DEVELOPMENT OF LANE GROUPING METHODOLOGY FOR THE ANALYSIS OF SIGNALIZED INTERSECTIONS

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Abstract: The analysis of capacity and level of service of signalized intersections is accomplished primarily by each lane group in an approach. An exclusive left or right turn lane is a separate lane group. A shared turn-through lane could be either an actual shared lane or a de facto turn lane which operates as an exclusive turn lane. An actual shared turn lane is in a common lane group with through-lane. To identify a de facto turn lane, turning traffic volume is converted to through-car equivalent volume in terms of saturation headway. An assumption that a driver has a tendency to choose a less congested lane while approaching, waiting, or being discharged is used. Some mathematical equations are developed to discriminate an existence of equilibrium conditions that a de facto turn lane is based on.

Key Words: lane group, de facto turn lane, through-car equivalent

1. INTRODUCTION

The analysis of capacity and level of service of signalized intersections is accomplished by individual intersection approaches. An approach may consist of several lane groups having different operational performance, and each lane group is analyzed separately. The different operational performance of individual lane group is caused by both the geometry of the intersection, and the distribution of traffic movements.

An exclusive left-turn lane or lanes should be designated as a separate lane groups, because the traffic performance in this lane would not be the same as those in the other lanes. When an approach with more than one lane includes a lane that may be used by both turning and through-vehicles, it is necessary to determine whether equilibrium conditions exist, or whether there are so many turning movements that the lane essentially acts as an exclusive turn lane, which is referred to as a *de facto turn lane*. Thereupon, the *de facto turn lane* should not be included in a lane group with adjacent through-lanes.

If the equilibrium conditions exist, that is, two or more lanes are included in a lane group for analysis purposes, all subsequent computations treat these lanes as a single entity. Determination of the turning adjustment factors and saturation flow rates for the lanes with the equilibrium conditions is preceded by this lane grouping process. The methodology for lane grouping, however, does not have clearly been developed.

USHCM(2000) suggests some general guidelines:

i)An exclusive left-turn lane or lanes should normally be designated as a separate lane group unless there is also a shared left-through lane present, in which case the proper lane grouping will depend upon the distribution of traffic volume between the movements. The same is true of an exclusive right-turn lane.

ii)On approaches with exclusive left-turn or right-turn lanes, or both, all other lanes on the approach would generally be included in a single lane group.

iii)The existence of de facto left-turn in a shared lane can be identified by computing the proportion of left-turns in the shared lane. If the proportion equals 1.0, the shared lane is considered a de facto left-turn lane.

The second item above implies that an exclusive turn(*e.g.* left) lane would accompany a single lane group which comprises through-movements and the other turning(right) movements. However, if the other turning movements are so heavy to become another de facto turn lane, it could not be included in a single lane group. Considering about the third item above, even in a de facto turn lane, the proportion of left-turns may be less than 1.0, because some through-vehicles can arrive in the shared left-turn lane before the first left-turn vehicle.

2. CONCEPT OF LANE GROUPING

Lane groups can be categorized by the existence of the exclusive turn lane and type of signal controls. Table 1 shows various cases which are numbered according to the existence of exclusive left-turn lane and type of signal controls. Since the effects of right-turn is common in all the cases, right-turns are not considered in the numbering scheme.

Table 1. CASES by the Type of Left-Turn and Signal Controls

<table>
<tr><th rowspan="2">Left-Turn Lane / Type of Signal Control</th><th colspan="2">No. of Exclusive Left-Turn Lanes</th><th colspan="2">No. of Left-Turn Possible Lanes</th></tr>
<tr><th>1</th><th>2 or more</th><th>1[1)]</th><th>2 or more[2)]</th></tr>
<tr><td>Protected LT only</td><td rowspan="2">CASE 1</td><td rowspan="2">CASE 2</td><td colspan="2"></td></tr>
<tr><td>Protected LT+Through</td><td>CASE 4</td><td>CASE 5</td></tr>
<tr><td>Permissive Left-Turn</td><td>CASE 3</td><td></td><td>CASE 6</td><td></td></tr>
</table>

1) One shared left-through lane
2) One or more exclusive left-turn lanes with a shared left-through lane.

