Application of surrogate safety measures for assessment of pedestrian versus left-turning vehicle conflict at signalized crosswalks

P. Chen¹  H. Nakamura¹  M. Asano²

¹Department of Civil Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan
email: peng@genv.nagoya-u.ac.jp
²International Center for Urban Safety Engineering (ICUS), Institute of Industrial Science, the University of Tokyo Bw605, 4-6-1 Komaba, Meguro-ku, Tokyo, 153-8505, Japan

Abstract

Pedestrian safety improvement at signalized intersections remains a critical issue. The major threat comes from frequent interaction with turning vehicles, especially left-turners (left-hand traffic system). This study gains insights into how surrogate safety measure (SSM) can be utilized for pedestrian versus left-turning vehicle conflict assessment, and although a small step, how to relate SSM to limited crash records for crash risk estimation. Based on the video data collected at several crosswalks in Nagoya City, Japan, SSMs, i.e., Post Encroachment Time (PET) and vehicle passing speed at conflict point were extracted for analysis. PETs were estimated for both near-side and far-side approaching pedestrians by identifying the potential conflict points and considering the physical size of left-turning vehicles. The effectiveness of SSMs to reflect the impact of site-specific geometric characteristics and operational conditions upon conflict risk has been demonstrated. Furthermore, crash risk estimation models were developed by using Poisson regression methods based on mean PET, the number of short PETs per hour and average vehicle passing speed at conflict point at each crosswalk. It demonstrates that high turning speed, in conjunction with higher frequency of short PETs result in higher crash rates.

Keywords – surrogate safety measure, pedestrian, left-turning vehicle, signalized crosswalk

1. Introduction and motivation

Pedestrian safety improvement at signalized intersections remains a critical issue. The major threat comes from frequent interactions with turning vehicles at crosswalk. Although signalized crosswalks are operated to give pedestrians prioritized right of way over vehicles, more than one-third of the total traffic accident fatalities in Japan are pedestrians at signalized and unsignalized crosswalks [15]. Many reasons exist behind such statistics, for instance, visibility, intersection geometry, traffic signal control policy, user behavior, etc.

In Japan, where vehicles travel on the left side of the road (left-hand traffic system), left-turners typically have to filter through conflicting pedestrian flow during permitted signal phase. Under the mixed impact of surrounding environment, crosswalk geometry, signal operation and pedestrians moving in different directions, left-turners might take risky behavior by not yielding to pedestrians or passing through small gaps in pedestrian flow, which poses a threat to pedestrian safety.
Thus, the conflict between left-turners and pedestrians needs special attention in the context of safety assessment and improvement of signalized intersections. In this regard, the Manual on Intersection Accident Countermeasure of Japan [13] suggests modifying intersection corner geometry or the crosswalk position as potential safety countermeasures. However, the quantitative evaluation of these countermeasures before installation is yet a challenge to be overcome.

So far the reactive strategies for the purpose of improving pedestrian safety have been primarily based on identifying sites with high crash rates. It is subject to less crash records or validity losing due to changes of road system and operation.

On the other hand, traffic conflict technique (TCT) represents an efficient approach to enable a preventive strategy development. Surrogate safety measures (SSM) serve as near-crash indicators to measure spatial and temporal proximity of road users. However, there are still few applications of SSM on pedestrian-vehicle conflict assessment and a lack of knowledge on converting SSM into crash frequency [21]. This study aims to gain insights into these two issues in the case of the conflicts between pedestrians and left-turning vehicles at signalized crosswalks. The remainder of the paper is organized as follows.

A thorough literature review on pedestrian-vehicle conflict assessment is presented first. Then the potential SSM candidates and their detailed definitions are provided. By using video data collected at several signalized crosswalks in Nagoya, Japan, post-extracted SSMs are compared in detail at each crosswalk.

Next, with regard to relating SSMs to crash records, crash risk estimation models are developed by using Poisson regression methods based on site-specific SSMs. Last, conclusions are drawn and recommendations are provided for future consideration.

2. Literature review

SSM’s are typically used to measure the severity and frequency of traffic conflict events as an alternative to crash risk estimation based on limited crash data. Various SSM’s have been suggested for safety evaluation of traffic facilities as shown in Allen et al. [3], Gettman and Head [8] and HSM [11]. Generally, a SSM satisfies two conditions in order to be useful for safety applications [21]: 1) A measurable or observable non-crash event that is physically related in a predictable and reliable way to crashes, and 2) A practical method for converting or calibrating the non-crash event into a corresponding crash frequency and/or severity. In the following sections, the literature on SSM for pedestrian safety assessment are reviewed in these two aspects.

