Unsteady Queue Discharge Characteristics of Shared Left-turn Lane at Signalized Intersections in Japan

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Abstract: In Japan, where vehicles travel on the left side of the road, the queue discharge rates of shared left-turn lane usually show comparable fluctuation, due to different departure characteristics of through and left-turning vehicles as well as interactions with pedestrians and bicycles. For a better evaluation of signalized intersections and then corridor performance, this study investigates stochastic queue discharge rates starting from shared left-turn lane and empirically explores its implications. Results show that efficient utilization of shared lane by through traffic can significantly improve discharge rate. At lower and higher pedestrian-bicycle volumes, discharge rates are relatively reliable. While at middle levels of pedestrian demands, more random arrivals and interactions between pedestrians and vehicles lead to rather unstable saturation flow rate fluctuation. For the shared lane with a larger left turning radius, its discharge rates display a stable trend. A comparative analysis between observed saturation flow rates, Highway Capacity Manual (HCM, 2000) and Japanese guideline (JSTE, 2007) estimations indicate both HCM and Japanese guideline usually overestimate the discharge rates in shared left-turn lane in Japan.

Key Words: Signalized intersection, Queue discharge rate, Fluctuation, Shared left-turn lane

1. INTRODUCTION

1.1 Background
In urban corridor operational performance evaluation, the quality of service provided to drivers by signalized intersections is usually measured in terms of average delay or travel time when passing through. Despite great efforts from previous research, the estimation results of these MOEs (Measure of Effectiveness) are not so promising yet. One of the major reasons can be attributed to insufficient concerns regarding heavy or unbalanced turning movements and their interaction with through traffic, which leads to, especially during the near or over saturation periods, unsteady queue discharge rates of all individual movements, disrupted
progression bandwidth along the corridor, and then fluctuated control delay or travel time.

As shown in Figure 1, the evolution process of traffic flow on a given corridor link can be decomposed into four stages, including upstream arrivals, platoon diffusion, merging into lane groups and departure. During saturation periods, traffic flow interactions normally take the form of frequent blockages among lanes or lane-groups. One case among these is shared left-turn interaction. Since a shared left-turn lane allows both left-turn and through vehicles to proceed into the intersection, left-turners tend to have a slower discharge rate due to turning maneuver, which would reduce the departure efficiency of following through traffic. Moreover in Japan, left-turners often do not have a protected phase due to space limitations, that is, a permitted phase. Left turning vehicles have to filter through a conflicting traffic stream, represented by pedestrians and bicycles in the adjacent crosswalk. As a consequence, owing to a certain lane blockage probability this shared lane’s queue discharge rates would be reduced even further. Meanwhile, the distribution of through vehicles among the available approach lanes would significantly change for the reduced “attractiveness” of shared left-turn lane, thereby affecting upstream inflow propagation and delay or travel time estimation.

1.2 Problem Statement

The stochastic interaction or blockage effects from shared left-turners could pronouncedly influence the discharge efficiency of through traffic. Despite increasing efforts have been made on this critical issue, some problems remain to be addressed.

- First, most studies analyze the queue discharge rates of through movement at a through-left lane group level. Shared left-turn lane is usually integrated with neighboring straight-through lanes, which could result in mitigated effects of filtering left-turners on through discharge rates.
- Secondly, the extents of queue discharge rates in shared left-turn lane with regard to pedestrians and bicycles have not been explicitly analyzed or modeled during near or over saturated conditions in Japan. Although versatile simulation models have been developed or used, the reliability of simulation results cannot be guaranteed especially during saturated periods.

Correspondingly, when unstable discharging states come up, the average evaluation indices for through traffic (i.e. delay and travel time), estimated based on integrated shared left-turn treatments, may not be accurate enough to reflect the variation trend inherent in operational performance.
1.3 Objectives and Scope
For a better evaluation of corridor performance, the global research framework is proposed as shown in Figure 2. Under the stochastic influence of turning interaction, saturation flow rate (hereafter SFR) of through traffic and then lane selection would be analyzed first. Then stochastic delay or travel time estimation along the corridor would be further explored with taking signal coordination effects into consideration.