Lane grouping is basically to identify the exclusive turn lane and the existence of the de facto turn lane. The exclusive turn lane is easily identified from the geometry of the intersection. CASE 1, 2, and 3 are the cases where an exclusive left-turn lane group exists.

If a shared left-through lane exists as CASE 4, 5, and 6, an approach may have one of 4 lane group combinations as followings : i)a de facto left-turn and a shared right-through lane groups, ii)a shared left-through and a de facto right-turn lane groups, iii)a de facto left-turn, a through only, and a de facto right-turn lane groups, iv)all movements in a common lane group.

Even though CASE 5 has one or more exclusive left-turn lanes and a shared left-through lane, all these lanes are considered as shared lanes as CASE 4 or 6. This is because the left-turn and through movements in these cases utilize the same signal phase(*ie*., can not use a protected left-turn-only phase), during which all the left-turn-possible-lanes have a tendency to maintain the equilibrium conditions. When through-traffic volume is relatively high, for example, the left-turning vehicles in the shared left-through lane have a tendency to be forced out to the exclusive left-turn lane or lanes. As long as left-turn volume is not so high as to generate a de facto left-turn lane group, the tendency makes both the left-turn-possible-lanes and through-lanes to be in equilibrium conditions.

However, there may be a rare case where CASE 5 operates as CASE 2. The case occurrs when left-turn volume is very low in comparison with the number of left-turn lanes and through-traffic volume is very high so that the shared left-through lane operates as a de facto through-lane. In an aspect of efficient signal operations, the shared left-turn lane of this case should be converted into a through-lane.

The methods of lane grouping are summarized as followings:

i)Exclusive left-turn lane or lanes(CASE 1, 2, and 3) belong to a separate lane group. Even though a protected left+through signal phase is used, the operational performance of this lane group could not be the same as that of the other lane group or groups composed of through and right-turn lanes

ii)An approach having one shared left-through lane(CASE 4, 6) should be analyzed as to whether the lane is a de facto left-turn lane or equilibrium conditions exist among the left and through-lanes.

iii)Exclusive left-turn lane or lanes with a shared left-through lane(CASE 5) are considered as shared lanes. The procedures to identify a de facto left-turn lane is the same as in CASE 4 or 6.

iv)All the right-turning movements, right-turn lane or lanes, and lane grouping procedures are treated with the same manner as left-turn. Therefore, to discern the existence of a de facto turn lane(left or right, or both) in the approach, left and right turn movements must be considered simultateously with through movement.

After these lane grouping process, calculations of the turning adjustment factors and saturation flow rates are conducted for each lane group. Figure 1 shows possible lane groups according to the geometry of the approach.

