A Microscopic Traffic Simulation Model for Safety Assessment of Left-turning Vehicle versus Pedestrian Conflict at Signalized Intersections

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The frequent conflict between left-turning vehicles and pedestrians needs special attention in the context of safety evaluation and improvement of signalized intersection. This study, as part of intensive efforts to develop a microscopic traffic simulation model for safety assessment at signalized intersections, helps demonstrate how the simulation as an innovative approach can be utilized for vehicle-pedestrian conflict assessment on crosswalks prior to implementation. Based on the field data collected by video cameras at a number of signalized intersections, road user behavior models, such as left-turning path, left-turning speed, pedestrian gap acceptance model, pedestrian path, pedestrian speed and so on, have been established and integrated into simulation. The typical feature of these empirical models is that they consider the stochastic behavior of road users under various layouts and operations of signalized intersections. It is demonstrated through validation that the simulation model can reasonably represent the conflict occurrence at signalized crosswalks.

Key Words: *microscopic simulation, signalized intersection, pedestrian, left-turning vehicle, traffic conflict, safety assessment*

1. INTRODUCTION

Signalized intersections are the most critical element in transportation network. Their operations considerably affect the performance of the whole road system. Road users of different types, from various directions and moving at different speeds have to use the same space, resulting in a large number of potential conflicts.

Various operational policies and design layouts have been implemented at signalized intersections. It is no doubt that they possess benefits as well as drawbacks in terms of reliability and efficiency. So far, the reactive strategies for the purpose of safety improvement have been primarily based on identifying sites with high crash rates. It is subject to fewer crash records or validity losing due to changes of road system and operation. However, a reliable tool which can quantitatively evaluate traffic safety prior to facility implementation is not available yet.

On the other hand, simulation provides a flexible and promising approach to enable a preventive strategy development. However, existing simulation models are mainly developed for the purpose of operational performance evaluation. Thus, crucial characteristics of road user behavior, such as path, speed and their stochasticity and sensitivity to intersection layout and operation have not been well represented in these existing simulation models, which prevents from achieving a reliable safety evaluation[1].

This study, as part of intensive efforts to develop a microscopic simulation model for safety assessment at signalized intersections[2], helps demonstrate how the simulation as an innovative approach can be utilized for left-turning vehicle (left-hand traffic system) versus pedestrian conflict assessment. It allows practitioners to evaluate the effects of various improvements in the geometric layouts and operations of crosswalks at signalized intersections prior to implementation.

The remainder of the paper is organized as follows. After the literature review, a comprehensive discussion upon the requirements of a reliable simulation model for safety assessment is presented. The key behavioral models are then summarized in the case of the conflict between left-turning vehicles and pedestrians at signalized intersections. The mechanisms of vehicle-pedestrian conflict occurrence are explained by integrating various behavioral models. Next, the validation of user behavior is conducted by simulation. Finally, it ends up with conclusions and future works.

2. LITERATURE REVIEW

Commonly, the safety of traffic facilities can be measured by the number of crashes, crash types and crash severity. Previous studies[3)4)5)6)] have focused on the establishment of safety performance functions in relation to the historical crash data. However, the major limitation is that a large amount of data, e.g., crash records, traffic volume and roadway physical characteristics, are required in order to obtain statistically significant results. Furthermore, the aggregated measurements of total crashes prevent from making an accurate prediction of crashes under different intersection layouts and operations as well as dynamic change in traffic conditions and road user behavior.

Microscopic simulations are regarded as effective tools to overcome the shortcomings of empirical crash analysis. They can represent various conflicts and help conduct safety assessment at the planning stage of road facility. However, existing simulation models are mainly developed for the operational performance evaluation of traffic flow. Many crucial models for representing the movements of road users inside signalized intersections, e.g., variations in turning paths and speed as well as reaction to signal operation, geometric layout and conflicting traffic flow are missing[7]. Thus, using these tools to assess the safety of signalized intersections is questionable or even not rational.

Gettman and Head[1] investigated surrogate safety measures that were obtained from the existing microscopic simulation tools. They listed several requirements for the simulations to fulfill in order to obtain reliable safety measures, which have not yet been achieved by existing simulation tools. Archer[8] conducted a more detailed analysis of the opportunities and shortcomings of microscopic simulations for assessments. It concluded that crucial behavior, including the speed of vehicles around intersections and yielding decisions to other users, is not yet realistically represented in existing simulations. These kinds of behavior are affected by geometric layout and the surrounding user behavior.

