Lane Utilization Analysis within Lane Group under the Influence of Shared Left-turn Traffic

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In Japan the existence of shared left-turn lane usually serves as an important influencing factor contributing to imbalanced traffic distribution among through lane group of signalized intersections. This study investigates the lane utilization within through lane group by taking into account the effect of shared left-turn traffic. It is found that filtered traffic state in shared lane might cause through drivers to distribute themselves unevenly across straight-through lanes as well as in shared lane itself. However as the demand keeps increasing to near capacity, a more uniform use of straight through lane and shared left-turn lane is indicated by field data collected at four signalized intersections. Then after comparing two lane selection strategies, it is shown that equal flow ratio principle used in Highway Capacity Manual 2000 provides a better representation of traffic distribution and delay estimation than equal lane volume strategy, which has been adopted by current JSTE manual.

Key Words : *lane utilization, signalized intersection, through lane group, shared left-turn traffic*

1. INTRODUCTION

So far in the context of signalized arterial performance evaluation, the traffic system has always been assumed as one-lane approach or single service point. Within this simplified case the vehicles have no option than following the preceding vehicles and FIFO (First In First Out) rule holds in both arrival and discharging process. However, it is rather frequent in practice to observe more than one lane dedicated to a flow stream. Unequal lane utilization may potentially affect the delay estimation and vice versa.

In Japan, the existence of shared left-turn lane usually serves as an important influencing factor contributing to imbalanced traffic distribution among through lane group. As the attractiveness of this lane to through traffic decreases when left turning vehicles have to filter through opposing pedestrians and bicycles, representing the shared lane with equalized lane utilization as straight through lane fails to account for dynamic lane selection behavior in multilane intersections.

Therefore, the main objective of this paper is to study the lane utilization within through lane group by taking into account the effect of shared left-turn traffic. More specifically, the study is focused on exploring the influence on lane utilization based on empirical data, and evaluating different lane selection strategies. The remainder of the paper is structured as follows. The following part reviews literature related to lane selection strategies. Next, lane volume data collected in six approaches at four intersections are summarized and basic lane selection trends are analyzed. Then, two common lane selection strategies are evaluated as well as their indications on shared traffic. Finally, conclusions and recommendation for future work are provided.

2. BACKGROUND AND LITERATURE REVIEW

In real traffic, lanes can be differently preferred by vehicles for various reasons, e.g. stay on the lane to favor desired speed as well as waiting time at the signal, or choose a lane, which favors turning or parking operation at downstream intersections. In the case of shared left-turn lane along signalized corridor, left turning vehicles need to filter through conflicting pedestrian and bicycle streams during permitted phase. This would undoutedly increase the hesitation of through traffic to utilize this shared lane. In consequence, the distribution of flows within lane group holds a key to many other research, such as queue formation or delay estimation, all being important to arterial operational evaluation.

By far, a large body of methods or procedures can be found upon lane selection estimation, which indicate several common estimation principles.

i) Equal degree of saturation

The Australian method[1] for lane flow allocation applies an equal degree of saturation to describe the results of lane choice behavior, as shown in **Equation (1)**. The procedure is iterative in the software of SIDRA[2] until the calculated volume-to-capacity ratios are equal in choice lanes. Meanwhile, equal lane degrees of saturation mean equal utilization of available lane capacities.

$$\frac{q_1}{c_1} = \frac{q_2}{c_2} = \ldots = \frac{q_i}{c_i} \qquad (1)$$

Where i is the number of lanes within the lane group; q_i and c_i are the lane volume and capacity of lane i, respectively.

ii) Equal flow ratio

The criterion of equal flow-to-saturation-flow ratio is being used in Highway Capacity Manual 2000[3](hereafter referred to as HCM), as in **Equation (2)**. It differs from the previous one only because it does not consider the difference in effective green times among lanes. In the case of through lane group in Japan, effective green times are equal for through and shared lanes, so that equal degree of saturation method is equivalent to equal flow ratio method.

$$\frac{q_1}{s_1} = \frac{q_2}{s_2} = \ldots = \frac{q_i}{s_i} \qquad (2)$$

Where s_i is the saturation flow rate of lane i.