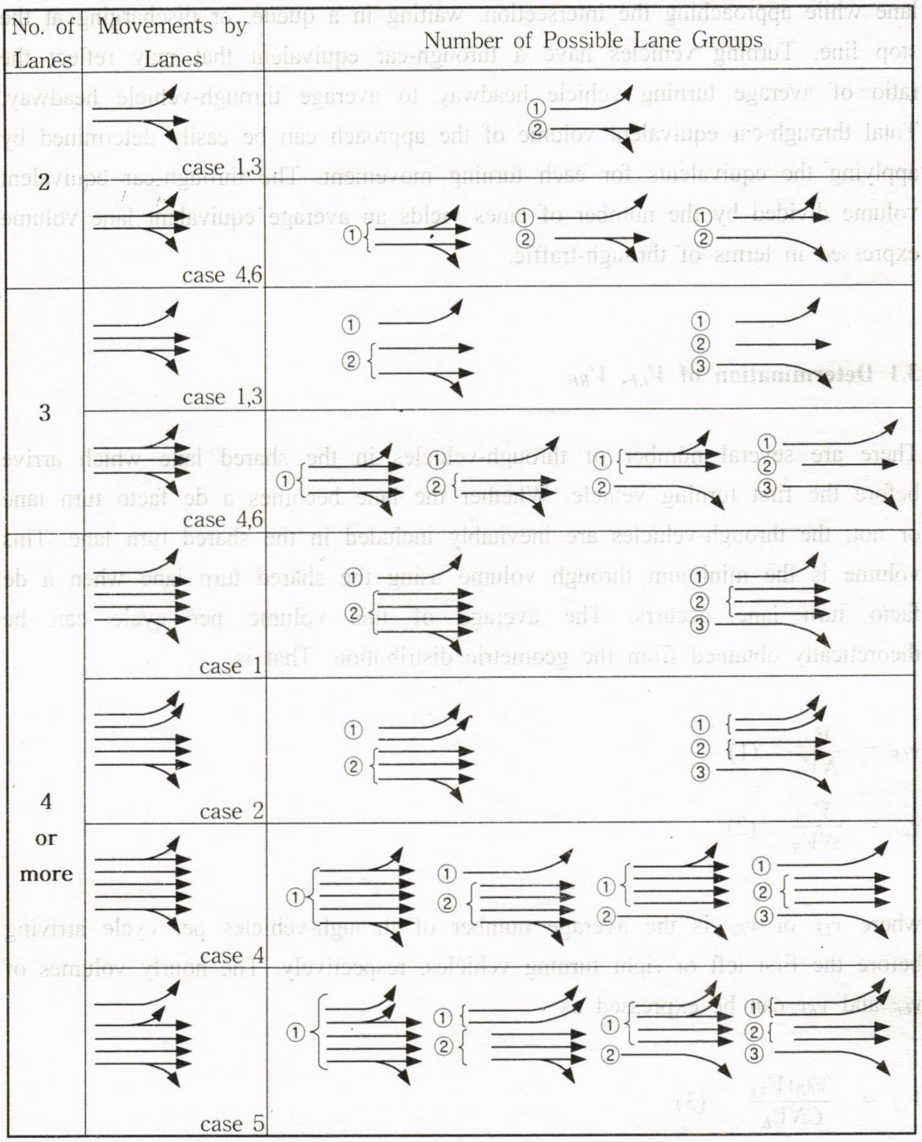

Figure 1. Typical Lane Groups for Analysis

3. METHODOLOGY FOR LANE GROUPING

Lane grouping with a shared turn-through lane is based on a primary assumption that traffic volume in each lane discharged at green time has a tendency to be balanced. The tendency implies that a driver would choose a less congested lane while approaching the intersection, waiting in a queue, or discharging at the stop line. Turning vehicles have a through-car equivalent that may reflect the ratio of average turning vehicle headway to average through-vehicle headway. Total through-car equivalent volume of the approach can be easily determined by applying the equivalents for each turning movement. The through-car equivalent volume divided by the number of lanes yields an average equivalent lane volume expressed in terms of through-traffic.

3.1 Determination of V_{LF}, V_{RF}

There are several number of through-vehicles in the shared lane which arrive before the first turning vehicle. Whether the lane becomes a de facto turn lane or not, the through-vehicles are inevitably included in the shared turn lane. This volume is the minimum through volume using the shared turn lane when a de facto turn lane occurrs. The average of this volume per cycle can be theoretically obtained from the geometric distribution. That is,

$$v_{LF} = \frac{V_{Th}}{NV_L} \quad (1)$$

$$v_{RF} = \frac{V_{Th}}{NV_R} \quad (2)$$

where v_{LF} or v_{RF} is the average number of through-vehicles per cycle arriving before the first left or right turning vehicles, respectively. The hourly volumes of v_{LF} and v_{RF} can be expressed as

$$V_{LF} = \frac{3600\, V_{Th}}{CNV_L} \quad (3)$$

$$V_{RF} = \frac{3600\, V_{Th}}{CNV_R} \quad (4)$$

where, C = cycle length(sec)
N = number of approaching lanes
(excluding the exclusive turn lanes for CASE 1, 2, 3)
= number of all approaching lanes for CASE 4, 5, 6
V_{Th} = through-traffic volume(vph)

V_L, V_R = left(or right) turn volume(vph)

Since CASE 5 has one or more exclusive left-turn lanes and one shared left-through lane, the former does not have V_{LF}. On the other hand, the latter has V_{LF} as the shared left-through lane in CASE 4 does.

