Delay Evaluation at Urban Arterial with Mixed Intersection Control Types

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Proper choice of intersection control types is the well interest of practitioners in the planning stage since the proper intersection types significantly decrease delay and achieve higher travel speed in urban arterial. Mostly, existing studies have dealt with isolated intersection control types, while effects of adjacent intersections were not considered. This study aims to conduct a comprehensive study and propose a simple analytical framework for the delay evaluation on a corridor with combination of signalized intersections and roundabouts considering link length, various traffic demand cases and platoon dispersion effect. Hypothetical simple corridors with two signalized intersections, two roundabouts and mixture of signalized intersection and roundabout were selected for the comparison study. Delay as a measure of effectiveness of these corridors are compared. The result shows the effect of coordination and types of adjacent intersection is significant in the selection of subject intersection types in the corridor in the planning stage.

Key Words: *urban arterial, delay, intersections control types, signalized intersection, roundabout*

1. INTRODUCTION

Recently, as modern roundabouts are getting popular in all over the world as one of the alternative intersections, demands for proper selection method of intersection control types has been increased. Ideally speaking from the efficiency viewpoint, intersection types are selected such that has optimum performance in terms of delay minimization to achieve higher travel speed.

Numerous studies have been conducted for performance evaluation of intersection control types at isolated bases. Highway Capacity Manual (HCM 2000, Exhibit 10-15) provides guidance for the selection of isolated intersection control types based on traffic demand on major and minor flow[1,2,3].

However, mostly the researches, which have been conducted so far, is on isolated intersection and not in arterials. In arterial, the control types of each intersection most likely affect the performance of adjacent intersections each other. Therefore, the complicated traffic situations of the link should be considered on the evaluation of intersection control types. Minimal comparative study of corridors with different intersection control types have been conducted.

Roundabout corridors have been studied by Arineloo, et al.[4)] They investigated the impact of roundabout corridors on business and traffic flow improvement in US. Result of their study was shown that the average travel time was lower compared to the time when the corridors was signalized. However, this was just a case study with specific traffic demand cases.

There are many studies at signalized segments. HCM 6th edition[5)] proposed methodology for evaluating the performance of signalized segment in terms of running time and segment delay. However, the methodology does not account the corridor with different intersection types and the mixture of the intersection types.

Regarding corridor with mixture of signalized intersection and roundabouts, few case studies have been conducted. For instance, Bared and Edara [6] showed that average delay of roundabout was comparable to the signalization alternative when the roundabout was operating at or below capacity. Hallmark [7] showed though roundabout in a signalized corridor did not improve traffic flow operation, it does not adversely effect on traffic performance at the traffic volume he evaluated. However, those case studies are all based on specific road and traffic demand conditions which did not propose methodology for proper selection of intersection control types.

Considering foregoing discussions, comprehensive study is needed to develop a simple methodology for the selection of intersection control types in corridors. Therefore, the objective of this comprehensive comparative study is proposing simple methodology on selection of intersection types in the planning stage considering various link length, traffic demands and platoon dispersion effect.

2. Research Methodology

Delay is used as the measure of effectiveness (MoE). Using analytical framework as explained in following sections, delay is calculated by applying existing delay models on hypothetical segments.

(1) Overall structure of delay calculation

The proposed structure of delay evaluation method is mainly divided into two parts as shown in **Fig. 1**. The first part is the link model. In this model for the very first intersection (intersection *i*) uniform departure flow profile is assumed. Then link model is applied which arrival flow profile (AFP) in downstream intersection (intersection $i + 1$) from the given departure flow profile (DFP) of upstream intersection is calculated considering the propagation of platoon. The second part is intersection delay model (IDM) as shown in