To sum up, the existing simulation models cannot fulfill the requirements to conduct safety assessment of signalized intersections. This study aims to develop a simulation model for safety assessment at signalized intersections. The concerned conflict is between left-turning vehicles and pedestrians on crosswalks.

3. SCOPE AND ASSUMPTIONS

The safety analysis by the proposed simulation model is mainly based on the traffic conflict technique (TCT). A traffic conflict is defined as a situation in which two or more road users approach each other in space and time to such an extent that there is risk of collision if their movements remain unchanged. The safety level can be presented by the frequency and the severity of these conflicts.

In the case of the conflict between left-turning vehicles and pedestrians, the behavior of both road users are assumed to be affected by geometric layout and the operation of intersections. For safety assessment, surrogate safety measure (SSM) is employed to represent their conflicts and further relate to crash risk estimation. Their relationship is illustrated in **Fig.1**. Note that, after conducting empirical modeling and analysis, simulation approach is then applied to analyze the conflict between left-turning vehicles and pedestrians under various geometric layout and operational conditions. Moreover, the ability of crash risk estimation model can be further highlighted based on extracted SSMs from simulation results. It also supports safety assessment even prior to facility implementation.

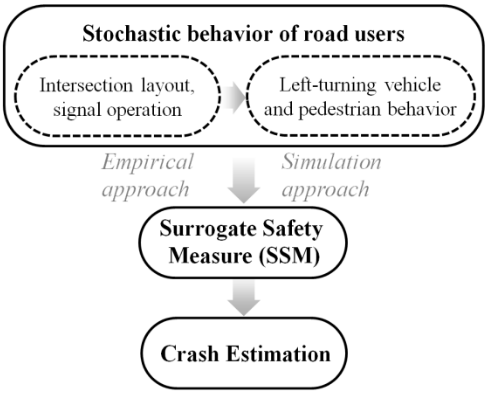


Fig.1 The flowchart of this study

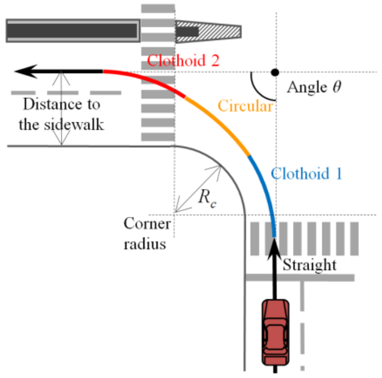


Fig.3 Path model for left-turning vehicles

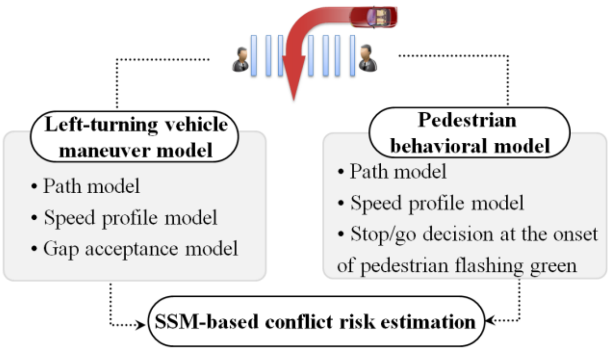


Fig.2 Basic models to be incorporated in the simulation

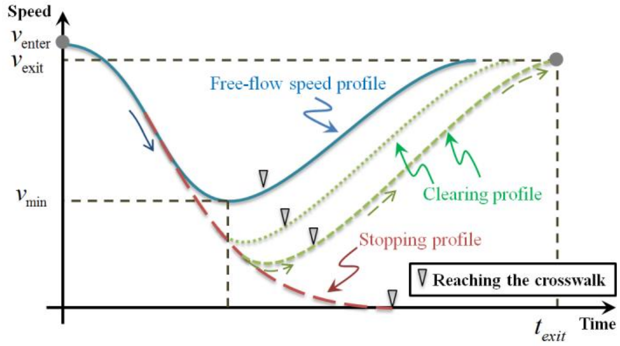


Fig.4 Free-flow, clearing and stopping speed profiles

4. MODEL DEVELOPMENT

As shown in **Fig.2**, the necessary models to present the conflict between left-turning vehicles and pedestrians can be classified into three main groups: left-turning vehicle maneuver model, pedestrian behavioral model, the SSM-based conflict risk estimation. The brief introduction of each model is given as follows.