2.1. SSM’s for pedestrian-vehicle conflict assessment

In the case of pedestrian-vehicle conflict at crosswalks, the related SSM’s including their definitions and descriptions are summarized in Table 1. The studies by Allen et al. [3], Gettman et al. [9] and Tang and Nakamura [20] demonstrates that PET is the best and the most common index to examine crossing conflict considering the ease of measurement, consistency over time and relation to other measures. It does not require estimating the time remaining to the conflict point, i.e., TTC, which is difficult to obtain precisely. To measure PET in the case of left-turning and pedestrian conflict, only their passing times at conflict point are necessary. Due to its simplicity, PET is also amenable to automated measurement methods using techniques such as video image processing. Another important property of PET is that it is continuous from crash-free operations to crash occurrences with a distinct boundary at zero. The smaller value of PET implies a greater risk of vehicle-pedestrian collisions.
In practice, Songchitruksa and Tarko [18] demonstrated the usefulness of the number of short PETs in explaining the variability of crash counts and concluded that the frequency of short PETs is a potential indicator in discriminating varying safety levels across survey sites.

Additionally, vehicle passing speed or speed distributions at conflict point are also good surrogate indices for safety assessments of left-turning vehicle versus pedestrian conflict. In a study by Westra and Rothengatter [24], based on the analysis of conflicts between vehicles and pedestrians at crosswalks of signalized intersections in four European countries, they concluded that if the passing speed of vehicles to crosswalks is higher, the probability to conflicts is greater. Speed can also be considered as a presentation of conflict severity. Higher speed at conflict points may contribute to higher conflict severity.

2.2. Relating SSM to crash records

Quantifying pedestrian safety in light of crash frequency is equally important to define safety indicators of pedestrian conflicts. The traditional analyses of SSMs relied on observed crash data in developing crash risk estimation models for motorists.

In the case of pedestrian crashes, empirical approach would not likely work due to infrequent pedestrian-vehicle crash occurrence and a long period of time needed to collect enough data for analysis. Thus, limited efforts conducted upon establishing the relationships between SSM and crashes at signalized intersection were reviewed.

Sayed and Zein [17] utilized the conflict technique to develop a predictive model relating the number of conflicts to traffic volumes and aggregated crashes from 92 intersections. The study established conflict frequency and severity standards in the form of an intersection conflict index and compared relative conflict risk among different intersections. The study found that both the conflicts and the crashes followed a Poisson distribution and the developed models were statistically significant which explained 70% and 77% of the variation between crashes and conflicts at signalized junctions.

Songchitruksa and Tarko [18] employed Extreme Value Theory to estimate the frequency of crashes. Based on PET characteristics, risk and frequency of right-angle crashes at signalized intersections were estimated, which showed a significant relationship between PET statistics and historical crash data.

Gettman et al. [9] conducted an extensive research on application of conflict technique and developed a computer program called Surrogate Safety Assessment Model (SSAM) to identify potential conflicts. For the field test, the SSAM outputs were compared with available crash records for 83 intersections. The analyses identified that the simulation-based conflicts data by SSAM were significantly correlated with the field crash data. However, efforts are still needed to address the scaling problems of converting surrogate frequencies to road crash frequencies, especially at a more disaggregate level of crash types.

Taken together, a variety of SSMs have been developed to represent the probability of collision or how close the conflict is to a collision. In the context of left-turning vehicle versus pedestrian conflict assessment, PET statistics and vehicle passing speed at conflict point can be potential SSM candidates.

Their detailed definitions and their ability to measure the degree of conflict are shown later. Additional efforts will be made on relating selected SSMs to crash records, by which crash risk can be estimated.