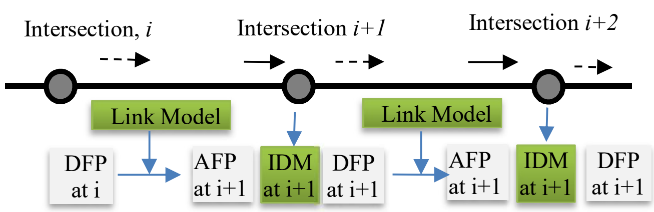

Fig.1 Overall Structure of Delay Calculations

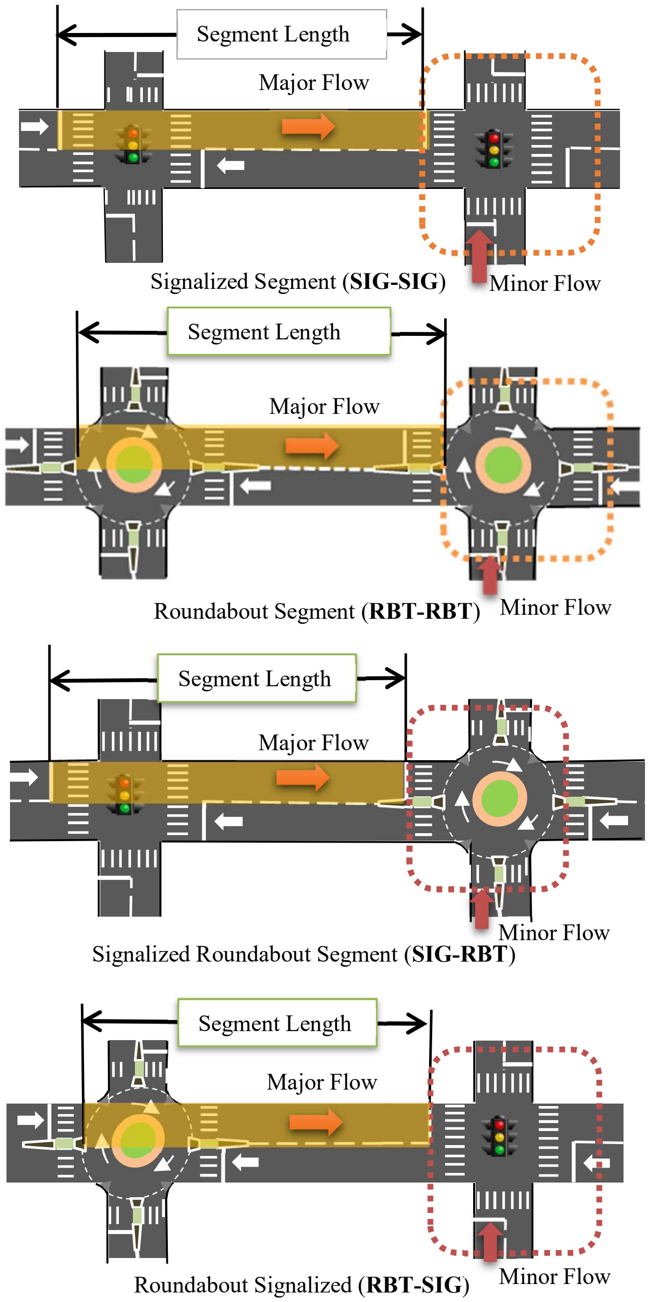

Fig.2 Hypothetical segments

Fig.1. In this model control delay based on the AFP is calculated. In this sense, mainly the link model and IDM is applied on hypothetical segments to calculate overall delay of the segments.

(2) Hypothetical segments

According to HCM, segment performance includes link performance and downstream intersection performance. Therefore, based on combination of intersection types on the segment four types of hypothetical segments as shown in **Fig. 2** is considered.

The first segment in **Fig. 2** is signalized segment which both boundary intersections of the segment is signalized intersections and shortly named as SIG-SIG. The second segment in the figure is roundabout segment which boundary intersections of the segment is roundabout and shortly named as RBT-RBT. The third segment is signalized roundabout (SIG-RBT) segment where the upstream intersection is signalized and the downstream intersection is a roundabout. The fourth segment type is roundabout signalized segment (RBT-SIG) where the upstream is a roundabout and the downstream is a signalized intersection.

The hatched areas in segments in **Fig. 2** represent the target area of the segments. A segment starts either at the stop line of the upstream signalized intersection or at the yield line of the upstream roundabout. The segment ends either at the stop line of the downstream signalized intersection or at the yield line of the downstream roundabout. Therefore, the segment delay includes the delay caused within the upstream intersection and the straight section of the segment and the delay to enter the downstream intersections which is bounded by dashed orange line. Segment delay calculation for each types of segments is explained in following sections.

(3) Link model:

For any types of DFP in upstream intersection the AFP is predicted. Mainly, two traffic features based on the segment type is considered; platoon dispersion and geometric delay as details and their impact on segment types are explained in following sections.

a) Platoon dispersion

Vehicles departing from the signalized upstream intersection after onset of the green phase start to move with short headways or tight platoons. As the platoon moves to downstream, gradually it tends to disperse because of speed variation of vehicles within the platoon. This phenomenon is so called platoon dispersion which is more dominant in SIG-SIG segment and also on segment which the upstream intersection is signalized.