As an initial step, the paper aims to investigate stochastic queue discharge rate starting from shared left-turn lane, empirically identify the logical relationships between the discharge rate of a shared left-turn lane and its influencing factors on the basis of field observation, and finally explore its implications for operation evaluation. Meanwhile, this study can also be considered as an extension of the authors’ previous work (Tang and Nakamura, 2007).

However, this study has some limitations. There is only one selected signalized intersection where all the data types relative to shared left-turn lane were gathered although considerable care was taken to choose a study section with sufficient saturated cycle samples and significant shared left-turn blockage phenomenon. More study sites with varying characteristics should be considered in the future.

The remainder of the paper is organized as follows. A thorough literature review would be presented first and followed by the proposed methodology of SFR measurement for shared left-turn lane. The next section demonstrates the discharge rate fluctuation phenomenon of shared left-turn lane at one signalized intersection in Japan, with all the potential influencing factors being empirically investigated. Then the estimation methods in HCM and Japanese guideline (JSTE, 2007) are brought into comparison with observed SFRs. The last section summarizes conclusions of this paper and provides recommendations for future works.
2. LITERATURE REVIEW

The planning, design and operation of signalized intersections all require estimations for lane discharge rates or SFR under prevailing traffic, geometric and signal control conditions. However, SFR for shared left-turn lanes notably differs from that for straight-through lanes according to discharge characteristics. The former is characterized by interactions between through and left-turning traffic, as well as making turns using filtering gaps. Highway Capacity Manual (HCM, 2000) uses a set of adjustment factors to estimate the shared left-turn SFR based on ideal SFR of through traffic. Note in U.S., vehicles travel on the right side of the road while right-turns correspond to left-turns in Japan. Herein the SFR of a shared left-turn SFR (in Japan) is to be determined as,

\[ s = s_0 N F_{RT} \]  

Where \( s \) is the estimated SFR for shared left-turn lane, in vehicles per hour of effective green interval per lane (vphgpl); \( s_0 \) is the ideal SFR, taken to be 1900 vphgpl; \( N \) is the number of lanes in the shared left-turn group; \( F \) is the product of seven adjustment factors related respectively to lane width, heavy vehicles, approach grade, parking, blocking effects of local buses, area type, and left-turns (in U.S.); and \( f_{RT} \) is the adjustment factor for right-turns.

Besides, it is worth mentioning that the analytical model for right-turn adjustment dealing with pedestrian-bicycle blockage, describing the interactions of left-turners and pedestrians, uses a conflict-zone-occupancy approach, which can also be found in Routhail et al. (1998) and Allen et al. (1998). It is applied to estimate the average pedestrian and bicycle occupancy at the conflict zone respectively, and then determines the relevant occupancy combining the effects of both pedestrians and bicycles. However it is simply based on a regression model with no rigorous theoretical background.

Similarly in Japan, the types of adjustment factors used in the guideline by JSTE (2007) are almost the same, although implemented in the form of a through-vehicle equivalent.

\[ \alpha = \frac{100}{(100 - L) + E_{LT} \cdot L} \]  

Where \( \alpha \) is the adjustment factor for shared left-turn SFR; \( E_{LT} \) is the through-vehicle equivalent for left-turning vehicles; \( L \) is the proportion of left-turning traffic in shared lane.

All the factors above are derived on the basis of simulation results. One obvious drawback in this guideline (JSTE, 2007) is that no analytical model embedded in the simulation is presented. Only reference values simulated at ideal situations (i.e. green split equals to 0.5; pedestrian volume per cycle is set to 5, 20, 40 and 60.) are given, which makes it difficult for practical SFR adjustment under non-ideal situations. Kawai et al. (2005) also found the simulated factors may not satisfy all the boundary conditions in reality and sometimes significantly deviate from field observation.

Meanwhile as another representative of shared left-turn SFR research in Japan, Kawai et al. (2005) dealt with this curb lane SFR theoretically, and presented a discharging flow model by dividing green phase into four intervals according to respective discharge patterns. Gap acceptance theory is included with a certain lane blockage probability. It is found that both HCM and Japanese guideline (JSTE, 2007) usually overestimate the SFR for shared lane. The proposed analytical model is capable of describing the generalized release process in such a
great detail that its applicability is somewhat weakened by so much parameter calibration and assumption treatment in microscopic modeling.

