Left-Turn Lane Capacity Estimation based on the Vehicle Yielding Maneuver Model to Pedestrians at Signalized Intersections

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Abstract: Crossing pedestrians may significantly affect the capacity of the left-turn (LT) lane at signalized intersections while sharing the same signal phase in the left-hand traffic system, the quantitative estimation method is still not intensively discussed when considering the vehicle yielding maneuver. Despite the Road Traffic Act in Japan mandating vehicles to yield to pedestrians, instances of vehicles crossing in front of pedestrians are frequent. This study aims to refine the evaluation of LT lane capacity by introducing a novel vehicle yielding maneuver model, considering factors such as pedestrian numbers, crosswalk length, and signal timing. The model, developed using data from various Japanese crosswalks, is subjected to Monte Carlo simulation for validation. Comparative analysis with existing methods in Japanese and U.S. manuals, along with observed data, highlights the effectiveness of our model. This innovative approach has the potential to mitigate vehicle–pedestrian conflicts and reduce air pollution. By incorporating techniques such as signal optimization and two-stage crossing, our model contributes to sustainability while maintaining efficient traffic flow.

Keywords: left-turn lane; capacity estimation; yielding maneuver model; signalized intersection

1. Introduction

Vehicles have become important sources of particulate pollution, contributing between 25% and 35% of direct emissions [1,2], which are the dominant source of air pollution in most urban cities [3]. This pollution primarily arises from the emissions generated by vehicles, including particulate matter and other pollutants. As the number of vehicles in urban areas increases, their impact on sustainability becomes increasingly significant. In particular, vehicles may often stop at intersections because of the conflict between vehicles and pedestrians in the urban area. By minimizing stop-and-go traffic patterns, signal optimization and two-stage crossing contribute to a reduction in greenhouse gas emissions and air pollution, thereby promoting environmental sustainability and public health.

Moreover, the impact of traffic congestion on the environment is primarily manifested in indirectly promoting environmental pollution by increasing vehicle fuel consumption and emissions. Traffic congestion not only increases the time vehicles spend on the road, but also decreases their fuel efficiency, leading to higher emissions. Intersections, in particular, play a significant role in traffic congestion due to the interactions between vehicles and pedestrians. When vehicles wait or move slowly at intersections to yield to pedestrians, their fuel efficiency decreases, and they may emit more pollutants. Furthermore, congestion often leads to vehicles starting and stopping more frequently, which further increases fuel consumption and emissions. Therefore, this situation has a significant impact on urban sustainability, capacity, and delays, thereby significantly affecting the environment.
Additionally, signal optimization ensures that traffic flows smoothly through intersections, reducing congestion and minimizing delays for both vehicles and pedestrians. By synchronizing traffic signals and optimizing signal timing, the overall efficiency of the transportation network can be significantly improved, leading to safer and more predictable travel experiences for all road users. The capacity of the left-turn (LT) lane at signalized intersections is considerably influenced by these interactions between pedestrians and vehicles. Assessing the effect of pedestrians on the capacity of LT lanes is essential to improve traffic efficiency and reduce emissions. However, the method provided in the Japanese manual (hereafter referred to as the JSTE manual [4]) for evaluating this is unrealistic, as it only considers the influence of pedestrians on left-turning vehicles (LTVs) in conflict areas. This may lead to an overestimation of capacity. Additionally, the saturation flow rate used in the manual, based on traffic conditions from several years ago, may no longer be accurate due to changes in driving behaviors and increased safety awareness. Moreover, according to the Road Traffic Act [5] in Japan, LTVs must yield to pedestrians on crosswalks or those about to cross, which is defined as the yielding maneuver, further complicating the traffic flow at intersections.