In the case of pedestrian-vehicle conflict at crosswalks, the related SSMs including their definitions and descriptions are summarized in Table 1.
### Tab. 1 - Summary of SSMs for pedestrian-vehicle conflict assessment

<table>
<thead>
<tr>
<th>No.</th>
<th>SSM</th>
<th>Definition and description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Time to Collision (TTC) [10]</td>
<td>The time that remains until a collision between two road users would have occurred if the collision course and speed difference are maintained.</td>
</tr>
<tr>
<td>2</td>
<td>Post-Encroachment Time (PET) [6]</td>
<td>The time difference between the moment when an offending road user leaves an area of potential collision and the moment of arrival of a conflicted road user possessing the right of way.</td>
</tr>
<tr>
<td>3</td>
<td>Time to Zebra (TTZ) [22]</td>
<td>A variation of TTC in order to estimate frequency and severity of critical encounters between crossing pedestrians and vehicles that are approaching the crosswalk.</td>
</tr>
<tr>
<td>4</td>
<td>Deceleration-to-Safety Time (DST) [12]</td>
<td>The necessary deceleration to reach a non-negative PET value if the movement of the conflicting road users remains unchanged.</td>
</tr>
<tr>
<td>5</td>
<td>Deceleration Rate (DR) [8]</td>
<td>A measure of the highest rate at which a vehicle must decelerate to avoid a collision.</td>
</tr>
<tr>
<td>6</td>
<td>Proportion of Stopping Distance (PSD) [8]</td>
<td>The ratio of the distance available for a maneuver to that of the necessary braking distance to a projected point of collision.</td>
</tr>
<tr>
<td>7</td>
<td>Gap Time (GT) [4]</td>
<td>Time lapse between the completion time of encroachment by one road user and the arrival time of the interacting road user if they continue with the same speed and path.</td>
</tr>
<tr>
<td>8</td>
<td>Pedestrian Risk Index (PRI) [5]</td>
<td>The potential severity of pedestrian-vehicle collision consequences.</td>
</tr>
<tr>
<td>9</td>
<td>Passing Speed at Conflict Point [16]</td>
<td>Speed distributions at conflict points.</td>
</tr>
</tbody>
</table>

### 3. Methodology

#### 3.1 Post-Encroachment Time (PET)

In general, PET is defined as the time difference of pedestrians and conflicting left-turning vehicle passing the conflict point. In view of bi-directional pedestrian flow [1, 2], it is assumed that pedestrian movements have their origins at either the near-side or the far-side of the crosswalk with reference to conflicting left-turning vehicles as illustrated in Figure 1. Near-side pedestrians are those who start crossing from the side of the vehicular traffic that exit the intersection, whereas far-side pedestrians are those who start crossing from the side of the incoming vehicular traffic. Accordingly, the conflict area is defined as the area occupied by the body of the vehicle at the crosswalk and surrounded by two boundaries, namely, near-side edge and far-side edge of the vehicle in light of pedestrian approaching directions (Figure 1). These boundaries serve as the reference lines for PET and conflict point estimation.

According to whether left-turning vehicle gives way to pedestrians at crosswalk, both positive and negative values of PET are related.
Positive PET values correspond to the situation when the left-turning vehicle gives way to conflicting pedestrians before passing the crosswalk, whereas negative PET values represent the opposite case when pedestrians pass the crosswalk after the conflicting left-turning vehicle. In order to extract both types of PET, conflict points need to be clearly defined by considering the physical size of left-turning vehicle and pedestrian approaching direction at the crosswalk.

Note that the definitions of conflict point are different for near-side and far-side coming pedestrians in the cases of positive/negative PET values. As shown in Figure 2, when PET has a positive sign, the left-turning vehicle gives way to conflicting pedestrians. For near-side coming pedestrians, the conflict point is defined as the intersection point of pedestrian trajectory and far-side edge of vehicle trajectory when passing the crosswalk. For far-side coming pedestrians, the conflict point is defined as the intersection point of pedestrian trajectory and near-side edge of vehicle trajectory. The reason for these definitions is that the physical width of left-turning vehicle needs to be sophisticatedly considered in order to make sure that pedestrians can safely pass the conflict area. However, this issue has received minimal attention in previous studies, which may cause inaccurate estimation of conflict points and PET values. The similar way of estimation holds for negative PET values. In such cases, conflict points correspond to the situations when near-side coming pedestrians arrive at the near-side edge of the vehicle trajectory or far-side coming pedestrians arrive at the far-side edge of the vehicle trajectory.

3.2. Passing speed at conflict point

At signalized intersections, left-turning speed profiles get influenced by numerous impact factors, such as entering speed into intersection, corner radius, angle and how turning vehicles react to conflicting pedestrians. Thus, passing speed at conflict point can be regarded as an indicator of the conflict between left-turners and pedestrians. The definition is also illustrated in Figure 2, i.e., the slope of left-turning time-space profile at the corresponding conflict points.

