concluded that drivers tend to accept short lags with individual pedestrians while being conservative about short gaps between several pedestrians. This clearly shows that drivers give more attention as the number of crossing pedestrians increases.

Further, it is found that the clearing speed v_c of left-turning vehicles significantly depends on the number of crossing pedestrians. Vehicles clear the conflict area with significantly higher speeds v_c when they accept lags with individual pedestrians. This indicates that conflicts with individual pedestrians are more severe. Simultaneously, drivers are most careful when they meet pedestrians coming from both sides of the crosswalk, which explains why they tend to accept long gaps only and why they tend to reduce their speeds significantly.

Further analysis on the effects of vehicle type, various crossing treatments and other specific conditions such as overtaking other vehicles while turning on the lag/gap acceptance and vehicle speed is necessary. Moreover, for more detailed information on driver behavior while passing the intersection which is not possible to get from video surveillance, using in-car video equipment would be a possible approach.

The developed lag/gap acceptance models are originally intended to be incorporated into an algorithm to reproduce the vehicle maneuver and its variations inside a microscopic simulation environment which is designed for the safety assessment of signalized intersections. This microscopic simulation model would allow practitioners to evaluate the effects of certain improvements in the geometric layouts and operations of signalized intersections on the overall safety performance. For instance, it would be possible to predict the impacts of adding channelization or adjusting the positions of crosswalks or intersection corner radii. And it can further be applied to modify the signal timing parameters such as all-red intervals.

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REFERENCES

Abernethy, R.B. (2004). The New Weibull Handbook, Fifth Edition. ISBN 0-9653062-3-2

Agrestic, Alan. (2007). An Introduction to Categorical Data Analysis, Second Edition. John Wiley & Sons Inc., Hoboken, New Jersey, USA.

Asano, M., Alhajyaseen, W. K. M., Suzuki, K. and Nakamura, H. (2011). Modeling Variation in the Trajectory of Left-Turning Vehicles Considering Intersection Geometry, Presented at the 90th Transportation Research Board Annual Meeting, Washington, D.C., USA.

Ben-Akiva, M. and Lerman, S. R. (1985). Discrete Choice Analysis: Theory and Application to Travel Demand. Page 70.The MIT Press, Cambridge/Massachusetts, USA.

Cassidy, J. M., Madanat, S. M., Wang, M., and Yang, F. (1995). Unsignalized Intersection Capacity and Level of Service: Revisiting Critical Gap. Transportation Research Record 1484, TRB, National Research Council, Washington, D. C., pp. 16-23

Chen, X., Shao, C. and Yue, H. (2008). Influence of Pedestrian Traffic on Capacity of Right-Turn Movements at Signalized Intersections. Presented at the 87th Transportation Research Board TRB Annual Meeting, Washington, D.C., USA.

Deutsches Institut für Wistschaftsforschung (DIW) (2010). Verkehr in Zahlen 2010, Der Bundesminister für Verkehr. (in German)

Federal Highway Administration (FHWA) (2004). NGSIM Task E.1: Core Algorithm Assessment. Publication No. FHWA-HOP-06-0009. Department of Transportation, Washington, DC., USA.

Geruschat, D. and Hassan, S. (2005). Driver Behavior in Yielding to Sighted and Blind Pedestrians at Roundabouts. In Journal of Visual Impairment and Blindness. Volume 99, Number 5.

Kloeden CN, Ponte G and McLean AJ. (2001). Travelling Speed and the Risk of Crash Involvement on Rural Roads. Road Accident Research Unit, Adelaide University. Report No. CR 204, ISBN 0 642 25568 7.

Madanat, S. M., Cassidy, M. J., and Wang, M. (1994). Probabilistic Delay Model At Stop-Controlled Intersection. Journal of Transportation Engineering. ASCE, 120(1). January/February, pp. 21-36.

Mahmassani, H., and Sheffi, Y. (1981). Using Gap Sequences to Estimate Gap Acceptance Functions, Transportation Research 15B, pp. 143-148.

National Police Agency, Japan. (2010). Fatal traffic accidents in 2009. http://www.npa.go.jp/toukei/kouki/0102_H21dead.pdf (in Japanese).

Schroeder, B.J. and, Rouphail, N.M. (2010). Event-Based Modeling of Driver Yielding Behavior at Unsignalized Crosswalks. Accepted for Publication by the ASCE Journal of Transportation Engineering. American Society for Civil Engineers. In Press

Sun, D., Satish, U., Benekohal, R. and Waller, S.T. (2003). Modeling of Motorist-Pedestrian Interaction at Uncontrolled Mid-Block Crosswalks. Presented at the 82nd Transportation Research Board TRB Annual Meeting, Washington, D.C., USA.

Suzuki, K. and Nakamura, H. (2006). TrafficAnalyzer - The Integrated Video Image Processing System for Traffic Flow Analysis. Proceedings of the 13th World Congress on Intelligent Transportation Systems, 8 pages in CD-ROM, London.

Troutbeck, R. J., and W. Brilon. (2002). Unsignalized intersection theory. Chapter 8 In: N. H. Gartner, C. J. Messer, and A. Rathi, eds. Traffic Flow Theory. Transportation Research Board Special Report. Available at http://www.tfhrc.gov/its/tft/tft.htm.

Viney, N. D., and Pretty, R. L. (1982). Saturation Flow of a Movement Subject to a Pedestrian Stream at Traffic Signals. Proceedings - Conference of the Australian Road Research Board, Vol. 11, pp. 157–166.