A COMPARATIVE STUDY ON OPERATIONAL PERFORMANCE BETWEEN ROUNDABOUTS AND INTERSECTIONS UNDER SIGNAL CONTROL

Yan BAI[1], Xin ZHANG[2] and Hideki NAKAMURA[3]

[1]Student Member, Doctor Course student, Graduate School of Environmental Studies, Nagoya University
(Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan)
E-mail: bai.yan@d.mbox-nagoya.uc.jp
[2]Member, Research Fellow, Dr.-Eng., Graduate School of Environmental Studies, Nagoya University
(Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan)
E-mail: zhang@genv.nagoya-u.ac.jp
[3]Fellow member, Professor, Dr.-Eng., Graduate School of Environmental Studies, Nagoya University
(Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan)
E-mail: nakamura@genv.nagoya-u.ac.jp

To relieve urban traffic pressure and improve operational performance of existing unsignalized roundabouts, foreign researchers have been working on signalization of roundabouts in recent years. However, comparison on operational performance between signalized intersections and signalized roundabouts under different traffic demand patterns has not been studied. Thus, the objective of this study is to clarify traffic conditions under which signalized roundabouts have better performance. Operational performance of signalized roundabouts, including capacity and delay, is compared with that of signalized intersections under the same conditions. The impacts of pedestrians on the operational performance of both signalized roundabouts and signalized intersections are considered.

Key Words: *roundabouts, intersections, signal control, capacity, delay*

1. INTRODUCTION

During last several decades, some countries were favored with building roundabouts, especially European countries, because of advantages of roundabouts on safety and operational performance. As urbanization grew and traffic demand increased sharply in recent years, roundabouts with limited capacity have begun to be oversaturated.

To improve capacity, the United Kingdom first tried to install traffic signals at roundabouts in 1959[1)]. To solve problems caused by excessive traffic demand from one direction, metering signals were invented. Studies have shown that metering signals can shorten delay and queue length of roundabouts, and improve safety[2)]. Since 1991, fully signalized roundabouts have become a popular solution for heavy traffic and unbalanced flow in many European countries[1)]. A case study was conducted to prove that signal control on roundabout is the most cost-effective way to balance the flow in roundabouts[3)]. Yang et al. developed second stop lines on circulatory lanes for left-turn vehicles and coordinated the signal control at second stop lines with traffic control on legs[4)]. Ma, et al. proposed that a signal optimization method for roundabouts and proved signalized roundabouts have better performance when left-turn ratio is high[5)] (right-hand driving system).

Currently in Japan, some signalized intersections located in central business districts are difficult to serve the high traffic demands in peak hours. Referring to experience from other countries, signalized roundabouts are came up with to see if operational performance of complicated intersctions in poor conditions can be improved.

Although some researchers have already studied the operational performance of signalized roundabouts compared with signalized intersections[6,7)], the variety of geometric layouts of roundabouts has not been considered. In multilane roundabouts, to avoid being trapped or changing lanes, spiral roundabouts were invented. FHWA Guideline[8)] defines spiral roundabouts as multilane roundabouts with spiral transitions or spiral markings, which makes the roundabouts have larger capacity than conventional ones. Fortuijn[9] developed turbo roundabouts in 1990s by using spiral central island and spiral lane markings. Besides, the impact of pedestrians on operational performance has not been studied.

Therefore, the main objective of this study is to find out the specific traffic demand conditions under which that signalized roundabouts perform better than signalized intersections (SIG). The impacts of pedestrians are considered and analyzed. Three signal phasing schemes are introduced, including approach-based control, two-phase control and twice-stop-right-turn (TSRT) control under left-hand driving system. Three types of geometric layouts of signalized roundabouts are discussed, including conventional, spiral and turbo roundabouts. After the comparison of their features, signalized turbo roundabouts under TSRT control are selected to compared with SIG under different traffic demand patterns. Capacity and average delay are selected as two indexes to evaluate the operational performance.