Tang and Nakamura (2007) concentrated on SFR variability for through lanes in Japan through investigating discharge patterns. They also discovered the drivers at curbside through lanes may have kept close gaps during queue dissolving period to avoid being interrupted by the through traffic existing at neighboring shared left-turn lanes. But no more guidance was given on the magnitude of these potential friction influences. Nor was SFR of shared left-turn lane itself.

Giannopoulos and Mustafa (1996) compared and evaluated 1985 HCM, ARRB (Australian Road Research Board) and the Canadian methods by estimating SFR values for both shared left-through and shared left-through-right lane (one lane approach) against different opposing traffic volumes under permitted phase control. It was found shared left-through lanes (in U.S.) subject to high opposing volumes show far more wide SFR fluctuation when compared to one lane approach. However, the influences of confliction between pedestrians and right-turners from one lane approach were not revealed and analyzed in their results.

As for comparison of simulation, analytical model (e.g. HCM) and field observations, Rouphail and Eads (1998) focused on evaluating CORSIM’s effectiveness for shared lane SFR estimation under four levels (i.e. none, light, moderate and heavy) of pedestrian-bicycle volume. The results showed that both analytical and simulation models suggest less pedestrian impedance in contrary to field data. However, there is one apparent limitation of this study that both turning proportion in shared lane and pedestrian volumes are fixed. Under fixed simulation scenarios, the pronounced stochastic nature existing in these influencing factors cannot be adequately captured.

To sum up, some empirical studies have discovered or implied the discharge pattern in shared left-turn lane is more like a stochastic process, and the deterministic functions in existing guidelines for SFR estimation may not achieve so promising results yet. On the other hand, the SFR fluctuation for shared left-turn lane and its potential influence on the whole approach are not sophisticatedly taken into account in the capacity and delay estimation procedure. Therefore, this study intends to explore the stochastic nature of shared left-turn SFR, initially investigate the magnitude of variability it may occur, and make a comparison between observed SFRs and existing guidelines e.g. HCM. Hopefully, this work would serve as a basis for capacity and delay reliability analysis in the authors’ future work.

3. METHODOLOGY

3.1 Site Description

Being consistent with HCM, discharge headway was measured to estimate SFR in shared left-turn lane. Data used in this study was collected by video cameras from shared left-turn lanes on three approaches at Suemoridori-2 intersection, in Nagoya, Japan, as shown in Figure 3 (a). This intersection is on a key route to downtown area, characterized by higher vehicle volume and medium to high pedestrian-bicycle demands during peak hours. And the intersection is fixed-time controlled with a cycle length of 140 seconds. The signal phasing and timings are presented in Figure 3 (b). The left-turn phases are all permitted, indicating left-turners need to filter through conflicting pedestrian and bicycle streams. Also it should be noted that the pedestrian green phase ends 5 seconds earlier than the green phase (plus yellow time) for vehicles, as the most general case in Japan. This short green interval would be
crucial for SFR estimation in shared lane since both through and left-turn vehicles could fully utilize it without pedestrian interruption.

In addition, the three approaches selected have typical geometric characteristics (e.g. turning radius, turning angle, etc., as illustrated in Table 1), which generated a unique opportunity to study the influences that geometric characteristics may have on SFR estimation. The recording time was from 7:00 AM to 10:00 AM on June 16th and 18th, 2010 under good weather conditions, covering morning peak hours on weekdays. Only saturated cycle samples were selected for analysis, implying that all the passing vehicles in the cycle experience complete stop before passing.