Other countries have also issued strict regulations requiring vehicles to yield to pedestrians at crosswalks. However, the target area of pedestrians according to the law varies from country to country. In China [6], only pedestrians passing through a crosswalk are considered. In Texas [7], the target area is narrowed to half of the roadway. In Japan and California [8], the target area is the largest, which includes the crosswalks and waiting areas. These target areas affect the efficiency and safety of the signalized intersection, and they are important for quantitatively evaluating the relationship between the target area of the traffic law and efficiency and safety performance of the intersection. Even though the traffic law clearly stipulates that vehicles must yield to pedestrians, vehicles continue passing in front of crossing pedestrians, meaning not 100% of drivers comply with the traffic law. Because of the gaps between the reality, manual, and traffic law, an in-depth study on the characteristics of vehicle yielding maneuvers is urgently required. This study aims to investigate the characteristics of LTV yielding maneuvers under geometric conditions, signal settings, and behavior of pedestrians for capacity estimation.

This paper is organized thusly: Section 2 presents the existing literature on capacity estimation methods, yielding maneuvers, and their differences from those investigated in this study. Section 3 examines the geometric conditions of the survey sites and basic information on the data observed. In Section 4, the definition and model of the yielding probability are introduced. Furthermore, this section also present a sensitivity analysis for each influencing factor, the simulation results based on the vehicle yielding maneuver model, and a comparison of the capacity results of the two aforementioned methods. Finally, the last section summarizes the study and proposes future research directions.

2. Literature Review

2.1. Capacity Estimation Method

The effects of the pedestrian flow in different target areas have been considered in existing guidelines or manuals to estimate the turning vehicle capacity. For instance, the Highway Capacity Manual (HCM) [9], Planning and Design of At-Grade Intersections, Basic Edition, and Guide for Planning, Design, and Traffic Signal Control of Japan (JSTE manual [4]) evaluate the influence of pedestrians in the estimation of the capacity in turning lanes. Except for the adjustment factor methods used in the above manuals, the methods based on gap acceptance, game theory, and simulation also contain the effect of pedestrians on vehicle capacity at signalized intersections.

2.1.1. Japan Society of Traffic Engineers (JSTE) Manual

The influence of the pedestrian flow in conflict areas has been considered in Japanese manuals (Figure 1) to estimate the turning vehicle capacity. They quantify the influence of
pedestrians by adding the adjustment factor $f_L$ in Equation (1), which is measured based on the vehicle stopping probability model (Ikenoue and Saito [10]).

$$C_L = S_L f_L \frac{G_p}{c} + S_L \left(\frac{G - G_p}{c}\right),$$  \hspace{1cm} (1)

where $G$, $c$, $C_L$, $G_p$, and $f_L$ represent effective “green” time of vehicles (s), cycle length (s), capacity of the left-turn lane (veh/h), base saturation flow-rate of the LT lane (veh/h), sum of the pedestrian “green” time (PG) and pedestrian flashing “green” time (PFG, s), and adjustment factor of the effect of pedestrians on the LT lane, respectively.

To determine whether there exists a gap between the calculation results based on the JSTE manual in Equation (1) and those based on actual traffic capacity, the data of the north approach at the Heian 2–Chome intersection were selected (wherein the LTV volume was higher than those at other crosswalks) to compare both calculation results. Three problems with the JSTE manual method were identified. First, the suggested value of the saturation flow rate is too high for real-world situations. In this study, this value was replaced by the observed values. Second, there are two considerations: vehicles with pedestrian influence and those without pedestrian influence (Equation (1)). However, a few pedestrians remain in the second part. This problem was solved by combining the two parts into one, both multiplying the adjustment factor for correction. Hence, this study mainly focuses on solving the third problem, namely the high adjustment factor in the manual. Only the conflict area was considered in the calculation, while the influence of pedestrians on the vehicle in other areas was ignored. In the following section, the conflict area will be resized.