2. SIGNAL PHASING AND GEOMETRIC DESIGN FOR ROUNDABOUTS

(1) Signal phasing design

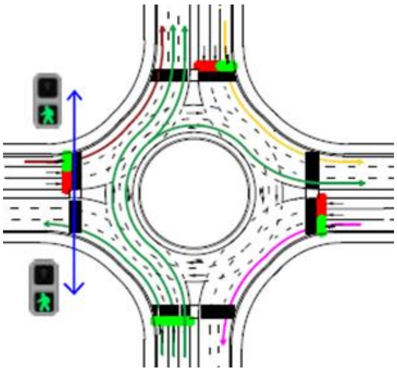
a) Approach-based control

Approach-based control is a simple way to control traffic by allowing vehicles from each leg to cross the roundabouts separately. Movements of vehicles coming from south and east and movements of pedestrians in signalized conventional roundabout (SCRAB) are shown in **Fig1(a)** and **Fig.1(b)**, where vehicles from different legs are distinguished by line colors. Traffic signal indication is presented by colors of stop lines in the figure. When green signal is given to entry vehicles, vehicles can safely drive a quarter of the way round the roundabout to reach the conflict points with the last vehicle entering roundabout during the last phase. This time period is enough for clearance of vehicles, so that for signalized roundabouts under approach-based control, there is no lost time.

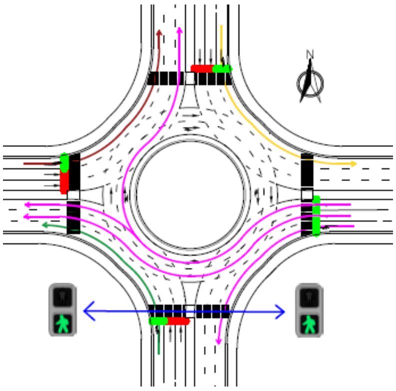
However, operating efficiency in approach-based control is low. Therefore, approach-based control cannot apply in many traffic demand conditions. For instance, in multi-leg intersections, as number of leg increases, the average delay of vehicles increases significantly. Besides, roundabouts under approach-based control cannot serve high demands because of risk of oversaturation. And because of the layout of roundabouts, there is large geometric delay for through (TH) and right-turn (RT) movements.

b) Two-phase control

Movements of both vehicles and pedestrians under

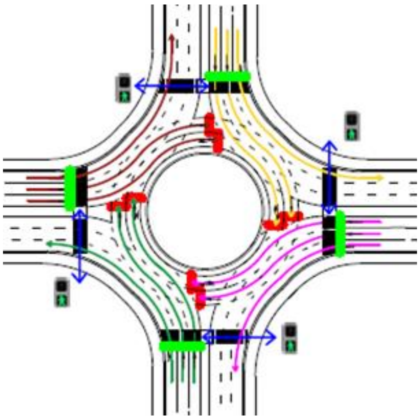


(a) Phase 1

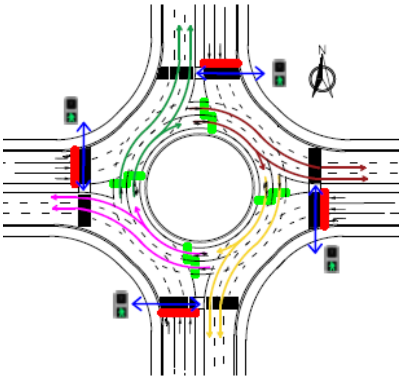


(b) Phase 2

Fig.1 Movements of vehicles and pedestrians under approach-based control of SCRAB.



(a) Phase 1



(b) Phase 2

Fig.2 Movements of vehicles and pedestrians under 2-phase control of SCRAB.

two-phase control are shown in **Fig.2**. To avoid the conflicts between vehicles from different legs, second stop lines with signal lights are set just before the potential conflict points. In the first phase (**Fig.2(a)**), all vehicles queuing at first stop lines are given in green signal, enter the roundabout, and queue on the circulatory roadways. In the second phase (**Fig.2(b)**), vehicles are prohibited to enter. All of the traffic lights for second stop lines turn into green, and queuing vheicles can turn around clockwisely and leave. Therefore, circulatory roadways are fully utilized and traffic is operated in efficiency. Cycle length is much shorter and average delay of vehicles is decreased.