### Table 1 Layout of the Suemoridori-2 Intersection

<table>
<thead>
<tr>
<th>Approach</th>
<th>Lane configuration</th>
<th>No. of Saturated cycles available</th>
<th>Lane width (m)</th>
<th>Left turning radius (m)</th>
<th>Left turning angle (degree)</th>
<th>No. of receiving lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>WB</td>
<td>LT, T, T, R</td>
<td>92</td>
<td>3</td>
<td>11.7</td>
<td>92</td>
<td>2</td>
</tr>
<tr>
<td>SB</td>
<td>LT, T, R</td>
<td>103</td>
<td>2.75</td>
<td>17.9</td>
<td>110</td>
<td>3</td>
</tr>
<tr>
<td>NB</td>
<td>LT, T, R</td>
<td>64</td>
<td>2.75</td>
<td>16.1</td>
<td>85</td>
<td>3</td>
</tr>
</tbody>
</table>

(Note: WB= Westbound, SB= Southbound, NB=Northbound; in Lane configuration, LT, T and R stand for shared left-turn lane, through lane and exclusive right-turn lane respectively; Left turning radius and Left turning angle are shown in Figure 3 (a) by taking Eastbound approach as an example; No. of receiving lanes refers to the total number of lanes in exit approach available for left turning vehicles.)

### 3.2 Data Processing

In this study, discharge headway is defined as the difference of passing time between the front axles of successive vehicles over the stop line. A time-recorder with a 1/10 second resolution helps data processing. Since only saturated cycles were selected for analysis, all discharged vehicles were either from a standing queue or joining the standing queue after the green light starts. To avoid the random impact of heavy vehicles on queue discharge, buses, mid-sized delivery trucks, and large trucks were excluded from the analysis. All the vehicles behind a large vehicle were also excluded. Then selected were saturated cycle samples with sufficient queue lengths and percentages of passenger cars.
Note here being different from HCM, saturation headway \( h \) in shared left-turn lane is obtained by averaging all the valid individual headways from the first vehicle, as shown in Equation (3).

\[
h = \frac{h_1 + h_2 + \ldots + h_{n-1}}{(n-1)}
\]

Where \( n \) is the number of queued vehicles, \( h_{n-1} \) is the \( n-1 \)th individual headway.

Then, saturation flow rate \( s \) is inversely proportional to saturation headway, which can be derived from Equation (4).

\[
s = \frac{3600}{h}
\]

Herein the reason why all the individual headways were taken into consideration is interpreted as follows. Generally, measuring shared left-turn SFR during permitted left-turn phase is complicated. HCM expects a steady discharging process in through lane after the first four vehicles crossing the stop line, as show in Figure 4. The proposed ideal SFR of 1900 vphgpl corresponds to a saturation headway of 1.9 seconds. Different from through lanes, the expected maximum discharge rate or constant saturation headways are hardly to be achieved in shared left-turn lane.

Instead, due to stochastic interactions between through, left-turn traffic, opposing pedestrians and bicycles, every discharge vehicle has the potential to get influenced. The vehicular movement in such a lane may not be continuous, so that discharge headways in shared left-turn lane usually show comparable fluctuation within the green phase. Figure 5 illustrates the phenomenon through one typical saturated cycle case at study site. Irregular fluctuations imply the stochastic diverging of through and left turning vehicles. Thereinto, some continuous extreme headways (e.g. over 5 seconds) correspond to total lane blockage situation caused by severe conflict between pedestrians and continuous left-turn vehicles. And it is more likely to happen at the beginning of green phase with heavy pedestrian-bicycle demands.

In this sense, the ideal discharge conditions and traditional saturation headway measurement methods are not often realistic in shared left-turn lane. Averaging all the valid individual headways practically represents the saturation headway resulting from “field departures” according to Li et al. (2002). It gives a more complete picture of the discharge process in shared lane considering stochastic interactions mentioned above.

![Figure 4 Headways in Through Lane in HCM (reproduced)](image1)

![Figure 5 Headways in Shared Left-turn Lane (One Typical Saturated Cycle Sample)](image2)
4. RESULTS AND ANALYSIS

4.1 Comparison of Shared Left-turn Lane Utilization

Turning proportion is a significant influencing factor on SFR estimation in shared lane. Meanwhile, it makes more sense with regard to lane group volumes in corresponding saturated cycles, based on the assumption that the shared lane utilization by through traffic would make a difference under different degrees of saturation in lane group or approach. Herein the lane group refers to the entity of through and shared left-turn lanes, which serves as a unit for analysis purposes.