iii) Equal lane volume

This principle is adopted by current JSTE manual[4]. All the lanes within through lane group are assumed to bear equal traffic volume. This ideal assumption in **Equation (3)** usually tends to ignore the interaction between vehicles having different headway characteristics, further resulting in too ideal traffic distribution within lane groups, as illustrated by Kawai, Y. et al[5].

$$q_1 = q_2 = \ldots = q_i \qquad (3)$$

Besides, other criteria, e.g. equal average delay, minimum travel time or equal queue length, have been scrutinized by Akcelik[6] and Nevers[7]. In particular, Nevers[7] gained insights into lane selection estimation against field data in U.S.. It is found equal queue length strategy outperforms others in the cases of three signalized intersections with permitted shared through/left-turn lane. Worth mentioning is that no influence was taken into account from pedestrian flows, which apparently present themself as a significant part in shared traffic analysis. A direct effect from that would be higher estimates of through traffic in shared lane and underestimation of traffic flows in median lane.

Interestingly, Bonneson[8] describes the probability of a lane change as a function of motivation and opportunity. Under very low traffic conditions, drivers have little motivation to change lanes; and under very high traffic conditions, drivers have little opportunity to change lanes. Although his studies seem successful in deriving analytical results, no field investigation was provided regarding multilane application.

Although a lot of work has been done upon lane selection strategy analysis, a systematic study on lane utilization is still worth conducting against field data, especially for through lane group sharing left-turn traffic in permitted phase. The conflicts between pedestrians and permitted left-turn flow definitely poses challenges to estimation of shared lane utilization. In this paper, as a small step, field data are collected to empirically characterize the general trends of lane utilization. Meanwhile by use of real data, we are able to examine the rationality of existing lane selection strategies, and assess which criterion is most reflective of actual lane utilization at signalized intersections.

3. FIELD OBSERVATIONS OF LANE UTILIZATION

Lane volume data used in this study were collected by video cameras from 6 approaches at 4 signalized intersections of arterials in Nagoya City, as shown in **Table 1**.

Table 1 Outline of geometric characteristics, traffic flow conditions and signal control at the surveyed intersections in Nagoya, Japan

Intersection	Approach	Lane configuration	LW (m)	LT radius (m)	Pedestrian and bicycle volume per hour	PoHV (%)	G(s)	C(s)	No. of cycles	Survey Time
Sakurayama	EB	LT,T,R	2.75	23	120	3	45	140	83	7:20 -10:20
	WB	LT,T,R	2.75	19.7	191	3	45	140	83	
Ueda_yipponmatu	SB	LT,T,R	2.75	15.6	85	2	60	160	46	14:00-16:00
Kawana	NB	LT,T,R	3	26	78	3	50	150	72	7:20 -10:20
Suemoridori	SB	LT,T,R	2.75	17.8	131	3	42	140	135	7:00 -10:00 (2 days)
	NB	LT,T,R	2.75	16.1	129	3	42	140	135	

(Note: SB=Southbound, EB= Eastbound, WB= Westbound, NB= Northbound; LW = Lane Width of shared left-turn lane; LT radius = Left-turn radius; PoHV = Percentage of Heavy Vehicles; G = Green Time; C= Cycle Length; No. of cycles = Number of all the valid observation cycles.)

The intersections are all fixed-time controlled with cycle lengths ranging from 140 to 160 seconds. In order to guarantee evaluation of similar scenarios, all the chosen approaches have one permitted shared left-turn lane, one straight through lane and one right turn lane, as illustrated in lane configurations. It indicates that through traffic have options for using either straight through lane or shared left-turn lane within through lane group. Generally the distribution of through traffic is most affected by permitted left turning movements. Under high-volume opposing pedestrian flows, left-turn movements would be likely to block the curb lane, causing through traffic to shift towards median straight through lane.

Meanwhile in this study, drivers' behavior for lane selection was assumed not to be influenced by any upstream or downstream conditions or by significant on-road parking, bus maneuvers and even right-turning interaction. Correspondingly, only valid cycle samples were screened out for analysis. Cycle-based lane utilization data were aggregated into 15-minute intervals and converted to hourly flow rates. A total of 72 data sets were prepared. Each set represents 15 minutes of lane utilization data by certain left turn movements and opposing pedestrian and bicycle flow rates.