2.1.2. Procedure of Highway Capacity Manual (HCM)

The HCM uses lane-group saturation flow rates to determine the capacity at signalized intersections. The HCM adjusts the base saturation flow rate using several factors that reflect the real conditions for a particular intersection movement, as expressed in Equation (2):

$$S = S_o N f_w f_{HV} f_{g} f_p f_b f_a f_{RT} f_{LT},$$  \hspace{1cm} (2)

where $S$ represents the saturation flow rate in passenger cars per hour on the “green” per lane; $S_o$ represents the base saturation flow rate (pcu/h); $N$ represents the number of lanes; and $f_w, f_{HV}, f_g, f_p, f_b, f_a, f_{RT}$, and $f_{LT}$ represent the adjustment factors for lane width, heavy vehicles in the traffic stream, approach grades for the existence of a parking lane and parking activity adjacent to a lane group, blocking effect of local buses that stop within the intersection area, area type, right turns in a lane group, and left turns in a lane group, respectively. The HCM uses the adjustment factors $f_{LT}$ and $f_{RT}$ to account for the efficiency-reducing effects of left and right turns, respectively, on vehicular saturation flow. Notably, the right turn in the HCM is the left in Japan. These factors are proposed based...
on the four-phase empirical analysis: determining the pedestrian flow rate during service, average pedestrian occupancy, relevant conflict area occupancy, unoccupied time, and saturation flow rate adjustment factor.

As in the JSTE manual, only a part of the crosswalk is considered a conflict zone in the HCM to estimate the pedestrian effect on the saturation flow rate of turning lanes. However, the pedestrians on the other part of the cross- and sidewalk also affect the vehicle maneuver. Hence, the relationships between vehicle maneuvers and positions of pedestrians must be analyzed in the real world.

2.1.3. Capacity Estimation Method Based on Various Models

Similar to the above manuals, many researchers focused on improving the adjustment factor method. Milazzo et al. [11] described the relationship between pedestrians’ occupancy and saturation flow. However, the size of conflict area in this research equals to only a lane width.

While many studies have been conducted using gap acceptance models, Lu et al. [12] quantitatively analyzed the capacity of the right-turn lane (right-hand traffic) using gap acceptance theory and found that the pedestrian volume has a significant impact on capacity. Viney et al. [13] presented a model to calculate the saturation flow rate when vehicles are required to give way to pedestrian flow. The green phase is divided into five intervals. In the first and third intervals, pedestrian platoons block the vehicles, with no vehicle crossing. In the second and fourth intervals, vehicles accept gaps in the pedestrian flow. In the fifth interval, the pedestrian flow ceases and vehicles cross at the saturation flow rate. The capacity is then calculated. Pollatschek et al. [14] presented a microscopic decision model for the driver gap acceptance behavior while waiting at an unsignalized intersection, and the resulting intersection capacity was estimated. Chen et al. [15] proposed an analytical model (improved gap acceptance model) for the right-turning movement capacity influenced by pedestrians at signalized intersections. Pedestrians significantly affect the right-turn capacities (left-turn in Japan) at low pedestrian volumes, and the effect of pedestrians decreases as the number of pedestrians increases. However, the limitation of this theory is that it only takes the distance or time between pedestrian and vehicle as the consideration to distinguish the priority of vehicle and pedestrian to pass, with too few factors considered.

Yang et al. [16] studied the influence of pedestrians on road capacity and proposed an exclusive right-turn lane capacity model that considered the pedestrian–vehicle interaction using game theory. The results showed that the overall relative error between the microscopic simulation and cellular automata models of vehicles and pedestrians was less than 15%. Whether the real situation is similar is unknown. Thus, investigating the influence of pedestrians on vehicle yielding maneuvers and identifying the influencing factors are essential to assessing the capacity.

2.2. Vehicle Yielding Maneuver

Malenje et al. [17] investigated the effects of the macroscopic factors on the vehicle yielding maneuvers at unsignalized midblock crosswalks. The results showed that the gap size and number of traffic lanes highly influenced the yielding decisions of drivers, and they were more likely to yield if e-police were present. Wang et al. [18] evaluated the yielding maneuvers of three types of vehicles under the “pedestrian priority” policy at unsignalized midblock crosswalks by processing the drone footage collected in Xi’an City, China, using a machine vision intelligent algorithm. Several studies have focused on vehicle yielding maneuvers at unsignalized midblock crosswalks, although vehicle yielding maneuvers at signalized intersections must also be analyzed.