Figure 4 shows the proportions of through traffic in shared left-turn lane to through-left lane group at WB, SB and NB approach, respectively. Note that the lane group at WB approach includes three lanes while two lanes at SB and NB approach. An increasing trend of shared lane utilization by through traffic could be roughly identified in Figure 6 (a) and (b) when traffic volumes rise. However, three approaches show different characteristics in terms of mean and standard deviation, as illustrated in Figure 6 (c). Due to more lane options available for through traffic, the proportions at WB approach are generally lower than those at SB and NB approach. The shared lane at SB approach is of highest utilization by through traffic. All these present a good scenario for subsequent SFR estimation and comparison.

![Figure 6 Proportion of Through Traffic in Shared Lane to Lane Group](image-url)
4.2 Observed Queue Discharge Rates and Their Fluctuation

Figure 7 presents observed SFRs in shared left-turn lane at three approaches. Each point in the figure stands for one saturated-cycle-based SFR sample under corresponding left-turn proportion in shared lane, pedestrian and bicycle volume. In order to facilitate a better understanding of the interrelationship, a trend surface is built by Cubic Spline Interpolation (2001) with all the SFR sample points on. The color bar on the right side helps show SFR scales. Meanwhile Table 2 presents both mean and standard deviation of observed SFRs at three approaches, depending on left-turn proportions and pedestrian-bicycle volumes at regular intervals.

(a) WB Approach  (b) SB Approach  (c) NB Approach

Figure 7 Observed SFRs in shared Left-turn Lane under Certain Through Proportion, and Pedestrian-Bicycle Volume

Although the sample sizes do not seem quite enough, especially at NB approach, some basic trends or fluctuation characteristics could still be identified.

a) The SFRs are likely to decrease with increasing left-turn proportions in shared lane.

It is easy to understand because through vehicles in general have higher travelling speeds and more compact headways than left turners, while left-turn vehicles have to slow down to take the corner and filter through conflicting streams, which contributes to a greater chance of acquiring lower SFRs. Moreover in the cases with left-turn proportions in shared lane ranging from 0.8 to 1, the shared lane sometimes becomes a de facto left-turn lane and the SFRs would decrease even lower. The probability of this occurrence should be carefully identified before SFR estimation.

b) Strong relationships exist between the number of through lanes in approach, pedestrian-bicycle volume and SFR.

For WB approach, due to higher pedestrian and bicycle volume, the SFRs in shared left-turn lane usually drop below 1300 vphgpl, as shown in Figure 7(a). Considering three lanes available for through traffic, the shared lane is not fully utilized by through traffic. Even
though sometimes the impedance impact of pedestrians are lessened, through vehicles remain not willing to use this lane and try to avoid delays associated with filtering left-turners.

While in the case of SB and NB approach, Figure 7 and Table 1 illustrate most SFR values beyond 1400 vphgpl with less fluctuation. Due to limited lane option and shorter green time, through vehicles do not have much of a choice except making the best of green time together with left-turn vehicles. As a result, it allows for a higher through traffic utilization and a higher SFR in share lane.

Besides, it is interesting to notice that identical SFRs can be achieved in different “boxes” in Figure 7. For instance at WB approach (a), SFRs about 800 vphgpl can appear with a pedestrian-bicycle volume of 600 per hour, but may even correspond to both lower and higher left-turn proportions e.g. 0.4 and 0.9 in shared lane. It further indicates the influences of turning proportion and pedestrians would be stochastic, and single SFR value cannot solely determine one traffic state in shared lane. However, the sample sizes in this study are not conclusive enough to clearly define the SFR state for each “box”. Large amounts of data should be collected in the future for this purpose.

c) Turning radius serves as another key influencing factor on SFR estimation.

Note here one possible reason for SB and NB approach performing higher SFRs than WB can be attributed to turning radius. According to Table 1, SB approach has an obtuse left-turning angle of 103 degree as well as a large turning radius, 17.9 meters. NB approach has a nearly right angle as WB but with a larger turning radius, 16.1 meters. The empirical observations show the maximum storage number of left-turn passenger cars within these radiuses is 4 (with no lane-overtaking behavior expected). For WB approach, the value is 3 under relatively smaller turning radius. To a great extent, it makes a difference to turning speeds and total lane blockage probability, which might finally determine lower SFRs at WB approach.

d) Under a certain turning proportion, SFR fluctuation range tends to firstly increase and then decrease with rising pedestrian-bicycle volume.

