ANALYSIS OF SATURATION FLOW RATE FLUCTUATION FOR SHARED LEFT-TURN LANE AT SIGNALIZD INTERSECTIONS*

By Peng CHEN**, Hideki NAKAMURA*** and Miho ASANO****

1. Introduction

In urban corridor performance evaluation, delay or travel time reliability serves as a crucial measure of traffic condition and traffic signal operation. A lot of research has been done on delay estimation based on traffic state information (e.g. volumes or speeds). However, the results are not so promising. One important reason is that the fundamental parameters behind traffic states are not fully investigated.

Among them, saturation flow rate (*SFR*) is regarded as one of the key parameters in estimating the capacity and delay at signalized intersections. Traditionally, *SFR* is defined as a deterministic value, the maximum number of vehicles in a period of time (commonly in one hour green) that can pass through a given lane group. However, increasing research1) shows that even for the same given conditions, *SFR* may well vary within a certain range around expectations. In view of that, it is preferable to analyze *SFR* stochastically rather than deterministically.

In Japan, where vehicles travel on the left side of the road, the *SFR*s of shared left-turn lane usually show comparable fluctuation, due to different departure characteristics of through and left turning vehicles as well as complicated interactions with pedestrians and bicycles. Therefore the reliability of lane group capacity, even intersection capacity would be potentially affected. For a better evaluation of corridor performance, the paper aims to investigate stochastic *SFR*s starting from shared left-turn lane and empirically explores its implications.

2. Background and Literature Review

Probably the most significant situation that may reduce the *SFR* of a lane to less than ideal conditions (i.e., level grade, passenger cars, etc.) is when turning vehicles shared the lane with through vehicles. Turning vehicles tend to have a slow discharge rate due to turning maneuver. Moreover in the case of shared left-turn lane in Japan, left turners usually do not have a protected phase, 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. Consequently, owing to certain lane blockage probability the lane's discharge rate would be reduced even further. To sum up, the *SFR* of shared left-turn lane at signalized intersection may bear large fluctuation.

Existing methods or procedures for estimating the *SFR* of shared left-turn lane at signalized intersections, can be categorized as follows: *i)* adjustment factor methods, *ii)* gap acceptance theory and, *iii)* simulation models.

According to HCM2), various adjustment factors are used in the estimation of left-turn *SFR*s, e.g. adjustment for heavy vehicles, lane width, grade, left-turn movements, pedestrians and bicyclists. While in Australian3) and Japan4) models, the adjustment factors for shared lane are quite similar to the HCM values, although implemented in the form of a through-vehicle equivalent. Gap acceptance methods have also been proposed. Kawai *et al.*5) presented a theoretical discharging flow model of shared left-turn lane by dividing green phase into four intervals according to respective discharge patterns. Besides analytical models, simulations6) have also been employed to evaluate the effects of pedestrians and bicycles on left-turn vehicles at signalized intersections.

However in the existing studies so far, fixed or deterministic *SFR* estimation in shared left-turn lane is still in the majority. The stochastic nature or fluctuation range of *SFR* is not sufficiently taken into account for its potential influences on signal design and intersection operational evaluation. In this paper, the stochastic *SFR* in shared left-turn lane is empirically analyzed.

---

* Keywords: *Saturation flow rate, Fluctuation, Shared left-turn lane*

** Student member of JSCE, M. Sc., Dept. of Civil Eng., Nagoya University

(Furo-cho, Chikusa-ku, Nagoya 464-8603, JAPAN, Tel: 052-789-5175, Fax: 052-789-3837, Email: peng@genv.nagoya-u.ac.jp)

*** Member of JSCE, Professor, Dr. Eng., Dept. of Civil Eng., Nagoya University

**** Member of JSCE, Assistant Professor, Dr. Eng., Dept. of Civil Eng., Nagoya University

3. Study Site and Data Collection

Traffic 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 1**. The intersection was fixed-time controlled with a cycle length of 140 seconds. The left-turn phases are all permitted, indicating left turners need to filter through conflicting pedestrian and bicycle streams. 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 picked up for analysis, indicating that all the passing vehicles in the cycle experience complete stop before passing. Besides, the site was selected so that each approach has typical geometric characteristics (e.g. turning radius, turning angle, etc., are shown in **Table 1**. This generated a unique opportunity to study the influences that geometric characteristics may have on *SFR* estimation.