This control scheme can only be used in roundabouts with large scale, which can offer enough storage area on circulatory roadways for TH and RT vehicles. The signal timing should be carefully designed to avoid overflow conditions. Besides, 2-phase control is applied to balanced demand patterns. The more balanced of total entry volume of each leg and balanced ratio of TH and RT volume, 2-phase control performs better.

c) TSRT control

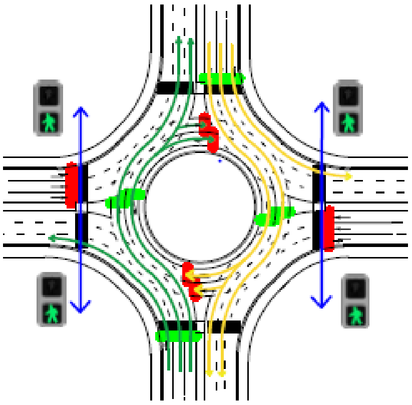
TSRT control is commonly used by many other countries and movements of vehicles and pedestrians for this control are illustrated in **Fig.3.** In phase 1 (**Fig.3(a)**), vehicles coming from south (green lines) and north (yellow lines) directions enter the roundabout simultaneously, and RT vehicles are stopped by second stop lines to avoid conflicts. After a clearance time for entry vehicles, green times are provided for queuing RT vehicles on circulatory roadways to dissipate in phase 2 (**Fig.3(b)**). Then, vehicles from west (dark red) and east (pink) have the same movements. Different within SIG, RT vehicles in the signalized roundabout can use both two circulatory lanes to circulate out during phases 2 and 4 (**Fig.3(d)**), which accelerates the dissipation of RT queues and shortens delay of all vehicles. Compared with 2-phase control, TSRT control is more flexible for unbalanced traffic volume.

(2) Geometric design

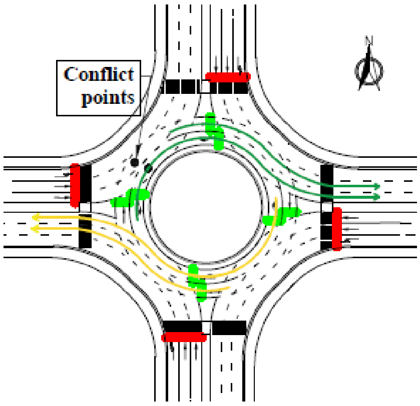
There are mainly three types of geometric design for roundabouts in the world, which are conventional, spiral and turbo roundabouts. The differences between them after signalization are discussed.

a) SCRAB

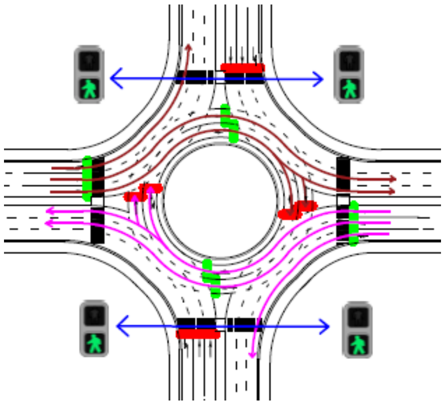
A typical SCRAB with three entry lanes and two circulatory lanes are shown in **Fig.4(a)**. The storage area for RT vhicles on circulatory roadways under TSRT control is shown in red shaded area. In practice, it is hard to guide RT vehicles to make lane changing from inner lane to outer lane within



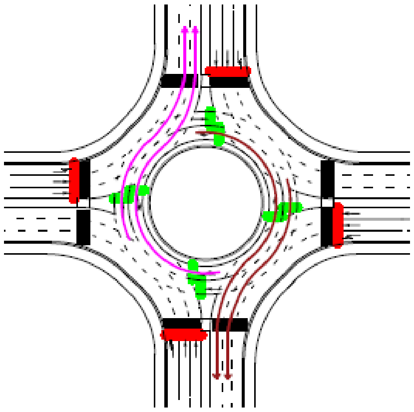
(a) Phase 1



(b) Phase 2



(c) Phase 3



(d) Phase 4

Fig.3 Movements of vehicles and pedestrians under TSRT control of SCRAB.

constrained area. Besides, potential risk of blocking TH vehicles is high if demand of RT vehicles is high, which will result in oversaturated conditions.

b) Signalized spiral roundabout (SSRAB)