4. Study Site and SSM Extraction

In order to investigate the potential SSMs and their relationship with crash records, video data were collected at several signalized intersections under various geometric characteristics and traffic conditions.
In total, video images of nine approaches at six signalized intersections in Nagoya City were recorded. Table 2 shows the detailed information of observed sites. Variation in geometric layouts can be identified such as left-turning angle, crosswalk length and setback distance. As for traffic conditions, the average demand of left-turning vehicles is relatively higher at Fushimi North approach and Honmachi East approach. Kanayama, Fushimi and Otsu intersections have heavier pedestrian demand whereas most of other sites have low-to-medium pedestrian demand. Note that all sites have a shared left-turn and pedestrian signal phase and left-turn on red is prohibited. Thus, frequent conflicts exist between two road users at crosswalks. In addition, the crash records of pedestrian versus left-turning vehicles at observed sites (from 2007 to 2010) are given by Nagoya National Highway Office. The variability in the safety levels of crosswalks offers a basis for conducting safety assessment, although the crash counts within recent four years are few and may somehow limit the transferability of the analysis results.

Next, based on the collected video data, discrete position-time pedestrian and left-turning vehicle trajectories were extracted by using video image processing system TrafficAnalyzer [19]. This system is designated to support manual tracking of vehicle/pedestrian trajectories along with their movements at any preset time step, e.g., 0.5s. As for left-turning vehicle, the point where the right-front wheel is touching the ground is set as the reference observation point for trajectory tracking. By doing so, the far-side edge of vehicle trajectories is readily obtained. The near-side edge of vehicle trajectories can be derived by shifting the far-side edge of trajectories according to the dimension of the vehicle. For pedestrians, the projection of their centers of gravity on the ground is considered as the reference observation point. Next, Kalman filter technique is used for correcting the measurement errors and smoothing the estimated user position and speed. A more detailed explanation was given by Alhajyaseen et al. [2]. After that, smoothed vehicle and pedestrian trajectories are processed to estimate their conflict points and accordingly vehicle passing speed at conflict point. Meanwhile, positive/negative PET values can be obtained in light of pedestrian approaching direction as shown in Figure 3.

5. SSM characteristics

To examine the suitability of potential SSMs to represent the pedestrian-vehicle conflict, the basic statistics of PET and passing speed at conflict point are analyzed at all sites. Their representative indicators are utilized to demonstrate the site-specific conflict level and then relate to crash records.
Tab. 2 - Geometry characteristics and traffic conditions at observed sites

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Objective approach</th>
<th>Crash records*</th>
<th>Left-turn angle (deg.)</th>
<th>Crosswalk characteristics</th>
<th>Survey period</th>
<th>Left-turn vehicle demand (veh/h)</th>
<th>Crossing pedestrian demand (ped/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanzawa</td>
<td>North</td>
<td>1</td>
<td>81</td>
<td>36.2×5.8</td>
<td>8:30-8:40, 9:30-13:00</td>
<td>62</td>
<td>335</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>0</td>
<td>95</td>
<td>16.2×5.8</td>
<td>9:00-13:00</td>
<td>74</td>
<td>180</td>
</tr>
<tr>
<td>Ueda</td>
<td>South</td>
<td>0</td>
<td>118</td>
<td>20.8×5.2</td>
<td>7:30-10:00(2 days), 14:30-16:00</td>
<td>88</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>1</td>
<td>66</td>
<td>28.7×6.3</td>
<td>7:30-10:00(2 days), 14:30-16:00</td>
<td>23</td>
<td>34</td>
</tr>
<tr>
<td>Fushimi</td>
<td>South</td>
<td>1</td>
<td>50</td>
<td>35.4×6</td>
<td>10:00-11:00, 14:00-15:00</td>
<td>61</td>
<td>326</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>0</td>
<td>90</td>
<td>34.1×6</td>
<td>8:13-8:45, 11:45-12:15, 16:15-16:45</td>
<td>100</td>
<td>310</td>
</tr>
<tr>
<td>Yamada</td>
<td>East</td>
<td>1</td>
<td>120</td>
<td>15.2×5.7</td>
<td>7:00-10:00(2 days), 14:30-17:00</td>
<td>25</td>
<td>43</td>
</tr>
<tr>
<td>Otsu</td>
<td>West</td>
<td>2</td>
<td>90</td>
<td>34.1×6.3</td>
<td>10:00-11:00, 14:00-15:00</td>
<td>47</td>
<td>288</td>
</tr>
<tr>
<td>Honnami</td>
<td>East</td>
<td>0</td>
<td>90</td>
<td>33.3×5.7</td>
<td>8:13-8:45, 11:45-12:15, 16:15-16:45</td>
<td>102</td>
<td>175</td>
</tr>
</tbody>
</table>