There are two well-known platoon dispersion models; Pacey [8)] model and Robertson [9)] model. Seddon[10)] and Tracz[11)] conducted comparative evaluation of platoon dispersion models. They concluded, that Robertson model performed better in terms of accuracy, complexity and computation cost and has satisfactory agreement with field data. It is also the most well-known model which is implemented in TRANSYT software as well. Therefore, in this research Robertson model is applied.

AFP in downstream intersection is determined using Roberston model. In this model upstream signal cycle is divided into an integer number of intervals called time step, *dt*. According to HCM dt is between 1 to 3 seconds. In this research one second time step is used for the accuracy of the calculations. Input to the model is discharging flow profile of upstream intersection, as defined in terms of the flow rate for each time step.

Output of the model include the arrival time of leading vehicles in the platoon to the stop line at downstream intersection, and the flow rate for each time step at this intersection.

The general form of Robertson platoon dispersion model is as follows,

$$q'_{a|u,j} = Fq'_{u,i} + (1-F)q'_{a|u,j-1} \tag{1}$$

$$j = i + t' \tag{2}$$

where;
$q'_{a|u,j}$ = arrival flow in time step j at a downstream intersection from upstream intersection u (veh/step)
$q'_{u,i}$= discharge flow in time step i at upstream source, u (veh/step)
F = smoothing factor
j = time associated with platoon arrival time
t' = platoon arrival time, steps

The general forms of smoothing factor in Robertson model is shown as follows,

$$F = \frac{1}{1+(1-\beta)T'_r} \tag{3}$$

where;
T'_r = average running time in steps.
β = platoon arrival time calibration coefficient.

Bonneson et al.[12)] conducted regression analysis and proposed equation (4) for calculation of smoothing factor as it also used in HCM 6th edition. For calculation of smoothing factor equation (4) is used in this research.

$$F = \frac{1}{1+0.138t'_R+\dfrac{0.315}{d_t}} \tag{4}$$

$$t'_R = \frac{t_R}{dt} \tag{5}$$

where;
t'_R = segment running time (steps)

t_R =segment running time (s)
d_t = time step duration (s/step)

Segment running time which is shown in equation (5) is calculated by using equation (6). Conceptually, segment running time represents the sum of four-time components. The first component represents residual start-up lost time to account the difference between the real lost time and assumed lost time. The second component represents the free -flow running time and the proximity adjustment factor to account the effect of roadway geometry and traffic density. The third component represents delay to through vehicles when turn in access points. The fourth component delay due to other sources (i.g., curb parking, pedestrian, bicyclist, etc).

$$t_R = \frac{6.0 - l_1}{0.0025L} f_x + \frac{3{,}600\ L}{5,\ 280\ S_f} f_v + \sum_{i=1}^{N_{ap}} d_{ap,i} + d_{other} \quad (6)$$

where;
l_1 = start-up lost time (s)
L = segment length (ft)
f_x =control type adjustment factor (f_x=1 for signalized intersection)
S_f = free-flow speed (mile/h)
$d_{ap,i}$ = delay due to left and right turns from the street into access point intersection i(s/veh)
N_{ap} = Number of influential access point approaches along the segment.
d_{other} = delay due to other sources along the segment (e.g., curb parking or pedestrian) (s/veh)
f_v = proximity adjustment factor (calculated from equation 18-6 HCM 6^{th} edition)

Delay due to access point in the mid segment and delay due to other sources in equation (6) is assumed zero in this research.

Then platoon arrival time is calculated using equation (7).

$$t' = t'_R - \frac{1}{F} + 1.25 \quad (7)$$

In equation (7) the last constant term includes 1 plus 0.25. The value of 0.25 represents calibration coefficient based on field data and the constant value of 1 is part of the original model.

b) Geometric delay

Additional travel time created by geometric features of roundabout that cause drivers to reduce their speed is so called geometric delay. This is one of the difference in traffic features of the link in roundabout