Suemoridori-2, Nagoya, Japan

Figure 1: Study site description (source: Google Earth)

Table 1 Outline of the Suemoridori-2 intersection

Approach	Lane configuration	No. of Saturated cycles available	Left turning radius (m)	Left turning angle (degree)	No. of receiving lanes
WB	TL, T, T, R	92	9.7	88.3	2
SB	TL, T, R	103	17	117	3
NB	TL, T, R	64	16.5	88.7	3

(Note: WB= Westbound, SB= Southbound, NB=Northbound; in lane configuration, TL, 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 1** 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.)

4. Analysis Methodology

Being consistent with HCM, discharge headway was measured to estimate *SFR* in shared left-turn lane. In this study, it 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 is obtained by averaging all the valid individual headways, as shown in **Equation (1)**:

$$h = (h_1 + h_2 + \ldots + h_{n-1}) / (n-1) \tag{1}$$

Where n is the number of queued vehicles, h_{n-1} is the $n\text{-}1^{th}$ individual headway.

Then, saturation flow rate s is inversely proportional to saturation headway, which can be derived from **Equation (2)**.

$$s = 3600 / h \tag{2}$$

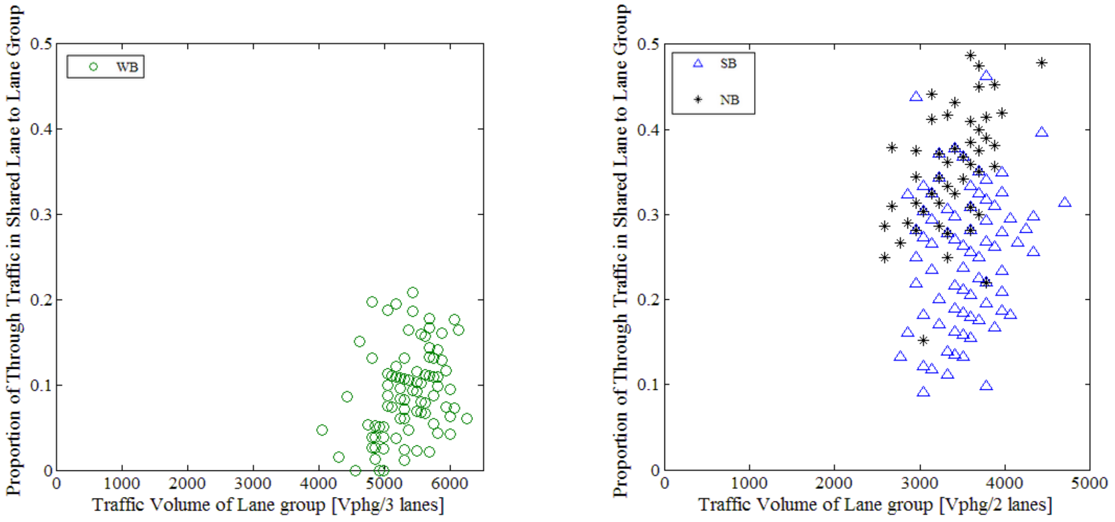
Herein the reason why all the individual headways were taken into consideration is interpreted as follows. Generally, measuring shared left-turn *SFR* during permitted left-turn phase is complicated. HCM expects a steady discharging process in through lane after the first several vehicles crossing the stop line. 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. Therefore discharge headways in shared left-turn lane usually show large fluctuation within the green phase. In this sense, averaging all the valid individual headways practically represents the saturation headway resulting from “field departures”. It gives a more complete picture of the discharge process in shared lane considering stochastic interactions.

5. Results of Analysis

(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. Here the lane group refers to the entity of through and shared left-turn lanes, which serves as a unit for analysis purposes.

Figure 2 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 when traffic volumes rise. However, 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.



(a) WB Approach

(b) SB and NB Approach

Figure 2: Proportion of Through Traffic in Shared Lane to Lane Group

(2) Observed *SFR*s and Fluctuation

Table 2 presents observed *SFR*s in shared left-turn lane at three approaches. Each *SFR* sample corresponds to a certain left-turn proportion, pedestrian and bicycle volume in one saturated cycle. In order to facilitate a better understanding of the interrelationship, both mean and standard deviation of *SFR*s are given. 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 *SFR*s 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 *SFR*s. Moreover in the cases with proportions of left-turn traffic in shared lane ranging from 0.8 to 1, the shared lane sometimes becomes a de facto left-turn lane and the *SFR*s would decrease even lower.