Unlike the above studies, where the attention is centered on the analysis of the yielding maneuvers and its effect on traffic flow, the following work delves into their effects on CO₂ emission and energy dissipation. Perez Cruz et al. [19], in a study leveraging the principles of complex systems, explores the microscopic interactions between vehicles and
pedestrians, explaining the consequential emergent effects on CO$_2$ emissions. The results show that a raised crosswalk results in lesser repercussions in CO$_2$ emission and energy dissipation by eliciting traffic calm.

2.3. Vehicle Trajectory Processing Method

Chen et al. [20] analyzed automated guided vehicle (AGV) trajectory movement from port surveillance videos. Motivated by the newly emerging computer vision and artificial intelligence (AI) techniques, they proposed an ensemble framework for extracting vehicle speeds from port-like surveillance videos for the purpose of analyzing AGV moving trajectory. The research findings suggest that cutting-edge AI and computer vision techniques can accurately extract on-site vehicular trajectory-related data from port videos, and thus help port traffic participants make more reasonable management decisions.

Chen et al. [21] proposed the ship trajectory extraction started by detecting ships from maritime images with the support of the poly-YOLO model, which outputs ship positions frame by frame. After that, the position data series for the same ship target is mapped via the EDS module. They have verified the proposed ship trajectory extraction model under four typical maritime traffic scenarios (e.g., good visibility, fog weather condition, ship encounter situation). The experimental results suggested that their proposed ship trajectory can accurately obtain ship position in each maritime image without ship misdetection.

3. Data Collection and Empirical Analysis of Yielding Maneuver

3.1. Study Site and Data Collection

To investigate the vehicle yielding maneuver, video data were collected at three signalized intersections in Nagoya City, Japan, under different traffic conditions. Table 1 presents the observation time, geometric characteristics of the observed sites, results of the average turning vehicle, and pedestrian volumes during the observation periods. Signal time of observed intersections includes pedestrian green time (PG), pedestrian flashing green time (PFG), and vehicle green time (G), as shown in Table 1. The focus was on peak and off-peak hours. The observed sites had considerably different geometric layouts, such as the crosswalk length.

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Crosswalk Position</th>
<th>Observation Time ( Weekdays )</th>
<th>Crosswalk Length L (m)</th>
<th>Signal Timings (s)</th>
<th>Volume LTVs (veh/h) Pedestrian (ped/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PG ( s )</td>
<td>PFG ( s )</td>
</tr>
<tr>
<td>Kanayama South</td>
<td>17:35–18:25</td>
<td>36</td>
<td>42</td>
<td>10</td>
<td>54</td>
</tr>
<tr>
<td>Kanayama North</td>
<td>17:35–18:25</td>
<td>37</td>
<td>42</td>
<td>10</td>
<td>54</td>
</tr>
<tr>
<td>Nishiosu East</td>
<td>8:15–9:15</td>
<td>22</td>
<td>60</td>
<td>10</td>
<td>72</td>
</tr>
<tr>
<td>Nishiosu West</td>
<td>7:15–8:15</td>
<td>25</td>
<td>79</td>
<td>8</td>
<td>90</td>
</tr>
<tr>
<td>Imaiike East</td>
<td>9:00–10:00</td>
<td>21</td>
<td>42</td>
<td>8</td>
<td>52</td>
</tr>
<tr>
<td>Imaiike West</td>
<td>10:00–11:00</td>
<td>20</td>
<td>42</td>
<td>8</td>
<td>52</td>
</tr>
</tbody>
</table>

Vehicle and pedestrian trajectories, including the positions and timings, were extracted from the video data. The positions of each vehicle and pedestrian were recorded every 0.3 s, and the corresponding video coordinates were converted to global coordinates via projective transformation. The point at which the rear right wheel touched the ground was the reference observation point for all the vehicles. All video observations were conducted from high buildings surrounding the intersections. Thus, for all videotapes, the observation angle was large. This enabled us to track the right rear wheels of all turning vehicles without difficulties such as occlusions or high coordinate transformation errors. Figure 2 shows an example of the vehicle trajectory data (yellow line).
was the reference observation point for all the vehicles. All vehicles without difficulties such as occlusions or high coordinate transformation errors. Observation angle was large. This enabled us to track the right rear wheels of all turning vehicles from high buildings surrounding the intersections. Thus, for all videotapes, the observation angle was large. This enabled us to track the right rear wheels of all turning vehicles without difficulties such as occlusions or high coordinate transformation errors.