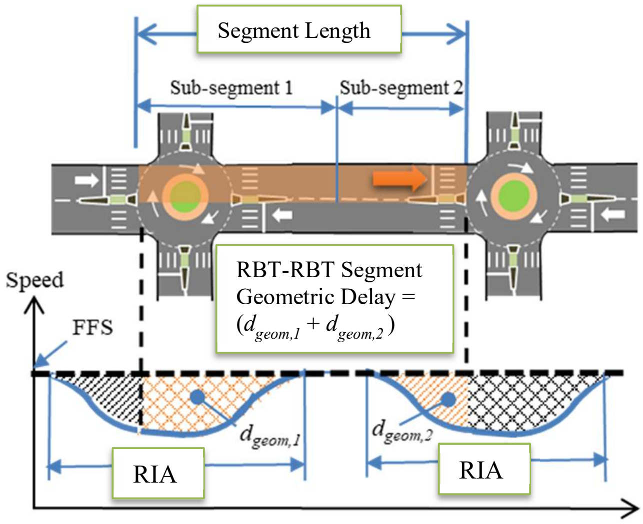

Fig.3 RBT-RBT Geometric delay

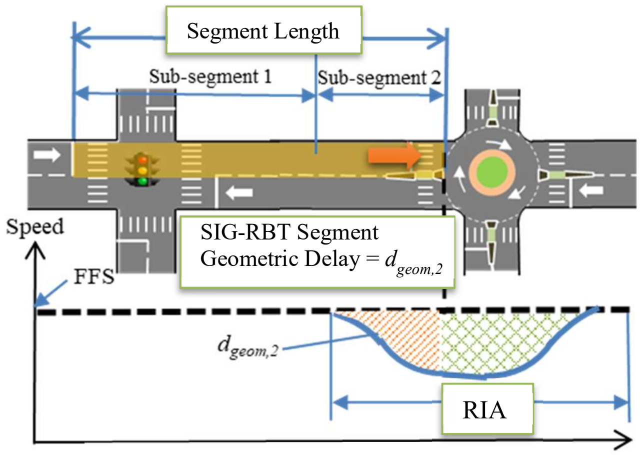

Fig.4 SIG-RBT Geometric delay

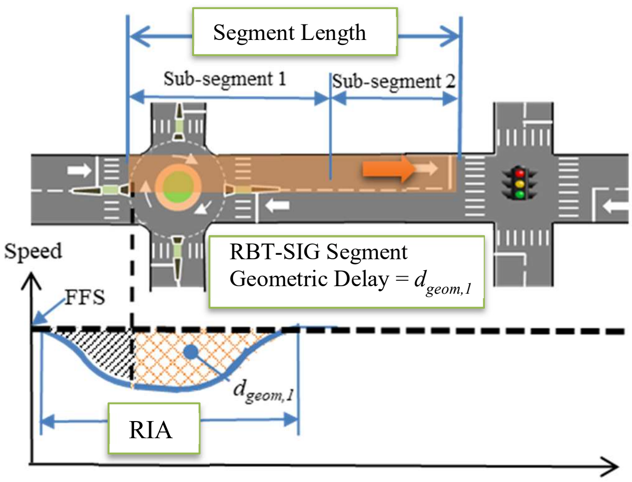

Fig.5 RBT-SIG Geometric delay

segments compared to signalized segments.

According to HCM methodology impact of

roundabout on speed reduction is not just at roundabout, but it is in some range upstream and downstream of roundabout so called roundabout influential area (RIA) as shown in hatched in **Fig. 3** to **Fig. 5**. Therefore, in this research geometric delay is considered as part of the link model. Bugg et al [13]. developed a model for calculating the length of RIA in corridors as it is used in HCM 6th edition as well. The length of RIA is a function of segment free flow speed and through movement circulating speed in roundabout. The objective of RIA model is to estimate whether two adjacent roundabouts overlap or not. If overlap happened, then the subsegment free flow speed reduced to account for the overlap. Equation 30-78 to equation 30-86 in HCM 6th edition is used to estimate the length of RIA and adjusted free flow speed.

According to HCM 6th edition for the geometric delay calculation the roundabout segment is divided into two subsegments as shown in **Fig.3** to **Fig. 5**. Then for each subsegment equation (8) and equation (9) is used to calculate geometric delay.

$$d_{geom,1} = max\left[-2.63 + 0.09S_f + 0.625ICD_1\left(\frac{1}{S_{c,1}} - \frac{1}{S_f}\right), 0\right] \quad (8)$$

$$d_{geom,2} = max\left(1.57 + 0.11S_f - 0.21S_{c,2}\,, 0\right) \quad (9)$$

where;
$d_{geom,1}$ = geometric delay for subsegment 1 (s/veh)
$d_{geom,2}$ = geometric delay for subsegment 2 (s/veh)
ICD_1 = Inscribed circle diameter for the upstream roundabout (ft)
S_f = segment free flow speed (mil/h)
$S_{c,1}$ = circulating speed for upstream roundabout (mil/h)
$S_{c,2}$ = circulating speed for downstream roundabout (mil/h)

c) Traffic Features of the link based on segment types

As a summary for the SIG-SIG segment platoon dispersion is considered in link model. For the other segment types because delay is greatly affected by the geometric features of roundabout therefore, geometric delay was considered as traffic feature of the link for RBT-RBT, SIG-RBT and RBT-SIG segments.