As for SFR fluctuation range, the analysis focuses on standard deviation variations. Table 2 is indicative of a trend that relatively stable SFRs can be obtained under both lower (e.g. 0-200 per hour) and higher (e.g. 600-800 per hour) pedestrian-bicycle volume, while unreliable SFR states usually appear at the middle level of pedestrian demand (e.g. 200-600 per hour). One possible explanation for the trend is different arrival characteristics. Under lower demand, the effect of pedestrian and bicycle arrivals on left turning vehicles is not significant enough. The influences on SFR mainly come from through and left turning traffic interaction. When pedestrian demands increase to middle level, their random arrival would have significant impacts on SFR fluctuation through interactions with left turners in a rather stochastic way. Then at high levels of pedestrian demand, despite severe influences on SFR, its fluctuation range is relatively stable because left turners must wait longer till finding gaps in dense pedestrian and bicycle streams, thus leading to lower SFRs but less fluctuation.

Limited by sample size in the current research, explicit reliability measures cannot be obtained to a more detailed level of turning proportions and pedestrian volumes. More comprehensive surveys should be conducted in future.
### Table 2 Saturation flow rates for shared left-turn lanes

<table>
<thead>
<tr>
<th>Proportion ranges of LT traffic in shared lane</th>
<th>Pedestrian and Bicycle Volume (No. per hour)</th>
<th>WB Approach</th>
<th>SB Approach</th>
<th>NB Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Saturation Flow Rates of Shared Left-turn Lane (vphgpl)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sample Size</td>
<td>Mean (Std.dev)</td>
<td>MAPE (v.s. HCM)</td>
</tr>
<tr>
<td>0.2-0.4</td>
<td>0-200</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>200-400</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>400-600</td>
<td>3</td>
<td>1274 (131)</td>
<td>26.71%</td>
</tr>
<tr>
<td></td>
<td>600-800</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.4-0.6</td>
<td>0-200</td>
<td>4</td>
<td>1323 (124)</td>
<td>20.30%</td>
</tr>
<tr>
<td></td>
<td>200-400</td>
<td>16</td>
<td>1321 (165)</td>
<td>21.38%</td>
</tr>
<tr>
<td></td>
<td>400-600</td>
<td>4</td>
<td>1155 (128)</td>
<td>38.42%</td>
</tr>
<tr>
<td></td>
<td>600-800</td>
<td>3</td>
<td>1012 (165)</td>
<td>47.13%</td>
</tr>
<tr>
<td>0.6-0.8</td>
<td>0-200</td>
<td>11</td>
<td>1304 (155)</td>
<td>18.05%</td>
</tr>
<tr>
<td></td>
<td>200-400</td>
<td>26</td>
<td>1199 (207)</td>
<td>24.49%</td>
</tr>
<tr>
<td></td>
<td>400-600</td>
<td>5</td>
<td>976 (193)</td>
<td>38.64%</td>
</tr>
<tr>
<td></td>
<td>600-800</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.8-1.0</td>
<td>0-200</td>
<td>8</td>
<td>1299 (199)</td>
<td>15.88%</td>
</tr>
<tr>
<td></td>
<td>200-400</td>
<td>9</td>
<td>914 (160)</td>
<td>43.80%</td>
</tr>
<tr>
<td></td>
<td>400-600</td>
<td>4</td>
<td>770 (81)</td>
<td>64.69%</td>
</tr>
<tr>
<td></td>
<td>600-800</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**MAPE of all samples**: 27.43% 20.00% 11.91% 10.05% 16.65% 13.37%

**RMSE of all samples**: 330 243 199 183 271 175
4.3 **SFR Field Observation versus HCM and Japanese Guideline**

HCM and Japanese guideline (JSTE, 2007) are brought into comparison with SFR field observation. The ideal SFR in HCM (1900 vphgpl) is adjusted for the less-than-ideal conditions in shared left-turn lane. Herein all the adjustment factors used are shown in Equation (1). On the other hand, according to Japanese guideline (JSTE, 2007), the ideal SFR value for shared left-turn lane is 1800 vphgpl, and adjustment factors are based on simulation results. Limited by space, the specific adjustment description is not reviewed here. Instead, emphasis is put on results comparison and analysis.