A SSRAB that has the same number of lane and lane configuration with SCRAB is illustrated in **Fig.4(b)**. Because of spiral markings, number of exit lanes can be reduced to two. Besides, the storage area for RT vehicles increased and unlike in SCRAB, RT vehicles make lane changing from outer lane to inner lane when approaching the second stop lines, which ensures safety of RT vehicles and avoids the influence of RT vehicles on TH vehicles.

c) Signalized turbo roundabout (STRAB)

The geometric layout of STRAB is shown in **Fig.4(c)**. The mechanism of STRAB is similar with SSRAB. Without using spiral markings, STRAB makes a spiraling traffic flow by changing the shape of central island. The size of storage area for RT vehicles is almost the same with that in SSRAB. A portion of the central island is utilized by RT vehicles, so that the land use in STRAB is more efficiency.

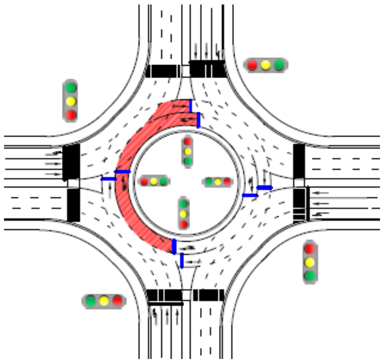
3. COMPARATIVE STUDY

(1) Geometric layouts and signal phasing

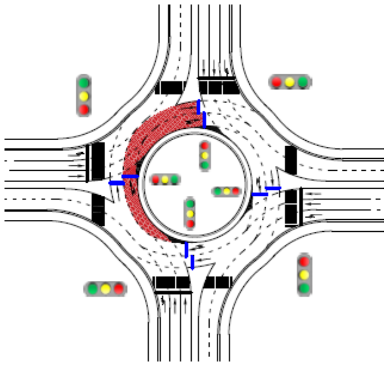
As discussed before, STRAB can provide larger storage area for RT vehicles with relative smaller scale compared with other two types of layout, it is selected to compare. The hypothesized layouts of SIG and STRAB are shown in **Fig.5**. In SIG, the width of entry lanes is 3.5 m and an infinite long RT pocket is assumed, so that its influence on RT capacity is neglected. For STRAB, the width of entry lanes is still 3.5 m, while the width of circulatory lanes is 4 m. The radius of central island is designed as 20 m, which ensures enough storage area on circulatory roadways for RT vehicles. To make a relative fair comparison, the same lane configuration is developed for both SIG and STRAB.

(2) Hypothesized senarios of traffic demands

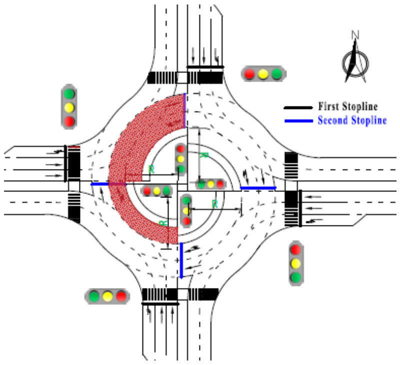
Several common traffic demand patterns are hypothesized and listed in **Table 1**. Because at intersections in central business districts, opposing traffic flows are likely to be balanced. Therefore, the directional split ratio is assumed as 0.5. Two main fators are changed, which are total entry volume for each leg and ratio of RT vehicles. For total entry volume of one leg, a high volume, which is 1,000 veh/h and a low volume, which is 400 veh/h are given. Since volume of left-turn (LT) vehicles has little effect on difference of performance between SIG and STRAB, a constant ratio of LT is given, which is 0.2. It is assumed that traffic flows arrive uniformly and only passenger cars are considered.



(a) SCRAB



(b) SSRAB



(c) STRAB

Fig.4 Geometric layouts of three types of SRAB and their storage area for RT vhicles on circulatory roadways.

(3) Signal phasing design

In this paper, fixed-time signal control is implemented. For SIG, two-phase control with permitted RT **(Fig.6(a))** is given for each scenario and if the RT movements are oversaturated, protected RT phase **(Fig.6(b))** is implemented to serve the demands. Because several demand patterns with different entry volumes and RT ratios are developed, for STRAB, TSRT control is implemented to serve different types of demand patterns. Its signal phasing diagram is shown in **Fig.6(c)**.