(4) Intersection delay model (IDM)

IDM is used to calculate delay at intersections for the given AFP from the link model and then delay and the DFP from the intersection is calculated considering the intersection control type (signalized intersection or roundabout).

a) Signalized intersection delay model

Control delay at signalized intersection is calculated using HCM 6th edition model as shown in equation (10). The model has three delay components; Delay due to uniform arrival (d_1), delay due random overflow (d_2) and delay due to initial queue at intersection(d_3).

$$d_{control} = d_1 + d_2 + d_3 \quad (10)$$

Delay due to uniform arrival is calculated using equation (11).

$$d_1 = PF\frac{0.5C\left(1 - {}^{g}/_{C}\right)^2}{1 - \left[\min(1, X)\,{}^{g}/_{C}\right]} \quad (11)$$

$$PF = \frac{1-P}{1-{}^{g}/_{C}} \text{x} \frac{1-y}{1-\min(1,x)P} \text{x} \left[1 + y\frac{1-\frac{PC}{g}}{1-\frac{g}{C}}\right] \quad (12)$$

where;
g = effective green time (s);
C = cycle length (s);
PF = progression adjustment factor
X = Volume-to-capacity ratio or degree of saturation
P = proportion of vehicles arriving during the green indication (decimal), which is calculated from equation (13).

$$P = 3{,}600\frac{V_g}{V_d C} \quad (13)$$

Where;
V_g= arrivals during effective green (veh)
V_d= lane group volume (veh/h)
C = Cycle length (s)

Progression factor which is shown in equation (12) accounts the effect of platoon dispersion. It mainly depends on proportion of vehicles which reach on set of green in downstream intersection. The value of p is estimated using equation (13) for each traffic demands from the arrival follow profile from the link model.

Delay due to random arrival as also called incremental delay is calculated using equation (14).

$$d_2 = 900T\left[x - 1 + \sqrt{(x-1)^2 + \frac{8kIx}{CT}}\right] \quad (14)$$

Where;
$d_2 =$ Incremental delay (s/veh)
T =Analysis period duration (h)
k =incremental delay factor;
I =Upstream filtering adjustment factor
C =lange group capacity (veh/h)

Capacity of signalized intersections mainly depends on saturation flow rate and green split. HCM equation (15) is used to calculate capacity of through lane.

$$c = Ns\frac{g}{C} \tag{15}$$

Where;
c = capacity (veh/h)
N = Number of lane in the lane group
g = effective green time (sec)
C = cycle length (sec)

The third part of control delay model in equation (10) is assumed zero in this research since there is not initial queue.

b) Roundabout delay model

Roundabout delay model is expressed by equation (16) which was originally developed by Akcelik [14] for two-way stopped control intersections. The first term in this equation represents the service time or minimum delay which experienced by an entering vehicle in the absence of the queue, the second term represents delay due to time spent as vehicle moves in the queue.

$$d = \frac{3600}{c} + 900T\left[x - 1 + \sqrt{(x-1)^2 + \frac{8x}{cT}}\right] \tag{16}$$

Where;
d = average control delay (sec/veh)
x = volume to capacity ratio of the subject lane
c = capacity of subject lane (veh/h), and
T = time period (h) (T=0.25h used for 15min analysis)

In HCM 6th edition two-way stopped control delay model added a constant +5 term in equation (16). This 5 s/veh account decelerations of vehicles from free-flow speed to the speed of vehicles in the queue and acceleration of vehicles from stop line to free flow speed.

Similarly, HCM roundabout delay model is same as two way stopped control intersection, except the last term which is modified, equation (17). This modification is necessary to account for the YIELD control on the subject entry, which does not require drivers to come to complete stop when there is no conflicting traffic[5].

$$d = \frac{3600}{c} + 900T\left[x - 1 + \sqrt{(x-1)^2 + \frac{8x}{cT}}\right] + 5min[x, 1] \tag{17}$$

Variables of above equation already described previously.

In the literature the first term of equation (16) and (17) is so called minimum delay also calculated using Adams' delay model[14]. Adams' model account the effect of bunching in circulating flow. In this research in order to consider the effect of bunching on circulating flow the minimum delay is calculated using Adams' model.

As shown in delay model, the average control delay is a function of the capacity of roundabout and degree of saturation. Therefore, the accuracy of delay calculation strongly depends on the capacity model which will be used in delay calculations.

Capacity of roundabout mainly depends on gap acceptance behavior of entry vehicles and as well as gap size distributions in circulating flow. Therefore, different capacity models are available based on gap size distribution function in circulating flow and the functions for entry vehicles which these types of models originally developed in Germany. HCM 6th edition capacity model assumed random arrival headway distributions on circulating flow which does not account effect of bunching while German model considered the minimum headway and bunching effect of circulating flow.