(1) Left-turning vehicle maneuver model

As shown in **Fig.2**, the necessary models to present left-turning vehicle behavior at signalized intersections include path model, speed profile model and gap acceptance model. In general, the trajectory of a vehicle consists of two components, paths and speed profiles. They represent the movement of the vehicle at each moment inside the intersection.

In this study, the path and free-flow speed profile models are built to represent the distribution of vehicle turning paths and speeds as a function of intersection geometry. Alhajyaseen et al.[9] and Asano et al.[10] developed models that can stochastically reproduce the paths of left-turning vehicles at signalized intersections. These models are based on approximating the path of individual vehicles by using a combination of Euler spiral and Circular curves as shown in **Fig.3**. The parameters of the approximated paths are empirically modeled as a function of intersection geometries (e.g., angle and corner radius), vehicle speeds and vehicle types.

However, left-turning vehicles may change their free-flow trajectories as their reaction to conflicting pedestrians on crosswalk. The dynamic process is illustrated in **Fig.4**.

When a left-turning vehicle enters the intersection, it follows free-flow speed profile if getting no effect from surrounding conditions. When pedestrians exist at crosswalk, they will check the available lags/gaps[12] between pedestrians to anticipate when the vehicles are supposed to arrive at the crosswalk under the current intended free-flow speed profile. They make a decision whether to proceed or yield according to the lag/gap acceptance model. This anticipation and decision process is updated dynamically at every Δt interval. If they reject the existing lags/gaps, they yield by preparing to stop and follow the stopping speed profile. In the following time intervals, if drivers decided to accept a lag/gap, they switch from the stopping speed profile to the clearing speed profile for acceleration.

All of these models are empirically estimated based on observed data as probabilistic functions of intersection geometries (e.g., corner radius, intersection angle and crosswalk setback distance). The influencing factors of each model were proved to be statistically significant.

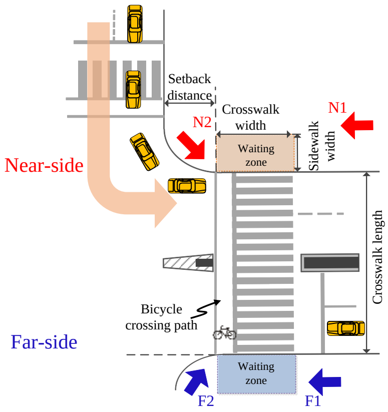


Fig.5 Definition of crosswalk geometry and Pedestrian OD movement

(2) Pedestrian behavioral model

Pedestrian behavior on crosswalk also plays an important role in the conflicts with left-turning vehicles. In the simulation environment, the key models to represent the movement of pedestrians include path model, speed profile model and stop/go decision model at the onset of pedestrian flashing green (PFG), as shown in **Fig.2**.

It is assumed that the changes in pedestrian trajectory are mild and pedestrians change their walking directions only after passing near-side, middle and far-side cross-sections of the crosswalk. Near-side means the side where pedestrians and exiting turning vehicles have potential conflict, whereas far-side is the opposite side as shown in **Fig.5**. Pedestrian movements are assumed to have their origins and destinations at either the near-side or the far-side of the crosswalk.

Fig.6 shows 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. All of them are measured as the perpendicular distance from the edge of bicycle crossing path. It is assumed that individual pedestrian determines his/her next cross-section position when passing the current cross-section. For example, a pedestrian moves from near-side to far-side as shown in **Fig.6**. 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. Weibull distribution is adopted to model three cross-section passing positions as a function of intersection geometry, pedestrian OD movement, previous passing position and the density of other road users along the crosswalk.