*The records of pedestrian versus left-turning vehicle crashes at surveyed crosswalks (2007-2010)

Fig. 3 - PET extractions from observed left-turning vehicle and pedestrian trajectories

5.1. Post-Encroachment Time (PET)

Such studies as Songchitraksu and Tarko [18] utilized a constant threshold value to select SSM at different sites for analysis, under the assumption that the risk is the same across locations regardless of intersection layouts and operation policies. It has critical drawbacks because there rarely exist identical traffic systems and thus risk performance is assumed to be different across sites. The consequence of an incorrect threshold specification can be severe because it can influence all the components of the study, ranging from data collection to analysis results.
In addition, there is no basis to support the practice of a constant threshold other than simplicity. It indicates a need for more careful definitions of the risk across sites.

In this study, with different geometric features and operational conditions at observed crosswalks, the threshold values set for PET analysis are assumed to be different at each site. Here, the average walking time to conflict point is employed for this purpose. It is assumed that both near-side coming pedestrians (from near-side cross-section) and far-side coming pedestrians (from middle cross-section) need a certain time period to pass conflict points and avoid conflict risk. When observed PETs are less than this value, it represents a relatively risky situation. As shown in Figure 4, the measurement differs with pedestrian approaching directions in positive/negative PET cases, which relate to different conflict points as aforementioned.

Based on the estimated average walking time to conflict point at all sites, Figure 5 shows the threshold values for both positive and negative PETs in addition to the number of samples within these thresholds. The horizontal axis is arranged according to the ascending order of crosswalk length. It shows that the longer crosswalk, e.g., Kanayama North crosswalk appears to have the larger PET threshold values. Yamada East approach with the shortest crosswalk of 15.2 m has the smallest PET threshold values. It reveals that geometric characteristics need to be carefully considered when analyzing site-specific SSMs. Meanwhile, Figure 5 helps show a significant amount of variability in the PET data available for analysis. The number of samples of positive and negative PETs implies that most of left-turning vehicles give way to conflicting pedestrians at crosswalk. In order to enable a direct comparison of the conflict level at sites, a representative PET statistic needs to be set for this purpose. Because the negative PET values are of small numbers and relate to less risky situation when pedestrians pass the conflict point after vehicles, only positive PET values are selected for analysis. Table 3 shows the statistics of positive PET values under the defined thresholds at all sites. Note that the maximum mean value of positive PETs is 4.64 s at Kanayama North crosswalk and the minimum one is 1.89 s at Yamada East crosswalk. The difference between mean PETs is significant. In addition, the number of short PETs per hour, after the unification of time units of total counts across sites, has apparently larger variability. Larger number of short PETs indicates a higher level of conflict frequency.

5.2. Passing speed at conflict point

By referring to the selected positive PETs, vehicle passing speeds at conflict point are extracted as another SSM for analysis.
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Tab. 3 - Basic statistics of positive PETs at each site

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Objective approach</th>
<th>Crash records*</th>
<th>The number of short PETs (per hour)</th>
<th>Min.</th>
<th>1st quartile</th>
<th>Mean</th>
<th>3rd quartile</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanayama</td>
<td>North</td>
<td>1</td>
<td>71</td>
<td>1.61</td>
<td>3.77</td>
<td>4.64</td>
<td>5.56</td>
<td>6.40</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>0</td>
<td>8</td>
<td>1.52</td>
<td>2.06</td>
<td>2.27</td>
<td>2.52</td>
<td>2.78</td>
</tr>
<tr>
<td>Ueda</td>
<td>South</td>
<td>0</td>
<td>5</td>
<td>1.38</td>
<td>1.90</td>
<td>2.00</td>
<td>2.29</td>
<td>2.49</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>1</td>
<td>11</td>
<td>1.47</td>
<td>2.58</td>
<td>3.08</td>
<td>3.62</td>
<td>4.57</td>
</tr>
<tr>
<td>Fushimi</td>
<td>South</td>
<td>1</td>
<td>21</td>
<td>1.46</td>
<td>2.47</td>
<td>3.39</td>
<td>3.89</td>
<td>4.51</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>0</td>
<td>16</td>
<td>1.50</td>
<td>2.27</td>
<td>2.67</td>
<td>3.06</td>
<td>4.10</td>
</tr>
<tr>
<td>Yamada</td>
<td>East</td>
<td>1</td>
<td>10</td>
<td>1.31</td>
<td>1.60</td>
<td>1.89</td>
<td>2.18</td>
<td>2.39</td>
</tr>
<tr>
<td>Otsu</td>
<td>West</td>
<td>2</td>
<td>49</td>
<td>1.82</td>
<td>2.96</td>
<td>3.61</td>
<td>3.61</td>
<td>5.11</td>
</tr>
<tr>
<td>Honnachi</td>
<td>East</td>
<td>0</td>
<td>11</td>
<td>1.64</td>
<td>1.91</td>
<td>2.39</td>
<td>2.78</td>
<td>3.38</td>
</tr>
</tbody>
</table>