As different roundabout capacity models evaluated, HCM model over estimates the capacity for medium to high circulating flow. Therefore, for accuracy of the calculations Japan Roundabout Manual capacity model[15] which is based on German model is used in this research.

(5) Segment delay

Segment delay includes delay of the link and control delay at downstream intersection. Delay at downstream intersection is calculated based on intersection control types. For delay comparison, of each hypothetical segment average delay of the segment considering both direction is used.

As part of the link model for SIG-SIG segment, platoon dispersion effect is considered on delay calculation at downstream intersection. This is because platoon dispersion greatly affects the arrival pattern of downstream intersection, and accordingly affect delay at downstream intersection.

For RBT-RBT, SIG-RBT and RBT-SIG as part of the link model geometric delay is calculated. However, existing platoon dispersion models is not clear for the SIG-RBT or RBT-SIG segments. It is most likely that in SIG-RBT arrival pattern of downstream roundabout is affected by upstream signal. Currently in the literature this impact is not included in delay models of roundabouts. In RBT-SIG the departure flow pattern at roundabout because of downstream signalized intersection and arrival pattern of downstream signalized intersection because of upstream roundabout is affected which this impact has also not been considered in the existing intersection delay models. Therefore, in this research platoon dispersion is not considered for other segment types except SIG-SIG.

3. Scenarios for Numerical Calculations

A hypothetical corridor consists of two intersections as shown in Fig. 2. is considered as a test network of numerical calculations. Input parameters and following scenarios is used for the calculation of segment delay.

(1) SIG-SIG Segment

Input parameters listed in **Table 1** and hypothetical SIG-SIG is used to calculate segment delay.

(2) RBT-RBT Segment

The input parameters listed in **Table 2** and hypothetical RBT-RBT and geometric delay concept as shown in **Fig.3** is used for the analysis.

(3) SIG-RBT Segment

The input parameters listed in **Table 1** and **Table 2** and hypothetical SIG-RBT segment and geometric delay concept as shown in **Fig.4** is used for the analysis.

(4) RBT-SIG Segment

The input parameters listed in **Table 1** and **Table 2** and hypothetical RBT-SIG segment and geometric delay concept as shown in **Fig.5** is used for the analysis.

4. Analyses and Results

(1) Delay calculation at hypothetical corridors

Using link and intersection delay models, delay at each of the following hypothetical segment was calculated. Then the average delay of the corridor is obtained

a) SIG-SIG Segment

Cycle length for each traffic demand settings is determined using Webster's formula and splits are set in proportion to the flow ratio. Platoon dispersion model applied in link model and then intersection delay model applied and delay was calculated for each 5seconds offset for both directions. The sample case of

Table 1 Scenarios settings for SIG-SIG Segments

Traffic Demands Settings		
Major Flow	0 – 1000 (veh/h)	50veh/h increments
Minor Flow	0 – 1000 (veh/h)	50veh/h increments
Link Length	400m	
Assumptions:		
Total Lost time	8 sec	
Saturation Flow rate	1800 veh/h	

Table 2 Scenarios settings for RBT-RBT and SIG-RBT Segments

Traffic Demands Settings		
Major Flow	0 – 1000 (veh/h)	50veh/h increments
Minor Flow	0 – 1000 (veh/h)	50veh/h increments
Link Length	400m	
Inscribed Circle Diameter	40m	
Default values of gap parameters (Japan roundabout manual)		
t_c (critical headway)		4.1 sec
t_f(Follow-up Headway)		2.9 sec
τ(minimum circulating headway)		2 sec

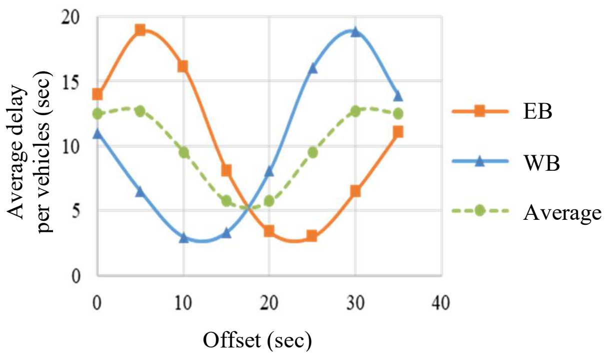

Fig.6 Average delay based on optimum offset (sample case; Major stream flow = 600veh/h and Minor stream flow = 400veh/h)

delay calculation is shown in **Fig. 6**. Optimum offset was selected that delay is minimized. The optimum offset is the lowest point of the green sinusoidal graph in **Fig. 6**. Delay based on optimum offset in addition of random delay as calculated using equation (14) is the delay of the segment between subject intersections.