Table 2 Saturation Flow Rates for Shared Left-turn Lanes

Proportion ranges of LT traffic in shared lane	Pedestrian and Bicycle Volume (No. per hour)	Saturation Flow Rates of Shared Left-turn Lane (vphgpl)								
		WB Approach			SB Approach			NB Approach		
		Sample Size	Mean (ST DEV)	*MAPE* (*v.s.* HCM)	Sample Size	Mean (ST DEV)	*MAPE* (*v.s.* HCM)	Sample Size	Mean (ST DEV)	*MAPE* (*v.s.* HCM)
0-0.2	0-200	0	-	-	1	-	-	16	1522 (200)	20.43%
	200-400	0	-	-	1	-	-	6	1387 (133)	27.37%
	400-600	0	-	-	0	-	-	0	-	-
	600-800	0	-	-	0	-	-	1	-	-
0.2-0.4	0-200	1	-	-	23	1532 (143)	13.63%	19	1514 (112)	12.21%
	200-400	1	-	-	13	1424 (100)	11.05%	18	1420 (166)	18.84%
	400-600	3	1274 (131)	26.71%	2	-	-	0	-	-
	600-800	1	-	-	0	-	-	1	-	-
0.4-0.6	0-200	4	1323 (124)	20.30%	29	1489 (153)	10.79%	4	1402 (83)	15.79%
	200-400	16	1321 (165)	21.38%	12	1388 (189)	12.69%	1	-	-
	400-600	4	1155 (128)	38.42%	3	1215 (50)	12.68%	0	-	-
	600-800	3	1012 (165)	47.13%	0	-	-	0	-	-
0.6-0.8	0-200	11	1304 (155)	18.05%	18	1498 (130)	9.03%	1	-	-
	200-400	26	1199 (207)	24.49%	3	1342 (257)	17.24%	0	-	-
	400-600	5	976 (193)	38.64%	0	-	-	0	-	
	600-800	1	-	-	0	-	-	0	-	-
0.8-1.0	0-200	8	1299 (199)	15.88%	2	-	-	0	-	-
	200-400	9	914 (160)	43.80%	0	-	-	0	-	-
	400-600	4	770 (81)	64.69%	0	-	-	0	-	-
	600-800	0	-	-	0	-	-	0	-	-
MAPE of all samples				27.43%			11.91%			16.65%
RMSE of all samples				330			199			271

b) **Strong relationships exist between No. of through lanes available, pedestrian volume and *SFR*.**

For WB approach, due to higher pedestrian and bicycle volume, the *SFR*s in shared left-turn lane usually drop below 1300 vphgpl. 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, 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.

c) **Turning radius seems to be 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 117 degree as well as a large turning radius, 17 meters. NB approach has a nearly right angle as WB but with a larger turning radius, 16.5 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 *SFR*s at WB approach. Unfortunately, the sample size is not conclusive enough for a better analysis and comparison.

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

As for *SFR* reliability, the analysis focuses on standard deviation variations. **Table 2** is indicative of a trend that relatively reliable *SFR*s 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. 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 *SFR*s but higher reliability.

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.

(3) *SFR* Field Observation *versus* HCM

In the comparison between observed *SFR*s and HCM, an ideal *SFR* in HCM[2)] is adjusted for the less-than-ideal conditions in shared left-turn lane. Herein all the adjustment factors used are shown in **Equation (3)**.

$$s = s_0 f_w f_{HV} f_a f_{LT} f_{Lpb} \tag{3}$$

Where s is the estimated *SFR*, passenger cars per hour green per lane (pcphgpl);

s_0 is the ideal *SFR*, 1900 pcphgpl;

f_w is the adjustment factor for lane width;

f_{HV} is the adjustment factor for heavy vehicles;

f_a is the adjustment factor for type of area;

f_{LT} is the adjustment factor for left turns;