4. EMPIRICAL ANALYSIS OF LANE UTILIZATION TRENDS

Based on the data sets, through traffic distribution, especially shared left-turn lane utilization by through traffic, is characterized by left-turn flow rates, through lane group flow rates and opposing pedestrian and bicycle volume, as shown in **Fig.1**, **2** and **3**, respectively. In all three figures, the vertical axis represents the percentage of approach through traffic that discharges from shared left-turn lane. That is to say, 100 percent indicateds all through traffic use the shared lane; a zero percent indicates no through traffic use the shared lane, thus corresponding to the case of a *de facto* turn lane. Further details about each figure are presented as follows.

a) Influence of left turn flow on shared lane utilization

Fig.1 shows as left-turn flow rates increase, the percentage of through traffic in shared lane tends to decrease.

The result is reasonable because the increase of left-turn flow would lead to high probabilities of lane blockage even by small number of pedestrians or bicycles, causing shared lane less desirable for following through traffic. Accordingly a heavy use of straight through lane can be expected in the case of lane blockage. On the other hand, with lower left-turn flow (around 50 vph in observed cases), shared lane utilization by through traffic can hardly be regarded as equalized to median lane. It indicates median lane is prefered by through drivers, who have always been aware of the potential hindrance from left-turn flow interaction existing in shared lane.

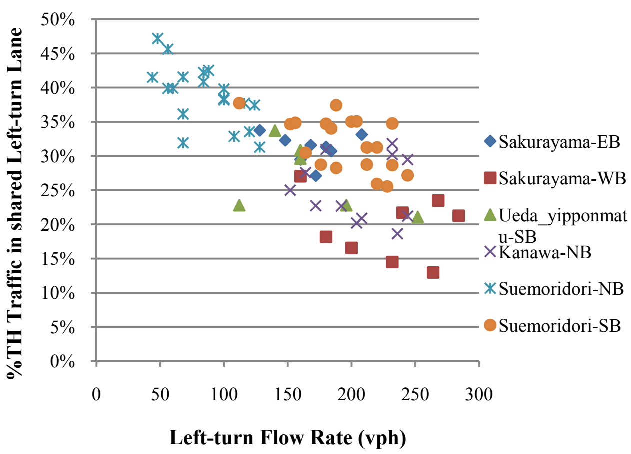

Fig.1 Influence of Left-turn Flow on Shared Lane Utilization

b) Influence of through lane group flow on shared lane utilization

Fig.2 illustrates the relationship between through lane group flow and shared lane utilization by through traffic.

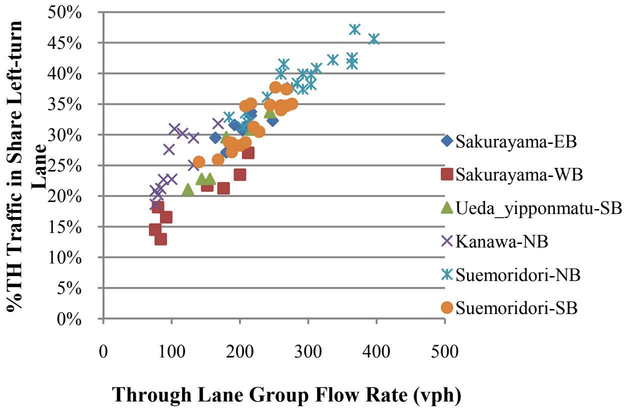

Fig.2 Influence of Through Lane Group Flow on Shared Lane Utilization

An increasing trend can be clearly identified as through lane group flow increases. It could be attributed to limited lane changing probability under higher flow conditions. In fact, the probability of lane changing is dependent on the headway distribution of vehicles on the target lane. Since median lane is always conceived as "safer" and heavily utilized (e.g. in WB approach at Sakurayama intersectioon), the likelihood for a through vehicle on shared lane shifting to median lane is low under high flow conditions. Therefore, the equality appears to occur in through group owing to seriously constrained lane choice behavior. This phenomenon is most typical in NB approach at Suemoridori intersection, as shown in **Fig.2**, which usually bear heavy through traffic.

c) Influence of opposing ped. And bike flows on shared lane utilization

Fig.3 depicts the effect of opposing pedestrian and bicycle volume on shared lane utilization by through traffic.