*The records of pedestrian versus left-turning vehicle crashes at surveyed crosswalks (2007-2010)

Figure 6 shows the basic statistics of passing speed at all sites. The horizontal axis is arranged according to the ascending order of setback distance. With the increasing setback distance, left-turning vehicles tend to have larger turning speed and pass the conflict point at a higher speed. For example, Ueda South approach with the largest setback distance shows a high average passing speed of 17.27 km/h. It demonstrates that geometric characteristics closely relate to SSM investigations.

Taken together, after a careful selection of potential SSMs in light of their effectiveness to reflect the impact of site-specific geometric characteristics and operational conditions on conflict risk, three SSMs are proposed to represent the conflict level of pedestrians versus left-turning vehicles at crosswalks, namely, mean PET, the number of short PETs per hour and average passing speed at conflict point. They are utilized to relate to crash records for crash risk estimation.

6. Relating SSM to crash records

Crash risk models offer an estimate of expected crash frequency for safety assessment. Extensive research [14] has been performed to examine the crashes as a function of traffic flow features, e.g., traffic volume and speed, and roadway geometries, e.g., lane width and crosswalk length. In view of the fact that the selected SSMs have adequately reflected the effect of geometry and traffic flow, the statistical linkage between SSM and crash data needs to be established toward a better performance.

Note: L is crosswalk length (m).

Fig. 5 - PET threshold values at surveyed crosswalks
In this study, this pressing issue is addressed by relating three SSM candidates to 4-year crash records at observed crosswalks.

Because crash counts are non-negative integer values, the standard least-square regression models are inappropriate. Linear regression models yield predicted values that are non-integers and can also predict values that are negative. There are a number of methods that can be used to properly model crash counts. The most commonly used ones are Poisson and negative binomial regression models [23].

Poisson regression can be used to model the number of occurrences of crashes as a function of some independent variables. In this study according to Poisson regression, the probability of location \( i \) having \( y_i \) counts of traffic crashes is given by:

\[
P(y_i) = \frac{e^{-\lambda_i} \lambda_i^{y_i}}{y_i!}
\]

where \( \lambda_i \) is the Poisson parameter for location \( i \), which is equal to the expected number of crash counts at location \( i \). The most common relationship to specify \( \lambda_i \) is the log-linear link as:

\[
\lambda_i = \exp(\beta X), \quad \text{or} \quad \log(\lambda_i) = \beta X
\]

where \( X \) is a vector of explanatory variables and \( \beta \) is a vector of estimable coefficients. Maximum likelihood estimation is used for parameter estimations. The log-likelihood function for the maximum likelihood estimation procedure is given as:

\[
L(\beta) = \sum_{i=1}^{n} [-\exp(\beta X) + y_i \beta X - \log(y_i!)]
\]

The likelihood ratio test is used to assess the goodness-of-fit between nested models. The likelihood ratio test statistic is:

\[
-2[L(\beta_R) - L(\beta_U)]
\]

where \( L(\beta_R) \) is the log-likelihood at convergence of the restricted model (i.e., only constant term is added) and \( L(\beta_U) \) is the log-likelihood at convergence of the unrestricted model.
This statistic follows $\chi^2$ distribution with the degrees of freedom equal to the difference in the number of parameters of two competing models. Another measure of overall model fit is the $\rho^2$ statistic, which is given by:

$$\rho^2 = 1 - \frac{L(\beta_1)}{L(\beta_k)}$$  

(5)

The value of $\rho^2$ is between 0 and 1 where the value closer to 1 implies a better model fit; in other words, the more variance the estimated model is explaining.