(4) Signal timing calculation model

a) Saturation flow rate of permitted RT

Under permitted RT phasing control in SIG, RT vehicles are required to find an available gap time between opposing approach traffic volume. Equation (1) is derived based on the gap acceptance theory to estimate the saturation flow rate (SFR) of RT movement[10].

$$S_R = \frac{V_0 e^{-V_0 * \frac{t_c}{3600}}}{1 - e^{-V_0 * \frac{t_f}{3600}}} \qquad (1)$$

Where, S_R: SFR of permitted RT movement (veh/h); V_0: opposing demand flow rate (veh/h); t_c:critical gap time, taken as 4.5 sec; t_f: critical follow-up time: 2.5 sec.

b) Pedestrian impact on SFR

The conflicts between pedestrians and turning vehicles reduce SFR of turning vehicles. Method illustrated in HCM[10] is used to estimate the adjusted SFR for turning vehicles. For permitted LT operation and protected RT operation, the pedestrian flow rate during the pedestrian service time is computed by Equation (2).

$$v_{pedg} = v_{ped} \frac{C}{g_{ped}} \qquad (2)$$

Where, v_{pedg}: pedestrian flow during pedestrian service time (ped/h); v_{ped} : pedestrian flow rate in the subject crossing (both direction) (ped/h); C: cycle length (sec) and g_{ped}: pedestrian service time (sec).

Based on v_{pedg}, average pedestrian occupancy OCC_{pedg} can be calculated by Equation (3).

$$OCC_{pedg} = \begin{cases} \frac{v_{pedg}}{2000}, & v_{pedg} \leq 1{,}000 \\ 0.4 + \frac{v_{pedg}}{10{,}000}, & v_{pedg} > 1000 \end{cases} \qquad (3)$$

Relevant conflict zone occupancy OCC_r is obtained by Equation (4).

$$OCC_r = \frac{g_{ped}}{g} OCC_{pedg} \qquad (4)$$

Where, g: effective green time for one phase (sec), which is assumed to be equal to pedestrian service time. Therefore, OCC_r is equal to OCC_{pedg}.

Then, SFR adjustment factor for both permitted LT operation f_{lp} and protected RT operation f_{rp} in an exclusive lane can be computed by Equation (5).

$$f_{rp} = f_{lp} = 1 - OCC_r \qquad (5)$$

For permitted RT movements, the pedestrian flow rate during the pedestrian service time is also computed by Equation (1) shown above. RT movements are in conflict with the opposing TH and LT movements. The average pedestrian occupancy after opposing queue clears OCC_{pedu} is given by Equation (6).

$$OCC_{pedu} = OCC_{pedg}\left(1 - \frac{0.5 g_q}{g_{ped}}\right) \qquad (6)$$

Where, g_q: opposing queue service time $(g - g_u)$ (sec) and g_u: duration of permitted RT green time that is not blocked by an opposing queue (sec).

Corresponding relevant conflict zone occupancy is computed by Equation (7).

$$OCC_r = \frac{g_{ped} - g_q}{g_p - g_q}(OCC_{pedu}) e^{-5.00 v_0/3600} \qquad (7)$$

Where v_0 is opposing demand flow rate (veh/h).

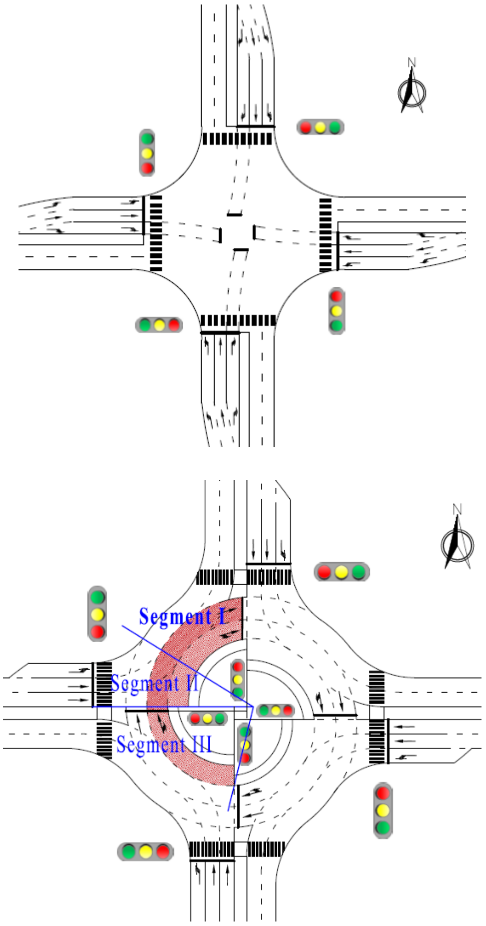
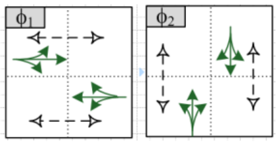
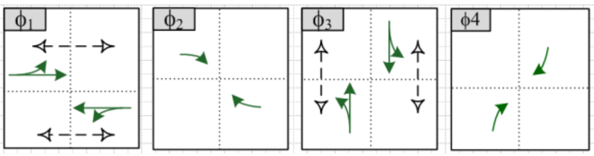