Note that with comparison to left-turning vehicle behavior, pedestrians need to react to the signal of PFG[13]. In essence, PFG is provided as a clearance time interval for pedestrians to safely finish passing

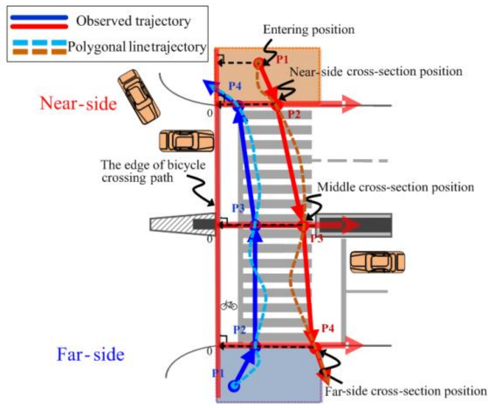


Fig.6 Definition of cross-section passing positions

the crosswalk before the end of pedestrian green indication. It is assumed that the pedestrians approaching the crosswalk during PFG decide to go or stop at the onset of PFG. This assumption indicates that pedestrians do not make their decision until they reach the crosswalk edge but do further upstream. Pedestrians are also assumed to adjust their speeds after PFG. Apparently, pedestrians who choose to go at the onset of PFG tend to have significantly higher walking speed than those who choose to stop.

By incorporating the aforementioned models, stochastic vehicle and pedestrian behavior can be represented inside the simulation, which offers a good basis for safety assessment.

(3) SSM-based conflict risk estimation

SSM serves as near-crash indicators to measure spatial and temporal proximity of road users. A variety of SSMs have been proposed and discussed as in Gettman and Head[1]. However, there are still few applications of SSM on pedestrian-vehicle conflict assessment and a lack of knowledge on converting SSM into crash frequency[14]. This study gains insights into these two issues in the case of conflicts between left-turning vehicles and pedestrians at signalized crosswalks.

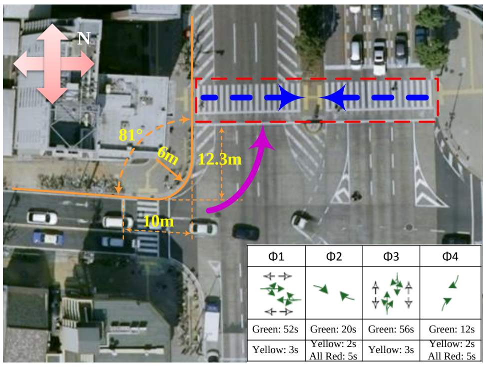
Based on the field data collected by video cameras on nine crosswalks at signalized intersections in Nagoya City, Post-Encroachment Time[15] (PET) and vehicle passing speed at conflict point[4] are extracted. The representative statistics, e.g., mean PET, the number of short PETs per hour and average vehicle passing speed at conflict point on each crosswalk are selected as candidate SSMs. Their effectiveness to reflect the impact of site-specific geometric characteristics and operational conditions on conflict risk is examined based on field data. Furthermore, by referring to the crash records of pedestrians versus left-turning vehicles at observed sites (from 2007 to 2010) according to Nagoya National Highway Office, crash risk estimation models are developed by using Poisson regression methods[16]. It shows that high turning speed, in conjunction with higher frequency of short PETs result in higher crash rates.

5. SIMULATION VALIDATION

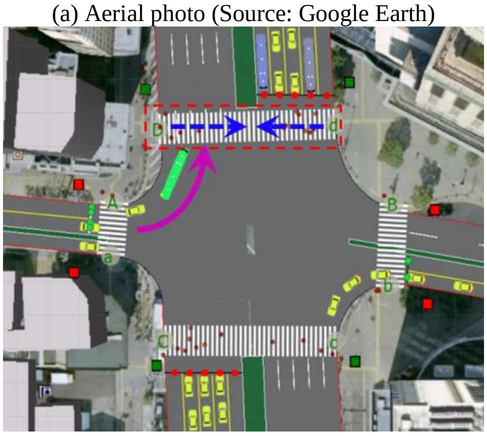
The following section focuses on the validation of the simulation model after incorporating various sub-models. The purpose of validation is to check whether the simulation model is able to reasonably represent the road user behavior at signalized intersections. Since the developed simulation is intended for safety assessment, the validation concentrates on inspecting the aspects of safety performance and comparing the conflicts which are identified by the simulation model to the observed conflicts at the same traffic systems.

(1) Site description

The North crosswalk of Kanayama intersection with long crosswalk length and heavy traffic demands is chosen as a study site. The characteristics of the site are shown in **Fig.7(a)**. The concerned conflict is between left-turning vehicles from the west approach and pedestrians at the north crosswalk as shown in **Fig.7(b)**.