Figure 2. Example of the vehicle trajectory data.

3.2. Definitions

Several researchers have only investigated factors related to LTVs. However, those related to pedestrians also play an important role. In this study, crossing pedestrians are categorized into two groups based on the crosswalk direction: near-side and far-side pedestrians. A near-side pedestrian is one who approaches from the side closest to the LTVs, and a far-side pedestrian is one approaching from the other side.

Five areas, N1, N2, F1, F2, and F3 (Figure 3), for pedestrians from different directions were defined in this study. The sizes of these areas changed based on the choice of the LTV-receiving lane. The pedestrians in the conflict areas (N2 and F1), which are defined in the manual, not only influence the LTV maneuver, but also the other half of the crosswalk (F2) and waiting areas (N1 and F3). Based on the Japanese traffic law, LTVs must also yield to pedestrians who are about to cross. Therefore, to investigate the relationship between the vehicle yielding maneuver and number of pedestrians, the number of pedestrians in these five areas was recorded.

Figure 3. (a) Target areas for near-side pedestrians. (b) Target areas for far-side pedestrians.

In this study, the vehicle yielding maneuver was analyzed based on the yielding probability, which affects the capacity of the LT lane. The yielding probability \( P(\text{yielding}) \) is expressed by Equation (3), and it is the proportion of LTVs that choose to slow down or stop for yielding to pedestrians while passing the stop line to the total number of LTVs passing through the crosswalk within a certain time interval.

\[
P(\text{yielding}) = \frac{\text{No. of yielded LTVs}}{\text{No. of total LTVs}} \times 100\%. \tag{3}
\]

Several factors related to geometry and signals were used to evaluate the vehicle yielding maneuver based on different perspectives. To analyze the influence of each
factor, the yielding probability was calculated every 2 s. The average value of the yielding probability during each time interval of 15 min was estimated, because the pedestrian volume showed no significant variation over 15 min.

3.3. Empirical Analysis

Generally, the number of pedestrians, elapsed time from the onset of the PG, and crosswalk length are assumed to be the factors that influence the vehicle yielding maneuver.

Figure 4a shows the vehicle yielding probability at the Kanayama intersection with the number of pedestrians in different areas. For each area, sufficient samples existed with different mean values and low standard deviations (STDEVs), which were calculated using Equation (4). The STDEV values of each area indicate that all the data points \( X_i \) are close to the mean values \( X \). A comparison of the relationship between the yielding probability and number of pedestrians in each area indicates that the number of near-side pedestrians in N1 and N2 has a greater influence on the vehicle yielding maneuvers than those on the far side. A possible explanation is that drivers can notice pedestrians in N1 and N2 after passing the stop line and react to them first because they are very close. Moreover, when the distance between the far-side pedestrians and LTVs gradually increases, the correlation between them weakens because of the increasing gaps, thereby ensuring that the LTVs have sufficient time to cross.

\[
STDEV = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n - 1}}, \tag{4}
\]

Figure 4b shows that the vehicle yielding probability changes with elapsed time from the onset of PG \( t \). The PFG starts 42 s after the onset of the PG. When LTVs encounter a similar number of pedestrians in a similar area at 26, 28, and 46, the yielding probability is lower during the PFG than during the PG. This may be because LTVs do not want to wait for another cycle while waiting for pedestrians during a PFG. Therefore, vehicles are more willing to choose the crossing maneuver as time passes by.