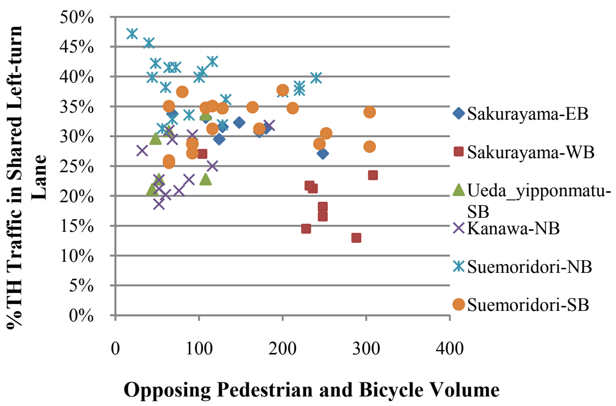

Fig.3 Influence of Opposing Flow on Shared Lane Utilization

The percentage of through traffic in shared lane varies scatteredly. One possible reason is that the real effects of pedestrian and bicycle flows on left-turn traffic, further on through traffic, are difficult to illustrate sophisticatedly. For instance, the transient shared lane blockage could be a product of many influencing factors, such as arrival time of opposing flows, the sequence of left-turn traffic within shared lane, even left turn radius and so on. Hereby, left turn bay could be regarded as buffer area to prevent lane blockage and in this sense decrease the influence on through traffic. In the case of NB approach at Kawana intersection, which holds the longest left turn radius, shared lane utilization by through traffic seems quite lower, narrowly varying between 18% and 32%. It indicates less effect on through discharging at this site, even during shared lane blockage periods. However, for more quantitative evaluation of opposing flow effects, comprehensive surveys are needed in future to ensure a more systematic analysis.

To sum up, the influence of left turn and through lane group flow appears to produce clearer trends than opposing flow with regard to shared lane utilization by through traffic.

5. EVALUATION OF LANE SELECTION STRATEGIES

In this part two lane selection strategies, equal flow ratio and equal lane volume method as introduced in Section 2, are evaluated against field data to determine the preferred one for reflecting actual operation conditions. Adjusted saturation flow rates according to HCM are used for analysis. The calculation detail is explained as follows.

Generally, HCM uses a set of adjustment factors to estimate saturation flow rate (hereafter referred to as SFR) of each lane. Following presented are SFR estimation equations for both straight through lane (i.e. **Equation (4)**) and shared left-turn lane (i.e. **Equation (5)**), respectively.

$$s_{TH} = s_0 f_w f_{HV} f_g f_a \qquad (4)$$

Where s_{TH} is the estimated SFR for straight through lane, vphgpl (vehicles per hour green per lane); s_0 is the ideal SFR, 1900 vphgpl; f_w is the adjustment factor for lane width; f_{HV} is the adjustment factor for heavy vehicles; f_g is the adjustment factor for grade; f_a is the adjustment factor for type of area.

$$s_{LT} = s_0 f'_w f'_{HV} f'_g f_a f_{LT} f_{Lpb} \qquad (5)$$

Where s_{LT} is the estimated SFR for shared left turn lane, vphgpl; f_w', f_{HV}', f_g' mean the same as the above; f_{LT} is the adjustment factor for left turns; f_{Lpb} is the adjustment factor for pedestrian-bicycle blockage.

By the way, the analytical model for f_{Lpb} in HCM[3)], describing the interactions of left turners and pedestrians, uses a conflict-zone-occupancy approach. 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.

Then, according to **Equation (2)**, we get

$$\frac{q_{TH}}{s_{TH}} = \frac{q_{LT}}{s_{LT}} \tag{6}$$

Where q_{TH} and q_{LT} are the traffic volumes on straight through lane and shared lane, respectively.

$$\frac{q_{TH}}{s_0 f_w f_{HV} f_g f_a} = \frac{q_{LT}}{s_0 f_w' f_{HV}' f_g' f_a f_{LT} f_{Lpb}} \tag{7}$$

Equation (7) can be simplified as **Equation (8)**.

$$\frac{q_{TH}}{f_w f_{HV} f_g} = \frac{q_{LT}}{f_w' f_{HV}' f_g' f_{LT} f_{Lpb}} \tag{8}$$

Since f_{LT} and f_{Lpb} are functions of left-turn proportion in shared lane, given the upstream arrival flow rates, traffic distribution could be approximated by simply solving the problem of cubic equations. Herein estimation results are focused on instead of concrete calculation process.