(a) Aerial photo (Source: Google Earth)



(b) Simulation scenario

Fig.7 The characteristics of Kanayama intersection

(2) Model validation

a) Left-turning vehicle maneuver model

To verify the performance of the path model for left-turning vehicles, **Fig.8** compares the distributions of observed and simulated paths of left-turning vehicles at the west approach of kanayama Intersection. The lateral path density distribution and the lateral cumulative distribution at three cross-sections along the turning paths are presented in **Fig.8**. According to two-sample t-test for difference of means (unequal variances), the distributions of simulated and observed paths are found to have the same tendency at the 95% confidence interval. The difference is mainly referred to the assumption that the exiting position of the vehicles is in the centerline of the lane whereas observations show that the exit positions are distributed to some extent throughout each exit lane. This assumption affects the parameters of the estimated paths. Thus in future, the incorporation of a lateral exit position model in the simulation will help improve the distribution of estimated paths.

Furthermore, the speed profiles of free-flow, stopping and yielding left-turning vehicles are presented in **Fig.9**. Stopping and yielding profiles reflect the interaction with pedestrians. Generally, generated speed profiles by simulation are found reasonable.

b) Pedestrian behavioral model

Fig.10 shows the distribution of observed and simulated pedestrian trajectories from N2 to F2 at Kanayama North crosswalk. No significant difference is found for the passing positions at the three representative cross-sections according to two sample t-tests for difference of means (unequal variances) at the 95% confidence level. However, the distributions of simulated paths agree with the observed ones better at the middle and far-side cross-sections than those 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, pedestrians walk around the waiting zone during red phase. For example, the near-side (N2) incoming pedestrians walk a certain distance from the edge of bicycle crossing path and then enter the crosswalk during PG. However, such behavior has not been considered in the simulation.

As for pedestrian speed validation, **Fig.11** gives an example of the first-half speed and the second-half speed for the near-side incoming pedestrians. The results of t-tests show that there is no significant difference between observed speeds and estimated speeds at the 95% confidence level. Thus, the pedestrian speed model is demonstrated to be able to reflect the real speeds and further be applied to pedestrian safety simulation.