b) RBT-RBT Segment

Under link model geometric delay was calculated then intersection delay model was applied to calculate control delay of downstream roundabout. For delay calculation for each traffic demand firstly, capacity was calculated based on default values and then delay was calculated using intersection delay models. Delay of the segment include geometric delay and control delay at downstream roundabout.

c) SIG-RBT Segment

In link model the geometric delay because of downstream roundabout was calculated. Then intersection delay model applied to calculate delay at downstream roundabout. The segment delay includes geometric delay of sub-segment 2 as shown in **Fig.4** and control delay at downstream roundabout.

d) RBT-SIG Segment

Geometric delay for sub-segment 1 was calculated because of upstream roundabout and then control delay at downstream signalized intersection was calculated. Delay of the segment include geometric delay of sub-segment 2 and control delay at downstream signalized intersection.

e) Average corridor delay

The total delay is calculated as the summation of all segments connected to the two intersections of the corridor. The delays at the segments between the subject intersections are calculated using the method mentioned above. The demand arrival patterns of other segments located at the edges of the network are assumed to be random arrival and the delays of these segments were calculated as the same approach as isolated intersections. The average delay is calculated dividing the total delay by the total number of vehicles which passed the segments.

(2) Delay comparison of a segment with and without considering upstream intersection

Average delay of SIG-SIG segment was calculated according to intersection demands and result is shown in **Fig.7**. Total intersection demands in the figure contain different flow ratios at major and minor stream which are reflected by the multiple plots in the figure in the same demand level. In the SIG-SIG corridor, because of the effect of signal coordination and platoon dispersion, average intersection delay is lower than the isolated cases.

(3) Optimum intersection control types in corridor

Fig.8. shows the feasibility performance area of

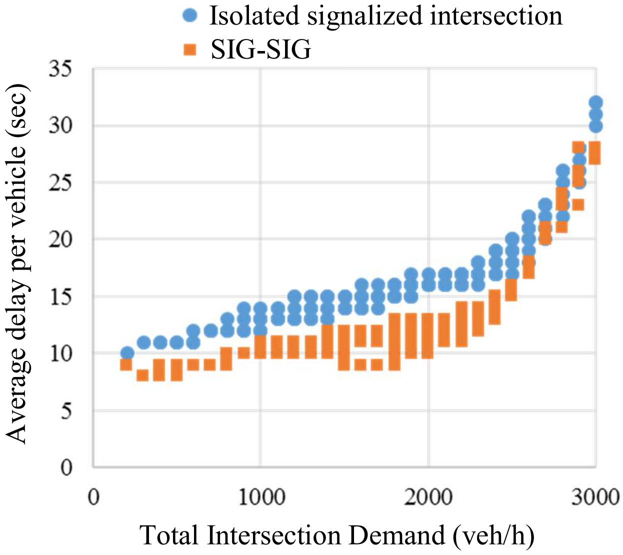

Fig.7 Delay comparison of isolated signalized intersection (SIG) and signalized corridor (SIG-SIG)

roundabout and signalized intersection in the case of isolated intersection with different demand conditions. This figure describes the control types which minimize delay under the given traffic demands. As known in the literatures, the roundabout has better performance is lower traffic demand and the signalized intersection is better in the higher traffic demand conditions.

Similarly, the feasibility area in the case of the corridor is shown in **Fig. 9**. The green dashed line shows the boundary between roundabout and signalized intersection in the isolated case in **Fig.8**. Since delay at SIG-SIG is less than the isolated case as shown in **Fig. 7**, so it is expected that coordination effect should be significant. It is true, but the geometric delay at RBT-RBT is less than the isolated RBT. Therefore, in overall the difference of the boundaries is not so significant. In this scenario, there are no conditions that RBT-SIG corridor has the best performance.