As one typical site, NB approach of Suemoridori intersection, was picked out for analysis. We try to avoid different influences coming from geometric characteristics, control plan and signal coordination effect at all sites. 15-minute data are aggregated for six hours, including lane volumes and opposing flows. Besides traditional mean and standard deviation, two other statistics, *Mean Absolute Percentage Error* (*MAPE*) and *Root Mean Squared Error* (*RMSE*), are introduced to evaluate the relative margin of estimation errors,. *MAPE* returns the absolute percentage difference while *RMSE* returns the average absolute difference.

(1) Lane Utilization Estimation by Lane Selection Strategies

Fig.4 gives the results of through traffic distribution in shared lane by lane selection strategies, corresponding to converted pedestrian and bicycle demand per hour. Their performance evaluation indices are illustrated in **Table 2**.

Table 2 Evaluation Indices for Through Traffic Distribution in Shared Lane by Lane Selection Strategies

	Equal flow ratio	Equal Volume	Field Observation
Mean(%)	42	44	39
Std.dev(%)	3	2	4
RMSE(%)	5	6	-
MAPE(%)	10.09	14.36	-

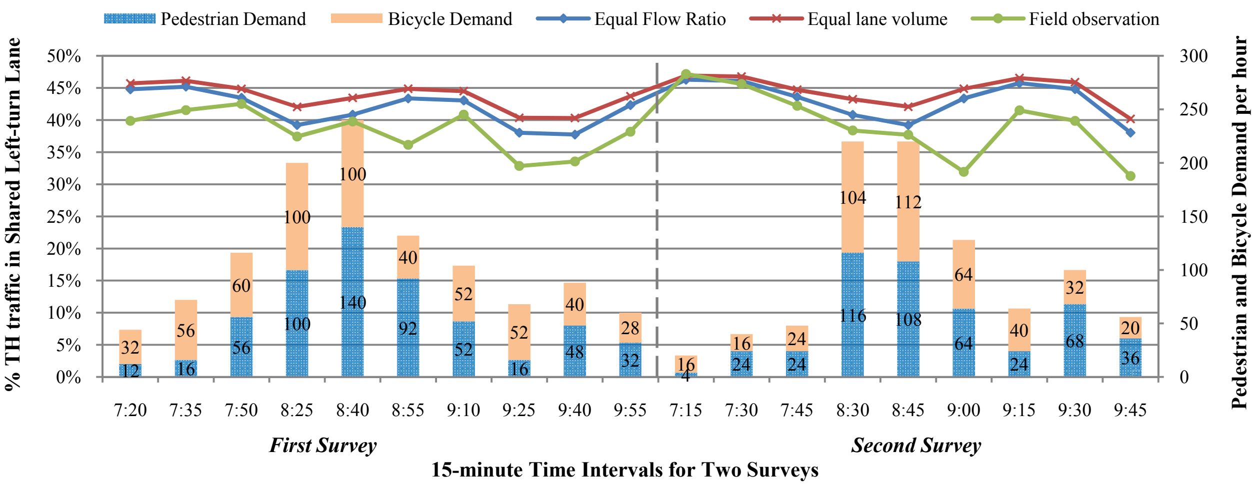

Fig.4 Comparison of Through Traffic Distribution in Shared Lane by Lane Selection Strategies

Field observation suggests, due to the influence of pedestrian or bicycle flows, shared lane utilization by through traffic usually bears larger fluctuation. The standard deviation helps to show it. On the other hand, both approximations by equal flow ratio and equal volume strategy display a general overestimation trend of shared lane utilization, as can be found in **Fig.4** or demonstrated by mean values in **Table 2**. *RMSE*s and *MAPE*s further indicate compared to equal lane volume, equal flow ratio strategy produces lower estimation errors.