It is known that the fundamental assumption of Poisson regression is that the variance should be equal to its mean, i.e., $\text{var}(y_i) = E(y_i)$. Sometimes, the variance of crash data can be significantly larger than the mean, i.e., $\text{var}(y_i) > E(y_i)$. In such a case, the data is said to be overdispersed. Typically, the negative binomial model aims to address this issue. The model is derived by rewriting equation (2) such that, for each observation $i$,

$$\lambda_i = \exp(\beta X + \epsilon_i)$$  

(6)

where $\exp(\epsilon_i)$ is a gamma-distributed error term with mean 1 and variance $\alpha^2$. The addition of this term allows the variance to differ from the mean as:

$$\text{var}(y_i) = E(y_i)(1 + \alpha E(y_i)) = E(y_i) + \alpha E(y_i)^2$$  

(7)

In this study, it is focused on applying the regression methods to develop crash risk estimation models based on potential SSM candidates.

Firstly, the crash data as shown in Table 1 are analyzed by referring to the relationship between mean and variance. Based on the limited crash records available in four years, the larger mean value of 0.78 compared to the variance of 0.44 indicates that the Poisson regression model is a suitable choice.

Next, crash models are developed by relating to individual SSM and combined SSMs, respectively.

6.1. Crash modelling by individual SSM

Three potential SSMs, i.e., mean PET, the number of short PETs and average vehicle passing speed at conflict point, are utilized to build the models separately at first. Table 4 summarizes the estimated Poisson regression models by each SSM. The t-values of the estimated model coefficients are statistically significant at a 90% confidence interval. The positive coefficients estimate of all individual SSMs implies that a crosswalk with higher mean PET, the number of short PETs or average passing speed at conflict point is likely to experience more left-turn versus pedestrian crashes. Also, it indicates that the selected SSMs can be viewed as exposures to crash. The increase of exposures is likely to give rise to higher crash frequency. In addition, the constant captures the variability of crash counts unexplained by single SSM. However, the $\rho^2$ statistic of each model is not significant due to limited crash records. Thus, as an alternative approach, individual SSMs are combined with each other to estimate the models.

6.2. Crash modelling by combined SSMs

Before combining individual SSMs for analysis, the correlation between each other was tested. Because mean PET and the number of short PETs have a strong correlation, only the combinations of 1) mean PET and average passing speed at conflict point and 2) the number of short PETs and average passing speed at conflict point have been analyzed.
Table 5 gives the estimation results. The coefficient estimates in both models are statistically significant at a 90% confidence interval except for mean PET. The signs of the coefficient estimates are consistent as in the individual SSM-based models. Note that $\rho^2$ statistic of the second model in Table 5 gets improved to 0.218 with comparison to the goodness of fit results in Table 4. It implies a potential synergy in the explanatory power when both the number of short PETs and average passing speed at conflict point are combined. It proves that each SSM carries additional safety information which is unexplained by other SSMs.

6.3 Sensitivity analysis

In order to demonstrate the usefulness of each SSM in explaining the variability of pedestrian versus left-turning vehicle crashes, sensitivity analysis is conducted.

The Model 2 presented in Table 5 is chosen as an example. Figure 7(a) illustrates the impact of the number of short PETs on annual crash frequency by assuming an average passing speed at conflict point of 16 km/h. Figure 7(b) illustrates the impact of average passing speed at conflict point on annual crash frequency by assuming the number of short PETs as 20 per hour. It shows that with the increasing of these SSMs, the annual crash frequency estimate is accordingly increasing. It gives indications that in order to reduce crashes pedestrian exposure to vehicular traffic and vehicle turning speed should be reduced. In this regard, tightening left-turning radius and crosswalk setback distance and improving sight distance or visibility between vehicles and pedestrians may help improve safety performance. It proves the usefulness of SSM for estimating crash risks. However, the results may be limited due to insufficient crash records at surveyed crosswalks. Future work is expected to include more crash records for analysis.