Furthermore, in the case of **Fig. 9**, control types of both intersections are optimized simultaneously. However, in real case mostly one existing intersection type is known then practitioners intend to select an intersection control types assuming that the control type of the other intersection is given. In this sense, **Fig. 10** shows the feasibility area given that one of the intersections is roundabout. In RBT-RBT the geometric delay is less than in the case of isolated roundabout. This is because in the RBT-RBT case the vehicle speeds do not recover to the base free flow speed within the segment and thus the average geometric delay of two roundabouts are less than that in the isolated case. Therefore, RBT-RBT feasibility area becomes larger than the isolated case. **Fig. 11** is the results that one of the intersections is given to be signalized. As shown in **Fig.11** the feasibility area for the selection of intersection control types considering adjacent intersection type is significantly changed than the case of selection of an intersection control types based on isolated assumption. This difference is because of coordination effect in SIG-SIG corridor that

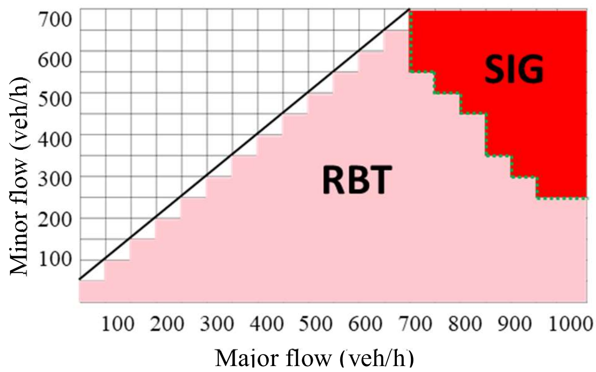

Fig.8 Optimum Isolated intersection control types performance

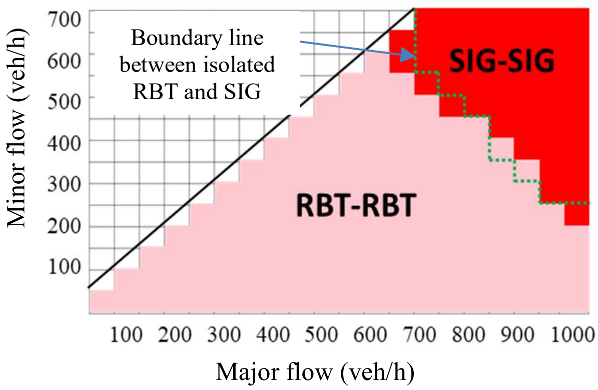

Fig.9 Optimum corridor performance

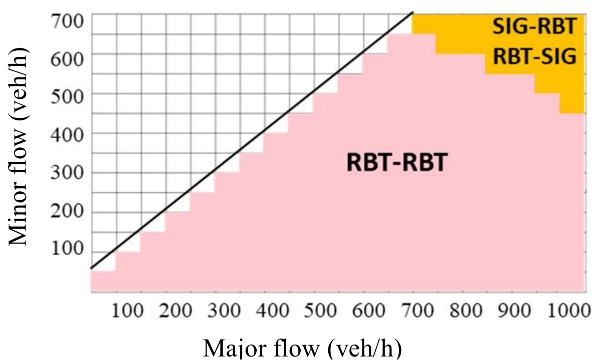

Fig.10 Comparison of corridor performance (RBT-RBT vs SIG-RBT and RBT-SIG)

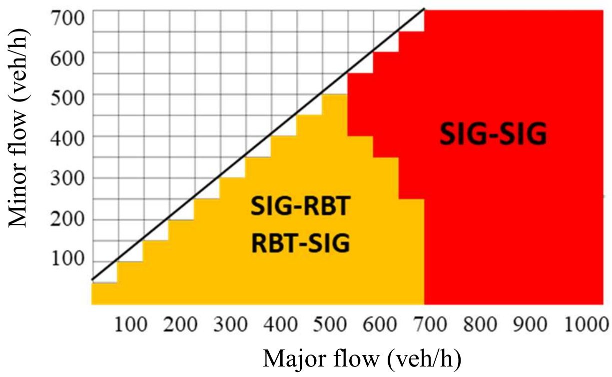

Fig.11 Comparison of corridor performance (SIG-RBT and RBT-SIG vs SIG-SIG)

minimized delay under the given demand conditions compared to SIG-RBT and RBT-SIG corridor as there is no coordination effect.

5.Conclusion and Future Works

This research analyzed the impact of adjacent intersection control type on the selection of optimal intersection control type. It was found that the optimal control type under isolated assumptions and that with consideration of adjacent intersection are significantly different. The findings help practitioners to select better intersection control types in corridor in the planning stage.

However, this study has several limitations. The major limitation causes the delay models themselves. For instance, effect of platoon dispersion is not clear for RBT-RBT, SIG-RBT and RBT-SIG segments though it may have less impact than SIG-SIG. Therefore, simulation study should be done to validate the analytical method and to adjust it if necessary.

Furthermore, as the limitation of this research, effect of link length and turning ratio, consideration of two-way stopped control as an alternative intersection type and continuation of this model to the multiple intersections should be studied in future.

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