The authors carefully re-checked the original data by taking into account the influence of pedstrian and bicycle flows. And it is found the effects of conflicting pedestrians and bicycles on shared traffic discharging, are hard to quantify especially at the middle level of opposing flow demands (limited by the data sample, we could only name it in this way). For instance, in the second survey of **Fig.4**, both lane strategies perform well from 7:00 to 7:45 am covering 3 samples with lower opposing flow demands. Following from 8:15 to 8:45 am, owing to higher pedestrian and bicycle demands, disparity starts to state itself in two estimation curves with the errors ranging from 2% to 5%. However, in the rest time of this survey, from 8:45 to 9:45 am, significant differences exist between estimation and field observation.

One possible explanation is that inaccurate estimation of shared left-turn SFRs may result in traffic distribution deviations, because the performance of equal flow ratio strategy is dependent on SFR estimation, especially for shared left-turn lane. To verify it, field observation of shared lane SFRs are used for comparison with HCM estimations, as shown in **Table 3**. The detail of field SFR calculation has been sophisticatedly introduced in Chen and Nakamura[9]. It is found HCM usually tends to overestimate shared lane SFRs, especially for middle level of pedestrian or bicycle demands, as vividly shown by the second survey results in **Table 3**. Meanwhile, the trend of SFR overestimation is consistent with that of shared lane utilization estimation by through traffic. It indicates the importance of SFR estimation for shared lane cannot be overemphasized in lane selection estimation. In order to avoid SFR estimation error as much as possible, derivation of more accurate SFR estimation method for shared lane is in need for future work.

As for equal lane volume strategy, it ideally assumes each lane to be equally utilized, but it is often inappropriate to reflect real traffic situation. Commonly, the attractiveness, or technically capacities of approach lanes, would always differ due to different movement effects. Drivers cannot be expected to favor shared lane even when facing heavy opposing pedestrian flows. In this sense, the equal lane volume strategy used in JSTE manual usually tends to overestimate through traffic distribution in shared lane.

(2) Lane Delay Estimation by Lane Selection Strategies

Inaccurate estimation of lane utilization would go on to influence lane-by-lane delay estimation. So as to illustrate the influence, we still use HCM delay equation to quantify its effects. The average control delay per vehicle is computed by **Equation (9)**. It is assumed HCM delay equation is valid in this study.

$$d = d_1(PF) + d_2 + d_3 \quad (9)$$

Where d=control delay per vehicle (s/veh); d_1=uniform control delay assuming uniform arrivals (s/veh); PF=uniform delay progression adjustment factor, which accounts for effects of signal progression; d_2=incremental delay to account for effect of random arrivals and oversaturation queues; d_3=initial queue delay, which accounts for delay to all vehicles in analysis period due to initial queue at start of analysis period (s/veh).

Table 3 Shared Left-turn Lane SFR HCM Estimation *v.s.* Field Observation in Two Surveys (vphgpl)

First Survey				***Second Survey***			
Time	HCM Estimation	Field Observation	Difference	Time	HCM Estimation	Field Observation	Difference
7:05-7:20	1667	1456	212	7:00-7:15	1686	1612	74
7:20-7:35	1667	1600	67	7:15-7:30	1680	1607	73
7:35-7:50	1638	1582	56	7:30-7:45	1654	1548	106
8:10-8:25	1566	1528	38	8:15-8:30	1580	1448	132
8:25-8:40	1576	1412	164	8:30-8:45	1559	1421	138
8:40-8:55	1632	1437	195	8:45-9:00	1635	1401	234
8:55-9:10	1636	1440	196	9:00-9:15	1674	1436	238
9:10-9:25	1599	1400	199	9:15-9:30	1656	1407	249
9:25-9:40	1586	1435	151	9:30-9:45	1600	1305	295
9:40-9:55	1639	1504	135				