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Explanatory variables</th>
<th>Estimated coefficient</th>
<th>t-value$^*$</th>
<th>Initial log-likelihood</th>
<th>Log-likelihood at convergence</th>
<th>$\chi^2$ statistic</th>
<th>$\rho^2$ statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mean PET (s)</td>
<td>0.621</td>
<td>1.95</td>
<td>-9.13</td>
<td>-8.12</td>
<td>2.01</td>
<td>0.110</td>
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<tr>
<td></td>
<td>Constant</td>
<td>-2.37</td>
<td>-1.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>The number of short PET (per hour)</td>
<td>0.0304</td>
<td>2.14</td>
<td>-9.13</td>
<td>-8.15</td>
<td>1.96</td>
<td>0.107</td>
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<tr>
<td></td>
<td>Constant</td>
<td>-1.13</td>
<td>-2.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Average passing speed at conflict point (km/h)</td>
<td>0.764</td>
<td>2.20</td>
<td>-9.13</td>
<td>-7.66</td>
<td>2.93</td>
<td>0.160</td>
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<tr>
<td></td>
<td>Constant</td>
<td>-12.7</td>
<td>-2.17</td>
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</tr>
</tbody>
</table>

*Note: 95% confidence limit: $t = 2.365$; 90% confidence limit: $t = 1.895$; 80% confidence limit: $t = 1.415$

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Explanatory variables</th>
<th>Estimated coefficient</th>
<th>t-value$^*$</th>
<th>Initial log-likelihood</th>
<th>Log-likelihood at convergence</th>
<th>$\chi^2$ statistic</th>
<th>$\rho^2$ statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mean PET (s)</td>
<td>0.375</td>
<td>1.38</td>
<td>-9.13</td>
<td>-7.44</td>
<td>3.38</td>
<td>0.185</td>
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<tr>
<td></td>
<td>Average passing speed at conflict point (km/h)</td>
<td>0.617</td>
<td>2.02</td>
<td>-9.13</td>
<td>-7.44</td>
<td>3.38</td>
<td>0.185</td>
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<tr>
<td></td>
<td>Constant</td>
<td>-11.5</td>
<td>-1.95</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2</td>
<td>The number of short PET (per hour)</td>
<td>0.0175</td>
<td>2.89</td>
<td>-9.13</td>
<td>-7.14</td>
<td>3.97</td>
<td>0.218</td>
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<tr>
<td></td>
<td>Average passing speed at conflict point (km/h)</td>
<td>0.629</td>
<td>1.99</td>
<td>-9.13</td>
<td>-7.14</td>
<td>3.97</td>
<td>0.218</td>
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<tr>
<td></td>
<td>Constant</td>
<td>-10.9</td>
<td>-2.00</td>
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</tbody>
</table>

*Note: 95% confidence limit: $t = 2.447$, 90% confidence limit: $t = 1.943$, 80% confidence limit: $t = 1.440
7. Conclusions and Discussions

Pedestrians at crosswalks are exposed to various potential hazards such as large vehicle volumes, high approaching speeds, multilane environments and signal control. Hence, quantification of pedestrian-vehicle conflicts is necessary for designing intersections that accommodate the needs of both road users and avoid the potential conflicts that may result into actual crashes. This study provides a step towards this target by applying SSMs for pedestrian versus left-turning vehicle conflict assessment and relating potential SSMs to crash records.

Based on the field data collected by video cameras at nine signalized crosswalks in Nagoya City, Japan, discrete position-time pedestrian and left-turning vehicle trajectories were extracted to estimate PET and vehicle passing speed at conflict point. Their effectiveness to reflect the impact of site-specific geometric characteristics and operational conditions on conflict risk was demonstrated. Furthermore, the relationships between SSMs and crash records were developed by Poisson regression models. The usefulness of mean PET, the number of short PETs and average passing speed at conflict point was examined. At the individual SSM level, the comparison of goodness-of-fit of each model reveals that average passing speed based model explains the variability of crash counts slightly better than the other two SSMs. When individual SSMs were combined, the goodness-of-fit measures indicate that more variability in crash data is being explained with comparison to the use of a single SSM variable.

In other words, there is an increase in the explanatory power of the model by combined SSMs. The combination of the number of short PETs and average passing speed at conflict point achieves a better model fit. However, it should be noted that the development of these models depends on limited crash records. A larger sample of sites is needed for future investigation.

In addition, this study was conducted as part of an extensive project to develop a simulation tool capable of assessing the safety of signalized intersections [7]. By means of simulation, it is expected that SSMs can be better applied to reflect the conflict between road users under various geometric features and operational conditions. Moreover, the ability of the crash risk estimation models will be further highlighted through simulation, which supports safety assessment even prior to facility implementation. The work in this regard is going on.

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References