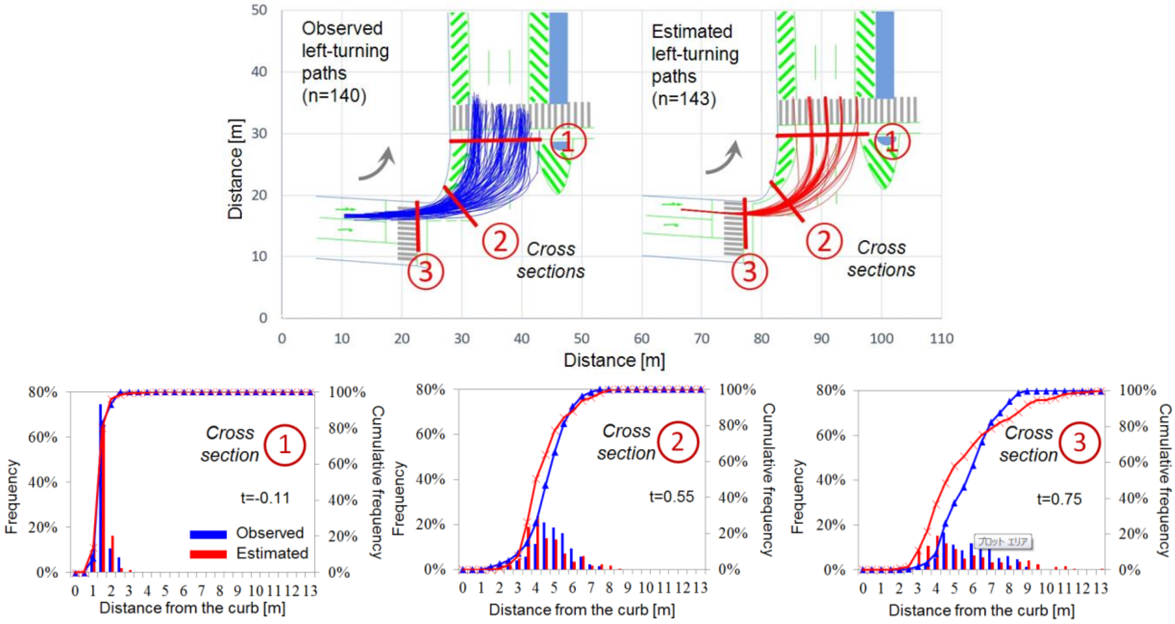


Fig.8 Comparison of observed and simulated paths of left-turning vehicles

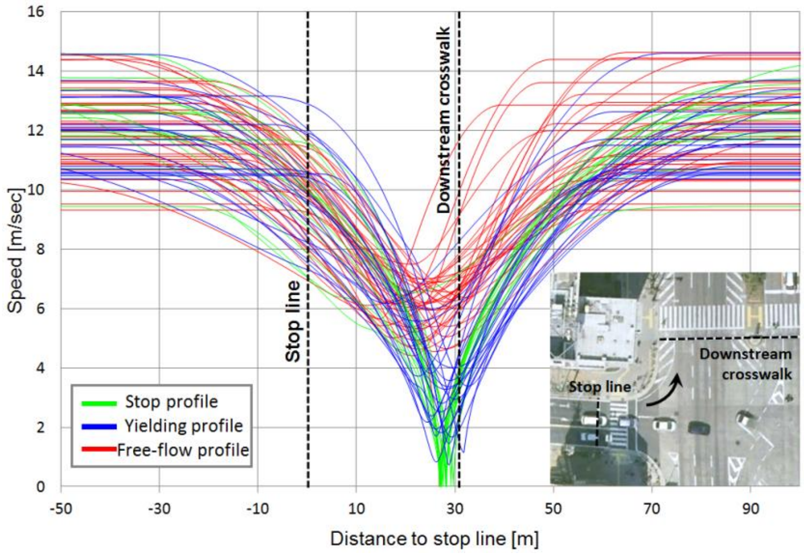


Fig.9 Simulated speed profiles of left-turning vehicles

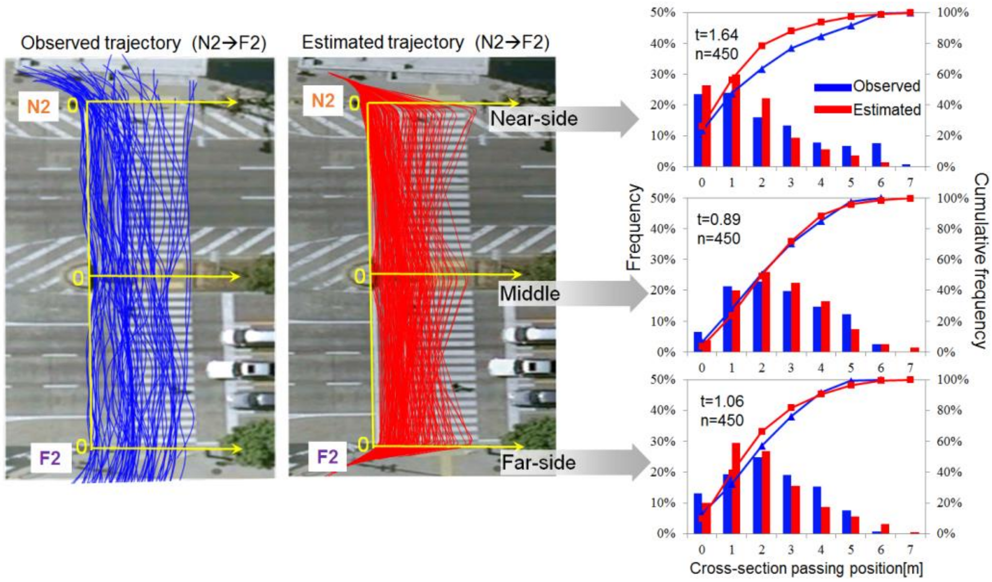
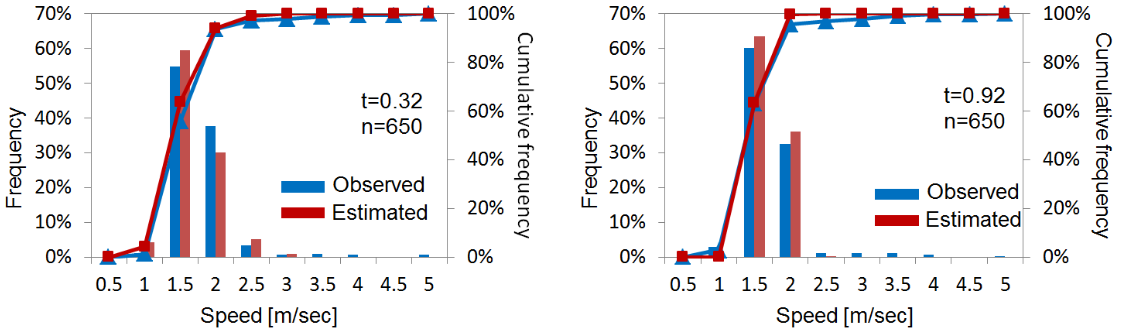