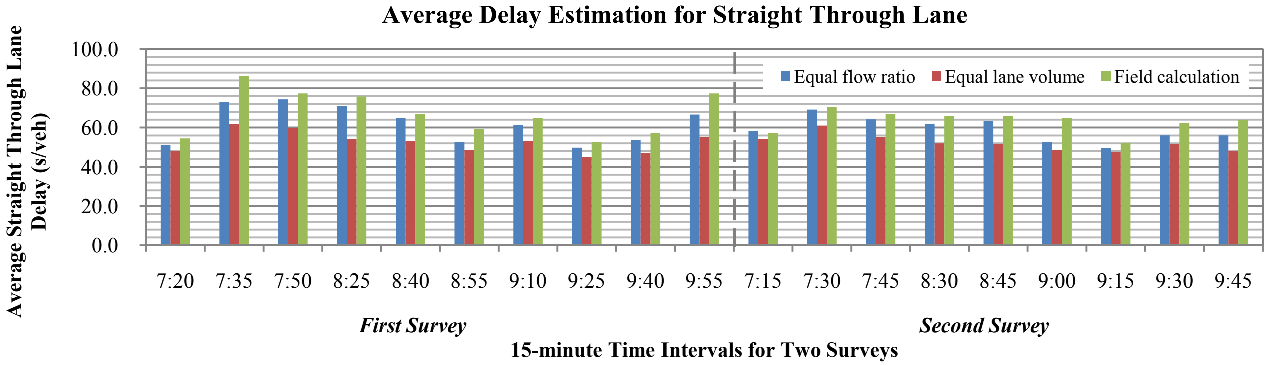

Fig.5 Comparison of Average Delay for Straight Through Lane by Lane Selection Strategies

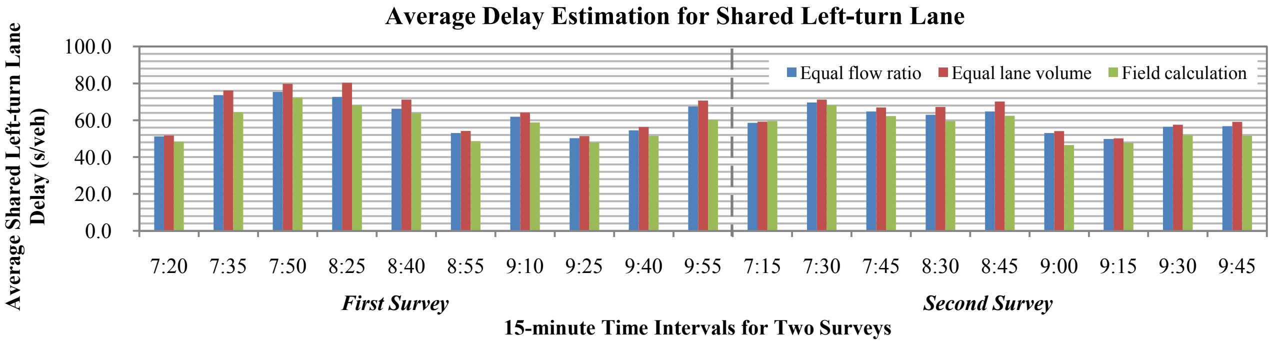

Fig.6 Comparison of Average Delay for Shared Left-turn Lane by Lane Selection Strategies

Table 4 Evaluation Indices for Delay Estimation by Lane Selection Strategies

	Equal flow ratio		Equal Volume		Field Calculation	
	TH	LT	TH	LT	TH	LT
Mean(s/veh)	60.5	61.2	52.5	63.7	65.4	57.6
Std.dev(s/veh)	8.0	8.3	4.8	9.7	9.2	8.1
RMSE(s/veh)	6.1	4.3	14.2	6.9	-	
MAPE(%)	7.5	6.6	19.2	10.7	-	

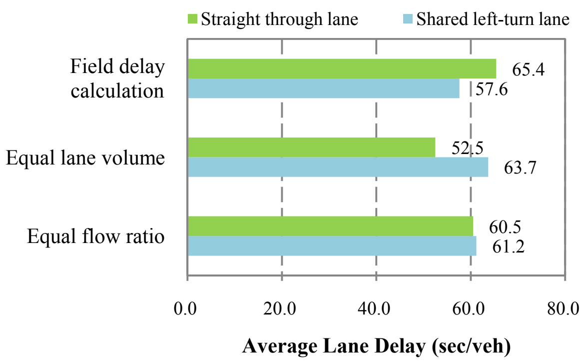

Fig.7 Comparison of Delay Estimation by Lane Selection Strategies

In the following part, **Fig.5** and **Fig.6** concentrate on comparison of average delay estimation for straight through lane and shared left-turn lane by two lane selection strategies.