Figure 8 presents the estimation comparison of observed SFRs and adjusted SFRs by HCM and Japanese guideline (JSTE, 2007) in shared left-turn lane at three approaches. The 45-degree trend lines make it easier to identify that in most cases HCM and Japanese guideline overestimate SFRs in shared lane. This result agrees well with that stated by Kawai et al (2005).

Furthermore, in order to evaluate the relative margin of estimation errors, two statistics are applied: Mean Absolute Percentage Error (MAPE) and Root Mean Squared Error (RMSE). MAPE returns the absolute percentage difference in both values while RMSE returns the average absolute difference. Their equations are provided below.

\[
\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2} \quad (5)
\]

\[
\text{MAPE} = \left( \frac{1}{N} \sum_{i=1}^{N} \frac{|x_i - \bar{x}_i|}{x_i} \right) \times 100\% \quad (6)
\]

Where \(x_i\) is observed SFR, and \(\bar{x}_i\) is adjusted SFR by HCM.

As shown in Table 2, MAPE and RMSE of all samples show that HCM is more likely to overestimate SFRs for shared left-turn lane than Japanese Guideline. Also the results reveal the shared lane at WB approach with the highest estimation error and the NB approach takes second place. The shared lane with the lowest estimation error relates to SB with the largest turning radius or maximum storage of turning bays, which can be recognized as a significant factor to reduce the interaction between through and left turning vehicles.

For the detailed error analysis, HCM and Japanese Guideline yield increasing estimation
errors with rising pedestrian-bicycle demand under certain turning proportion. At this example intersection, the upper limit of pedestrian-bicycle volume during survey periods is 800 per hour (31 per cycle), still not significant enough. However, the larger estimation errors especially correspond to the pedestrian-bicycle volumes ranging from 400 to 600 per hour (16-23 per cycle). It is indicative of more random arrival and stochastic interaction between pedestrians and vehicles within this range, where the empirical conflict-zone-occupancy approach in HCM may show drawbacks to accurately estimate the relevant occupancy considering all the stochastic influences. So does the Japanese Guideline based on average simulation results. To solid the conclusion and determine concrete boundary values, more field observations are needed for quantitative analysis in the future.

5. CONCLUSIONS

Based on the empirical data, a detailed analysis on queue discharge rate and its fluctuation in shared left-turn has been done in this study. The influencing factors are concentrated on lane utilization, turning proportion, turning radius, pedestrian and bicycle volumes. It is found that efficient utilization of shared lane by through traffic can significantly improve SFRs. At lower and higher pedestrian-bicycle volumes, SFRs are relatively stable. While at middle levels of pedestrian demands, more random arrivals and interactions between pedestrians and vehicles lead to rather unstable SFR fluctuation. Moreover, it needs to be mentioned that identical SFR values can be achieved under different turning proportions and pedestrian volumes. In other words, single SFR value cannot solely determine one traffic state in shared lane. For the shared lane with a larger turning radius, its SFRs display a stable trend since more turning vehicles can be stored within turning bays, thus corresponding to less lane blockage probability. A comparative analysis between observed SFRs, HCM and Japanese guideline estimations indicate both of them usually overestimate the SFRs in shared left-turn lane in Japan.

Due to insufficient saturated cycle samples available in this study, the analysis may be limited in scope and quantitative evaluation. To solid the initial conclusions, firstly more comprehensive surveys should be conducted in the future. Secondly, more microscopic analysis on the stochastic interactions between pedestrians, left-turn and through vehicles would help interpret conflict mechanism and contribute to a stochastic SFR modeling. Thirdly, based on SFR fluctuation range, capacity and delay reliability at signalized intersections should be further explored as well as their implications for signal control and operational performance evaluation.
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