Therefore, the V_{LF} and V_{RF} in CASE 5 can be expressed as;

$$v_{LF} = \frac{V_{Th}}{(N - N_L + 1)\,V_L/N_L} \quad (5)$$

$$v_{RF} = \frac{V_{Th}}{(N - N_L + 1)\,V_R} \text{ and } \quad (6)$$

$$V_{LF} = \frac{3600\,V_{Th}N_L}{C(N - N_L + 1)\,V_L} \quad (7)$$

$$V_{RF} = \frac{3600\,V_{Th}}{C(N - N_L + 1)\,V_R} \quad (8)$$

where, N_L = number of lanes possible to turn left
(including exclusive and shared left turn lanes)

3.2 LANE GROUPING BY CASES

The average through-car equivalent volume per lane, V_a, can be expressed as

$$V_a = \frac{V_{Th} + E_R V_R}{N} \text{ (for through and right-turn lanes in CASE 1, 2, 3)} \quad (9)$$

$$= \frac{V_{Th} + E_L V_L + E_R V_R}{N} \text{ (for all lanes in CASE 4, 5, 6)} \quad (10)$$

where E_L(or E_R) is an average through-car equivalent of left(or right) turning vehicles. This value is the average saturation headway of turning vehicle divided by that of through-vehicle, which reflects the extent of internal and external friction the turning vehicle experienced.

The average through-car equivalent volume per lane, V_a for the approach is compared with the through-car equivalent volume of turning vehicles plus V_{LF}(or

V_{RF}) in a shared turn-through lane. If V_a is higher than the later, the shared lane must be an actual shared turn-through lane. For example of left-turn, mathematically this is expressed as;

$V_a > E_L V_L + V_{LF}$ or

$V_a - E_L V_L > V_{LF}$ (11)

The left side of the second equation above means the total through volume using the shared turn lane. This volume comprises V_{LF} and additional through traffic discharged typically after turning vehicles. Therefore, in the actual shared lane, it is higher than V_{LF}.

On the contrary, if the sign of inequality in the equation above is opposite, the shared lane must be a de facto turn lane. This is the case when the through-car equivalent volume of turning vehicles plus V_{LF} in a shared turn-through lane is higher than the average through volume per through-only lane.

In operational analysis of a signalized intersection, though all lane groups in an approach move during the same green time, the de facto turn lane is analyzed separately due to difference of *v/c* ratios among lane groups. In planning or design analysis, one of the de facto turn lanes in a signal phase would be a critical lane group that determines the green-time requirements for the signal phase or gives a guideline on developing the phase plans.

When the de facto turn lane exists, a through-vehicle arrived in this lane during a red-time would; i)use this lane suffering from delay, or ii)change the lane and follow through-vehicle platoon in an adjacent through-lane. A through-vehicle arriving in a late part of green-time has a tendency not to use the de facto turn lane. In addition, a driver of through-vehicle familiar with this approach would avoid the lane whether he arrived early or late. Therefore, it is assumed that the through-traffic in a de facto turn lane is only V_{LF}(or V_{RF}).

The discriminant equations to discern a de facto turn lane for each CASE are summarized as follows:

(1) CASE 1, 2, 3

$$\frac{V_{Th} + E_R V_R}{N} - E_R V_R = (1/N)[V_{Th} - E_R V_R(N - 1)] < V_{RF}$$

(2) CASE 4, 6

$$\frac{V_{Th} + E_R V_R + E_L V_L}{N} - E_L V_L = (1/N)[V_{Th} + E_R V_R - E_L V_L(N - 1)] < V_{LF}$$

$$\frac{V_{Th} + E_R V_R + E_L V_L}{N} - E_R V_R = (1/N)[V_{Th} + E_L V_L - E_R V_R(N - 1)] < V_{RF}$$

(3) CASE 5

$$\frac{N_L(V_{Th} + E_R V_R + E_L V_L)}{N} - E_L V_L = (1/N)[N_L(V_{Th} + E_R V_R) - E_L V_L(N - N_L)] < V_{LF}$$

$$\frac{V_{Th} + E_R V_R + E_L V_L}{N} - E_R V_R = (1/N)[V_{Th} + E_L V_L - E_R V_R(N - 1)] < V_{RF}$$

As mentioned before, the left side of the inequality means the theoretically calculated total through volume using the shared turn lane. This volume denoted by V_{STL}, V_{STR} is very useful parameter to determine the proportion of turn volume in shared lane.

When considering both the left and right turning movements simultaneously, following criteria could be applied to lane grouping.