For straight through lane, distinct trends could be identified through all delay estimates, and fluctuation stands out for equal lane volume. As to shared lane, delays tend to be overestimated by two strategies, with trends being similar to shared lane utilization estimation by through traffic. By means of evaluation indices shown in **Table 4** and **Fig.7**, the reasons for so marked a difference are explored as follows.

Table 4 and **Fig.7** suggest equal flow ratio strategy performs better than equal lane volume for through lane delay estimation, 60.5s *v.s.* 52.5s, although being no desirable in comparison with field average delay 65.4s. As for delay estimation of shared lane, equal flow strategy goes on outperforming its counterpart. Instead, general overestimation results appear for both strategies.

It is clear that, the disparity between delay estimates for through and shared lane, derives from the estimation results of lane utilization in previous section. Overestimation of through traffic distribution in shared lane definitely corresponds to higher delay in shared lane, meanwhile lower delay in through lane. And finally it would result in erroneous evaluation for arterial operational performance. In the following part more light is shed on the basic principles of two strategies as well as their shortcomings.

Usually the lane capacities are not equal, as straight through lane and shared lane in this case. Unequal lane flows often occur in real instead of ideal equal lane volume. Apparently, equal lane volume fails to consider the difference between their discharging characteristics. Such a simple assumption in JSTE manual would usually lead to oversaturation conditions and delay overestimation in shared lane during high-demand periods, which in real are often alleviated by dynamic through shifting to median lanes.

On the other hand, the equal flow ratio, mean equal utilization of available lane SFR or capacities (when effective green times are the same within lane group). In this case, equal flow ratio strategy provides a relatively satisfactory estimation of shared traffic distribution and delay calculation. However, it is worth noticing that the fluctuations by equal flow ratio, as illustrated in **Fig.5** and **6**, indicate somewhat inaccurate SFR estimation at various levels of pedestrian or bicycle demand. Serving as a basis for lane utilization and delay estimation, development of more authentic SFR esimation method calls for extensive field surveys in the future.

6. CONCLUSIONS AND FUTURE WORK

In signalized arterial operational evaluation, unequal lane utilization would potentially affect the delay estimation. Accordingly, this study analyzed the lane utilization within through lane group by taking into account the effect of shared left-turn traffic. The influence of left-turn flow rates, through lane group flow rates and opposing pedestrian and bicycle flows are empirically analyzed on the basis of lane volume data collected in six approaches at four intersections.

It is found that filtered traffic state in shared lane might cause through drivers to distribute themselves unevenly across straight-through lanes as well as in shared lane itself. But as the demand keeps increasing to near capacity, a more uniform use of all the lanes available within through lane group is indicated by real data. Besides, by comparing two lane selection strategies, equal flow ratio principle used in HCM provides a relatively better representation of traffic distribution than equal lane volume strategy, which is adopted by current JSTE manual. Given the close relationship between traffic distribution and delay estimation, the authors go on to analyze its effects on delay calculation. It is found equal flow ratio tends to take into account the operational difference between through lane and shared lane, and consistently provides satisfactory performance in delay estimates. The results are in accordance with Akcelik[6].

However, the findings should be validated through more data collection. Other lane selection strategies, e.g. equal perceived delay or travel time, equal queue length, also need to be investigated against field data. Additionally, since any approach is a steady-state approximation to a dynamic process[6], microscopic analysis, such as driver's behavior, traffic composition, are supposed to be noted within lane utilization evaluation.

Meanwhile, it is worth noticing that flow ratio is dependent on SFR estimation. For shared left-turn lane, its SFRs usually bear lots of fluctuation. Some research[5][9][10] have indicated that the current manuals tend to overestimate SFRs for shared lane, as **Table 3** in this study suggested as well. Accordingly, the allocated traffic distribution and further delay estimation would be getting influenced as well. In order to avoid SFR estimation error as much as possible, derivation of more accurate SFR estimation methods for shared lane is in urgent need. The author would like to leave it as a future work.

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