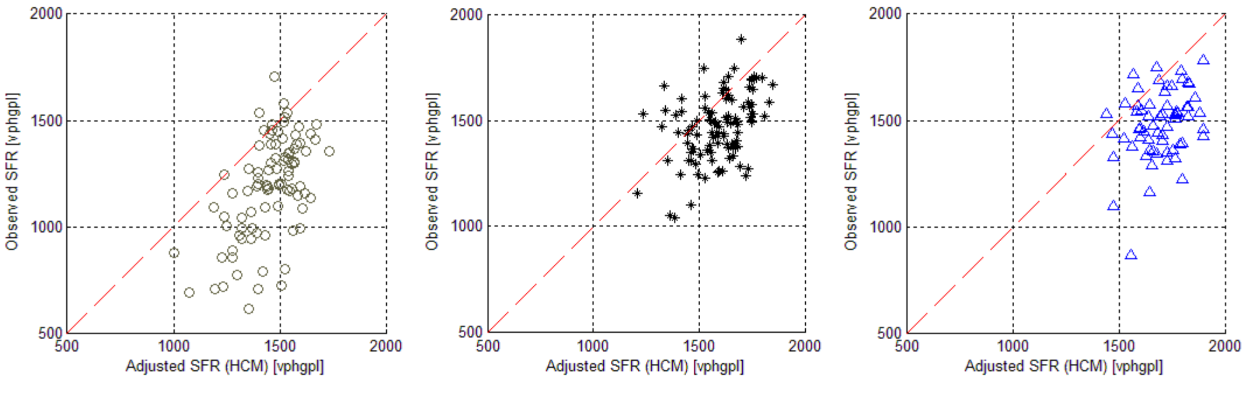
f_{Lpb} is the adjustment factor for pedestrian-bicycle blockage.

Besides, it is worth mentioning that the analytical model, describing the interactions of left turners and pedestrians, uses a conflict-zone-occupancy approach, as shown in **Equation (4)**. 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. At last all the associated adjustment factors are computed to estimate *SFR* in shared lane. Limited by space in this paper, concrete model description is not reviewed here. Instead, emphasis is put on results comparison and analysis.

$$f_{Lpb} = 1.0 - P_{LT}(1 - A_{pbT}) \tag{4}$$

Where P_{LT} is the proportion of left turning vehicles in shared lane, A_{pbT} is the permitted phase adjustment.

Figure 3 presents the comparison of observed *SFR*s and adjusted *SFR*s by HCM in shared left-turn lane at three approaches. The 45-degree trend lines make it easier to identify that in most cases HCM overestimates *SFR*s in shared lane. This result agrees well with that stated by Kawai *et al*[5)].



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

Figure 3: Comparison of Observed *SFR*s and Adjusted *SFR*s by HCM in Shared Left-turn Lane at Three Approaches

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. As shown in **Table 2**, *MAPE* and *RMSE* of all samples 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 yields 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 influences. To solid the conclusion and determine concrete boundary values, more field observations are needed for quantitative analysis in the future.

6. Conclusions and Future Works

Based on the empirical data, a detailed analysis on saturation flow 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 *SFR*s. At lower and higher pedestrian-bicycle volumes, *SFR*s are relatively reliable. While at middle levels of pedestrian demands, more random arrivals and interactions between pedestrians and vehicles lead to rather unstable *SFR* fluctuation. For the shared lane with a larger turning radius, its *SFR*s display a stable trend since more turning vehicles can be stored within turning bays. A comparative analysis of observed *SFR*s and HCM estimations indicate HCM usually overestimates the *SFR*s in shared left-turn lane. Due to small samples on hand, the analysis may be limited in scope and quantitative evaluation. More comprehensive surveys, and more microscopic analysis on the interactions between pedestrians, left-turn and through vehicles are needed to solid the conclusion in the future.

References

1) Tang, K. and Nakamura, H., An Analysis on Saturation Flow Rate and Its Variability, Proceedings of the 11th World Conference on Transportation Research, Berkeley, USA, 2007

2) Transportation Research Board, *Highway Capacity Manual 2000*, National Research Council, Washington, D. C.

3) Akcelik & Associates Pty Ltd, SIDRA Intersection User Guide, SIDRA Solutions, July 2009

4) Japan Society of Traffic Engineers (JSTE), *Revised Edition of Manual on Intersection Planning and Design*, 2007

5) Kawai, Y., Shikata, S., Katakura, M., and Oguchi, T., The Discharging Flow Model of Curb Lanes Concerning Pedestrians and Bicycles and the Analysis of Capacity at Signalized Intersection's Approaches. *Journal of Infrastructure Planning and Management* (JSCE), No.779/IV-66, pp 69-82. 2005

6) Rouphail, N. M., and Eads, B. S., Pedestrian Impedance of Turning-movement Saturation Flow Rates: Comparison of Simulation, Analytical, and Field Observations, *Transportation Research Record 1578*, Transportation Research Board, Washington, D. C., pp. 56-63, 1997