Figure 4c shows the yielding probability of crosswalk length at the eastern crosswalk. Among these sites, the yield probability increases with crosswalk length. A possible explanation for this phenomenon is that the pedestrian flow on a longer crosswalk is larger, resulting in a continuous passage of pedestrians, which makes it impossible for vehicles to choose a suitable gap to cross.
The elapsed time from the onset of the PG

<table>
<thead>
<tr>
<th>Factors</th>
<th>Coefficient</th>
<th>Std. Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of pedestrian in area N1 $x_1$</td>
<td>$1.95 \times 100$</td>
<td>$3.96 \times 10^{-1}$</td>
<td>$(1.18 \times 100, 2.73 \times 100)$</td>
</tr>
<tr>
<td>No. of pedestrian in area N2 $x_2$</td>
<td>$1.55 \times 100$</td>
<td>$2.77 \times 10^{-1}$</td>
<td>$(1.00 \times 100, 2.09 \times 100)$</td>
</tr>
<tr>
<td>No. of pedestrian in area F1 $x_3$</td>
<td>$3.39 \times 10^{-1}$</td>
<td>$9.27 \times 10^{-2}$</td>
<td>$(1.57 \times 10^{-1}, 5.21 \times 10^{-1})$</td>
</tr>
<tr>
<td>No. of pedestrian in area F2 $x_4$</td>
<td>$3.83 \times 10^{-1}$</td>
<td>$1.35 \times 10^{-1}$</td>
<td>$(1.19 \times 10^{-1}, 6.47 \times 10^{-1})$</td>
</tr>
<tr>
<td>No. of pedestrian in area F3 $x_5$</td>
<td>$1.79 \times 10^{-1}$</td>
<td>$1.70 \times 10^{-1}$</td>
<td>$(-1.55 \times 10^{-1}, 5.13 \times 10^{-1})$</td>
</tr>
<tr>
<td>The elapsed time from the onset of the PG $t$ (s)</td>
<td>$-8.09 \times 10^{-3}$</td>
<td>$2.20 \times 10^{-3}$</td>
<td>$(-1.24 \times 10^{-2}, -3.77 \times 10^{-3})$</td>
</tr>
<tr>
<td>Crosswalk length L (m)</td>
<td>$9.57 \times 10^{-3}$</td>
<td>$5.82 \times 10^{-3}$</td>
<td>$(-1.86 \times 10^{-3}, 2.10 \times 10^{-2})$</td>
</tr>
<tr>
<td>Constant</td>
<td>$3.34 \times 10^{-1}$</td>
<td>$1.16 \times 10^{-1}$</td>
<td>$9.28 \times 10^{-3}, 6.60 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

$R^2 = 0.526$

Sample size 585

AIC 507.16

The estimation results of the explanatory variable coefficients for the vehicle yielding maneuver model are listed in Table 2. All three variables are significant. The number of pedestrians ($x_1$–$x_5$) and $L$ positively influence the vehicle yielding probability, whereas $t$ negatively influences it. And the results show that the number of pedestrians in the areas closer to the LTVs have more influence on the vehicle yielding maneuver, because vehicles need to give way to pedestrians when they are close.
Based on the results, near-side pedestrians have a significant influence on the vehicle yielding maneuver because of their proximity to the LTVs. For far-side pedestrians, those in F1 and F2 have an almost similar influence on the vehicle yielding maneuver. This phenomenon may be attributed to the fact that, on most crosswalks, the size of F1 was very small. Hence, they had an influence on the yielding maneuver similar to those in F2. Thus, additional data under different geometric conditions at other crosswalks must be included in subsequent studies.

4.2. Validation of Vehicle Yielding Maneuver Model

The accuracy of the proposed model was validated using the empirical data obtained at the Kanayama and Suemori–dori intersections, which were not included in the model development. Basic information on the two crosswalks is as follows: the crosswalk lengths are 36 m and 17 m, PGs are 42 and 54 s, PFGs are 10 and 8 s, and pedestrian volumes during the observation time are 29 and 28 ped/h, respectively. A comparison between the observed and estimated yielding probabilities is shown in Figure 5. The mean absolute percentage error (MAPE) values of both crosswalks were 23.4%. The next section reveals that this model fits well and that it can be used to estimate capacity.

![Figure 5](image)

**Figure 5.** (a) Comparison of observed and estimated yielding probabilities at Suemori–dori intersection; (b) comparison of observed and estimated yielding probability at Kanayama intersection.