Fig.10 Comparison of observed and estimated pedestrian trajectories



(a) First-half speed (b) Second-half speed

Fig.11 Comparison of observed and estimated speed for near-side approaching pedestrians

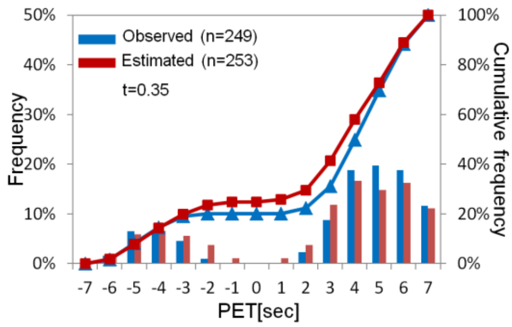


Fig.12 Comparison of observed and estimated PET

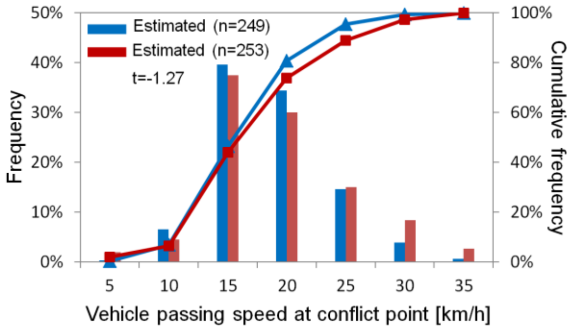


Fig.13 Comparison of observed and estimated vehicle passing speed at conflict point

(3) Validation of SSM

Fig.12 illustrates the comparison of observed PET values and the values extracted from simulation results. The result of t-test shows that there is no significant difference between them at the 95% confidence level. Thus, PET as one SSM can be utilized for conflict assessment at signalized crosswalks. However, it needs attention that the PETs with smaller absolute values (e.g., ≤1s) are of slightly larger share in the simulation. It indicates that the gap acceptance model based on limited data samples need further updates.

By referring to the PET values, vehicle passing speeds at conflict points are extracted from both video observation and simulation results. **Fig.13** gives the comparison. The result of t-test shows that there is no significant difference between them at the 95% confidence interval. Thus, vehicle passing speed at conflict point as another SSM can be utilized to estimate the vehicle-pedestrian conflict level at signalized crosswalks.

6. CONCLUSIONS AND FUTURE WORK

Vehicle-pedestrian conflict needs special attention in the context of safety evaluation and improvement of signalized intersection. This study, as part of intensive efforts to develop a microscopic simulation model for safety assessment at signalized intersections, helps demonstrate how the simulation as an innovative approach can be utilized for left-turning vehicle versus pedestrian conflict assessment at signalized intersections prior to implementation.

Empirical models have been established to represent the stochastic behavior of left-turning vehicles and pedestrians under various layouts and operations of signalized intersections. For safety assessment, SSMs were employed to reflect the conflicts and further relate to crash estimation. The validation results show that the developed simulation can reasonably represent road user behavior as well as the conflict occurrence at signalized crosswalks. In summary, the developed models and their realization in simulation proves the validity of the new approach. It enables a better understanding of conflict risks and the impact of geometric characteristics and signal operation on safety performance.

In order to provide more reliable results and broaden the applicability of the proposed simulation tool, it is necessary to update some key behavioral models, e.g., non-free-flow left-turning vehicle path/speed models and pedestrian waiting behavior at crosswalk during red phase. In addition, other conflict types such as right-turning vehicles versus opposing through traffic conflict is also supposed to be incorporated into the future development of the simulation model.

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