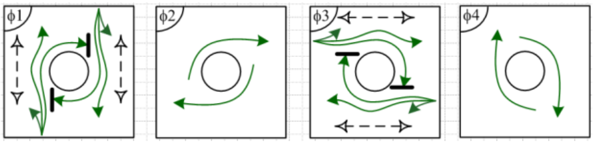
Fig.5 Hypothesized layouts of SIG and STRAB.



(a) Permitted RT control phasing diagram for SIG



(b) Protected RT control phasing diagram for SIG



(c) TSRT control phasing diagram for STRAB

Fig.6 Signal phasing diagrams for both SIG and STRAB

So, SFR adjustment factor for both permitted RT operation can be computed by Equation (8).

$$f_{rp} = 1 - OCC_r \tag{8}$$

In SRAB, there is no conflict zones between RT vehicles and pedestrians or opposing TH vehicles, so the SFR of RT movement is constant. The values of SFR for both SIG and STRAB are shown in **Table 1**.

c) Lost time

As the most commonly used method, Webster's method is chosen to estimate the optimal cycle length and effective green time. For signalized roundabouts, the calculation of signal timing will be in the same procedure with a few differences. Its total lost time of each cycle consists of two parts, which are clearance time L_1 and green time L_2 of phases 2 and 4. The clearance time includes the yellow time and all red time. To calculate clearance time, approaching speed of vehicles is designed as 40km/h. As explained earlier, phases 2 and 4 are given for queuing RT vehicles to circulate out the roundabout and no vehicles can enter. Therefore, these time periods are considered as parts of lost time. For calculating the timing length, storage areas for RT vehicles on circulatory roadways are the decision factor, which is shown in **Fig.5**. The storage area is separated into three segments and corresponding three scenarios are developed.

To start the calculation of L_2, a reasonable initia cycle length is assumed based on the given traffic demand. The number of coming RT vehicles in one cycle N_{RT} can be calculated by Equation (9).

$$N_{RT} = \frac{C_0 V_{RT}}{3600} \tag{9}$$

Where, C_0: hypothesized initial cycle length (sec); V_{RT}: volume of RT movement (veh/h).

For scenario 1, if N_{RT} is smaller than the storage capacity CAP_1 in segment I calculated by Equation (10), the last entering vehicle will not decelerate and can pass the conflict point with free speed.

$$CAP_1 = \frac{2}{3} * \frac{0.5\pi(r_1+r_2)}{L_v} \tag{10}$$

Where, CAP_i: storage capacity of RT vehicles of segment I, II and III for i =1, 2, 3, respectively; r_1, r_2: radius of inner and outer circulatory lanes (m).