4.3. Sensitivity Analysis

Figure 6 shows the changes in the vehicle yielding probability relative to the changing number of pedestrians in each area, crosswalk length, and elapsed time. Considering that the change in yielding probability is more significant when the PG is about to end, an elapsed time of 50 s was selected to conduct a sensitivity analysis of the number of pedestrians and crosswalk lengths.

Figure 6a shows the yielding probability as a function of the number of pedestrians in each area. While testing the number of pedestrians in each area, those in other areas were set to zero to eliminate their influence. The near-side pedestrians have a greater influence on the vehicle yielding maneuver because of their proximity to the LTVs. However, for far-side pedestrians (F1 and F2), the yielding probability also varies considerably with the number of pedestrians. When the drivers of vehicles contemplate whether they should yield or cross, they confirm the number of pedestrians in the area to find a suitable gap to pass. Particularly, when a crosswalk is short, the pedestrians in the area are very close to the vehicle, and proceeding to cross is more dangerous. Hence, the yielding probability for F1 and F2 increases. However, pedestrians in F3 have less impact on the vehicles. This is because they are very far from the LTVs. Thus, the LTVs may require considerable time to wait for them to pass.
were set to zero to eliminate their influence. The near-side pedestrians (N1 and F3) to determine the most obvious changes. Figure 6b shows the effect of the crosswalk length on the vehicle yielding probability. The crosswalk length has no considerable influence on the vehicle yielding maneuver for near-side pedestrians. For far-side pedestrians, when the crosswalk is longer, the probability of the vehicles yielding to the pedestrians is higher. This is because, in the empirical data used in this model, there were usually a higher number of pedestrians on long crosswalks, such as the north and south approach of the Kanayama intersection. When vehicles encounter a high pedestrian demand, finding a suitable gap to pass is difficult for them, because pedestrians constantly pass through and occupy the crosswalk. Hence, the vehicles can only use the pedestrian “red” time, which is only a short period.

As shown in Figure 6c, as the time increases, the vehicle yielding probability gradually decreases. This is because, towards the end of the PG or even the PFG, the number of pedestrians gradually decreases so that the vehicle has a suitable gap to pass through. Additionally, a vehicle does not want to wait for another cycle. Therefore, at the end of the entire cycle, the change in the vehicle yield probability over time is more prominent.

4.4. Case Study: Monte Carlo Simulation

A case study to estimate the capacity of the LT lane was conducted by using a Monte Carlo simulation based on the above model, which can represent the yield maneuver of the LTVs. The vehicle chooses to pass or yield under the influence of different pedestrian numbers in different areas and the maximum number of vehicles that can pass the crosswalk per hour is calculated to represent the actual situation.

Figure 7a shows a flowchart of the Monte Carlo simulation in this study. After inputting the elapsed time, signal-related factors of the length of pedestrian green time (PG)
and pedestrian flashing green time (PFG), cycle length, pedestrian volume, and geometric conditions of the subject crosswalk, the simulation starts from \( t = t_0 \) with is the onset of pedestrian green time and vehicle green time. Then, the LTVs which arrived at the stop line start approaching the crosswalk. Furthermore, the number of waiting pedestrians who enter the waiting area during the first 8 s from the onset of the PG in all the five areas can be obtained based on the Pedestrian Presence Probability (PPP) model (Emagnu et al., 2021 [22]), while that of arriving pedestrians in the five areas can be obtained based on the uniform distribution.

![Diagram](https://example.com/diagram.png)

**Figure 7.** (a) The flowchart of the Monte Carlo simulation. (b) Comparison results of different methods.

After calculating the number of pedestrians in each area, the yielding probability for each vehicle at time \( t \) can be estimated based on the vehicle yielding maneuver model. Additionally, to ensure the accuracy of the simulation, LTVs decide whether to yield or cross every 2 s by comparing the estimated probability with a random yielding probability. When the random probability is larger than the estimated value, the LTVs pass the crosswalk and the cumulative number of passed vehicles \( C \) is increased by 1, otherwise, they yield to pedestrians and the \( C \) will not be changed. This simulation procedure ends if the time \( t \) is greater than the sum of the PG and PFG of this cycle and the result of \( C \) is the capacity of LT lane in this cycle. Finally, in order to compare with the other suggested values in the manuals, the estimated capacity in one hour can be estimated by simulating several cycles over one hour.