1) CASE 1, 2, 3

(1) discriminant equation

$$V_{STR} = (1/N)[V_{Th} - E_R V_R(N - 1)] \qquad (12)$$

(2) left-turn : exclusive left-turn lane group

(3) right-turn :

* If $V_{STR} > V_{RF}$: shared lane group

* If $V_{STR} < V_{RF}$: de facto right turn lane group and through lane group

2) CASE 4, 5, 6

(1) discriminant equation

For CASE 4, 6 : $V_{STL} = (1/N)[V_{Th} + E_R V_R - E_L V_L(N - 1)]$ (13)

$V_{STR} = (1/N)[V_{Th} + E_L V_L - E_R V_R(N - 1)]$ (14)

For CASE 5 : $V_{STL} = (1/N)[N_L(V_{Th} + E_R V_R) - E_L V_L(N - N_L)]$ (15)

$V_{STR} = (1/N)[V_{Th} + E_L V_L - E_R V_R(N - 1)]$ (16)

(2) lane grouping

* If $V_{STL} > V_{LF}$ and $V_{STR} > V_{RF}$: all movements in a lane group
* If $V_{STL} > V_{LF}$ and $V_{STR} < V_{RF}$: a shared left-turn lane group, and a de facto right-turn lane group
* If $V_{STL} < V_{LF}$ and $V_{STR} > V_{RF}$: a de facto left-turn lane group a shared right-turn lane group
* If $V_{STL} < V_{LF}$ and $V_{STR} < V_{RF}$: each movement has their own lane group

4. CONCLUSION

The paper describes the needs and methodology of lane grouping for the analysis of capacity and level of service of signalized intersections. The basic assumption used is that a driver has a tendency to choose a less congested lane while he is approaching, waiting, or being discharged. Exclusive turn lanes or lane makes a single lane group. If the left or right turning volume is relatively low in a shared turn lane, the lane is apt to be an actual shared turn-through lane. It means that the shared turn and through-movements are in a common lane group. If the turning volume is relatively high, the shared turn lane is apt to operate as an exclusive turn lane, that is a de facto turn lane.

The core of lane grouping is to identify whether a shared turn lane is a de facto turn lane or not. There may be two conditions for the shared turn lane to be a de facto turn lane. First, turning movements are relatively high comparing with through-volume per lane which is supposed to be assigned to the shared turn-through lane. Second, even though turning volume is low, the through-car equivalent of the turning vehicle is relatively high so that, the through-car equivalent volume of it is very high. The equivalents reflect the average headway of turning vehicles which is affected by turning movement, permissive left turn, bus stop, parking, and so forth. Some mathematical equations were developed to discriminate the existence of de facto turn lane, which are based on the concepts described above.

Since the methodology is quite theoretical one, some parameters such as V_{LF}, V_{RF} must be refined on the basis of real-world. In addition, it may be necessry that the equations for V_{STL} and V_{STR} are calibrated to reflect the actual through traffic volume of the shared turn lane. The through-car equivalents of the turning vehicles must be expressed to reflect the combined effects of internal and external frictions of the turning lane.

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REFERENCES

Ministry of Construction and Transport(2000)A study of improving highway capacity manual, Final report. **Ministry of Construction and Transport of Korea.**

Doh, Tcheol-Woong(2000)Problems of USHCM for signalied intersection and its solving alternatives. **Journal of Traffic Safety Research, Vol.19,** 17-27.

Transportation Research Board(1999)Highway Capacity Manual 2000, **Special Report 209.**

Doh, Tcheol-Woong(2000)Capacity analysis of permitted left turn with an exclusive left turn lane. **Journal of Korean Society of Civil Engineers, Vol.20, No.1-D**, 49-56.

Doh, Tcheol-Woong(1997)A theoretical study on right turn adjustment factor at signalized intersection, **Journal of Korean Society of Civil Engineers, Vol.17, No.III-4,** 315-321.

Doh, Tcheol-Woong(1996)A development of rigid model for left turn adjustment factor of permitted left turn-A theoretical approach, **Journal of Korean Society**

of Civil Engineers, Vol.16, No.III-6, 455-462.

Ministry of Construction and Transport(1992)Highway capacity manual. **Ministry of Construction and Transport of Korea**