For comparison with the estimated result based on the proposed method in this paper, the observed value and the estimated capacities based on the JSTE manual and HCM, the north crosswalk of Heian 2–Chome intersection was chosen, where crosswalk length is 26 m, pedestrian volume is 42 ped/h, PG length is 44 s, and PFG length is 10 s.

In the real world, it is very difficult to find a suitable intersection to count the capacity of LT lane. Thus, this study assumed the capacity in one hour by using several saturated cycles, which means that there was a large traffic volume in the LT lane continuously passing the crosswalk till the end of vehicle green time. The effect of crossing pedestrian depends on the pedestrian number and arriving time. By observing the cumulative number of vehicles passing under the similarly low pedestrian volume in both selected cycles with continuous vehicle queues, the observed capacity was calculated using Equation (6).

Considering the different impact of pedestrian arriving time on the capacity, the average number of passed LTVs is defined as the observed capacity in this paper.

\[
\text{Observed capacity} = \frac{\text{No. of vehicles passed during saturated cycle}}{\text{No. of saturated cycle}} \times \text{total cycle during one hour} \tag{6}
\]
In Figure 7b, it is indicated that the results of the JSTE manual and HCM were estimated based on the suggested values and method. Furthermore, the result of the proposed method is the average value of ten runs of the Monte Carlo simulation for each cycle. To focus on the influence of the pedestrians, the adjustment factor $f_L$ was calculated from the capacity using Equation (1) (Figure 7b).

The JSTE manual and HCM method overestimate the observed capacity. Furthermore, the estimated capacity based on the vehicle yielding maneuver model is the closest to the observed capacity at the north crosswalk at the Heian 2-Chome intersection, which is not utilized in the database of the yielding maneuver model. Therefore, it is indicated that this model can represent the traffic situation and is more reliable for estimating the capacity of the LT lane compared to other existing methods.

5. Conclusions and Future Works

The conclusion of this study delves into the investigation of vehicle yielding maneuvers and the proposition of a model for estimating the capacity of LT lanes by considering the influence of pedestrian location and crosswalk length on vehicle yielding maneuvers and pedestrian signal groups. It is noted that this model can not only consider the pedestrian volume, but also represent the pedestrian location, which is the innovative point compared with the existing method.

The validation of the vehicle yielding maneuver model extended beyond the initial crosswalk to include additional observed data from another intersection. The goodness of fit of the model in representing vehicle yielding maneuvers was affirmed through this validation process. However, it is acknowledged that validation was constrained to the Kanayama and Suemori-dori intersections due to time limitations.

To further assess the reliability of the proposed model, extensive investigations were conducted under diverse traffic and geometric conditions. The capacity estimation results were compared against various benchmarks, including the JSTE manual, HCM, and a Monte Carlo simulation based on the proposed vehicle yielding maneuver model, as well as observed data. Notably, the JSTE manual’s tendency to overestimate capacity due to high-saturation flow rates and an insufficient consideration of pedestrians in certain areas was discussed. In contrast, the capacity estimation method derived from the vehicle yielding maneuver model in this study was deemed reliable.

Future research endeavors should encompass a broader array of crosswalks featuring distinct geometric conditions to facilitate model development and application of a generalized capacity estimation method. This expansion should not only consider peak hours, but also incorporate off-peak hours to account for varying pedestrian volumes. Additionally, the inclusion of more refined vehicle and pedestrian characteristics, such as vehicle speed, vehicle type, and pedestrian group size, will contribute to a more comprehensive understanding of capacity dynamics.

Following the model’s refinement, the prospect of testing methods to mitigate vehicle–pedestrian conflicts while preserving traffic flow capacity is anticipated. Strategies such as signal optimization, involving the separation of pedestrian and left-turning vehicle signals, or the implementation of a two-stage crossing approach, will be explored. This anticipates a reduction in vehicle–pedestrian conflicts, subsequently leading to a decrease in air pollution and aligning with sustainability objectives.

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