The length of L_2 can be calculated by Equation (11).

$$L_2 = \frac{D_1}{v_1} \tag{11}$$

Where, D_1: distance of trajectories between the first stop line to conflict points (m); v_1: average driving speed on circulatory roadways without deceleration (km/h). 40km/h is chosen as free speed driving on circulatory roadways. For scenario 2, if N_{RT} is between CAP_1 and CAP_2 (Equation (12)), length of L_2 is given by Equation (13).

$$CAP_2 = \frac{0.5\pi(r_1+r_2)}{L_v} \tag{12}$$

$$L_2 = 3 + 2\left(\frac{N_{RT}}{2}\right) - \frac{D_2}{v_2} \tag{13}$$

Table 1 Hypothesized traffic demand patterns and SFRs of LT and RT movements in SIG and STRAB

Number of scenario	Approach flow (veh/h)	TH:RT	SFR_STRAB	SFR_SIG	
			LT	LT	Permitted RT
1	Major: 1000; Minor: 1000	7:1	1144	1165	694
2		6:2	1093	1125	740
3		4:4	956	1200	838
4		2:6	1081	1260	943
5		1:7	1136	1116	898
6	Major: 1000; Minor: 400	7:1	1289	1296	624
7		6:2	1287	1296	675
8		4:4	1274	1333	799
9		2:6	1268	1363	944
10		1:7	1271	1371	1020
11	Major: 400; Minor: 400	7:1	915	1116	865
12		6:2	913	1116	876
13		4:4	910	1116	892
14		2:6	913	1116	898
15		1:7	915	1116	897

Where, L_v: average spacing of vehicles at standstill, usually taken 6m; D_2: distance of trajectories between conflict points and the second stop line (m) ; v_2: average driving speed on circulatory roadways with deceleration, taken 20km/h.

Length of L_2 ensures the last vehicle to decelerate and to pass the conflict points. For scenario 3, if N_{RT} is larger than CAP_3 calculated by Equation (14), which means RT vehicles queue in segment III of the storage area, length of L_2 is calculated by Equation (15).

$$CAP_3 = \frac{0.5\pi r_2 + \pi r_1}{L_v} \tag{14}$$

$$L_2 = 3 + 2\left(\frac{0.5\pi r_2}{L_v} + N_{RT} - \frac{0.5\pi(r_1+r_2)}{L_v}\right) - \frac{D_2}{v_2} \tag{15}$$

d) Cycle length

By using Webster's Equation (16), optimal cycle length can be obtained10).

$$C_{opt} = \frac{1.5(L_1+2*L_2)+5}{1-\lambda} \tag{16}$$

Where, C_{opt}: optimal cycle length (sec) and λ: the sum of critical flow ratio.

e) Effective green time

The effective green times are calculated by Equation (17) based on critical flow ratios. The minimum green time for one phase required in Japan Manual on Traffic Signal Control11) is 15s. Besides, effective green time given to vehicles should be larger than the minimum green time for pedestrians computed by Equation (18).

$$G_j = (C_{opt} - L)\frac{max(\frac{V_{LT}}{S_{LT}}, \frac{V_{TH}}{S_{TH}}, \frac{V_{RT}}{S_{RT}})}{\lambda} \tag{17}$$

$$t_p = \frac{L_p}{V_p} + \frac{p}{W * s_p} \tag{18}$$

Where, G_j: effective green time for each leg (sec), where j is the identifier of legs, j =1, 2, 3, 4; L: total lost time (sec), which equals $(L_1 + 2L_2)$; t_p: minimum green time for pedestrians (sec); p: pedestrian demand (ped/h); L_p: crosswalk length (m); W: cross walk width (m); s_p: pedestrian flow rate (ped/m) and V_p: average speed of pedestrians, taken 1m/sec.

For the given demand scenarios, the signal timing plans for SIG under permitted RT phasing control are summarized in **Table 2**. Because RT vehicles have conflicts with opposing TH vehicles and pedestrians, the SFRs of permitted RT are decreased a lot. It is difficult for RT vehicles to find a gap to cross and for scenarios 1 to 5 and 8 to 10 with high entry volumes and high RT ratios, permitted RT phasing control cannot serve the given RT demand. Therefore, For those scenarios, protected RT phasing control is then implemented and the signal timing plans are shown in **Table 3**. In scenario 5, the sum of critical flow ratio is equal to 1, so that Webster’s method cannot get the cycle length for this condition. For scenarios 9 and 10, although the SFR for RT movement increases by protected RT phasing, the lost time also increased and their cycle lengths are still too long.

The signal timing plans for STRAB are summarized in **Table 4**. Because RT vehicles can use two circulatory lanes to dissipate, lengths of phase 2 and 4 serving RT vehicles are much shorter compared with in SIG under protected RT phasing control. There is no clearance lost time between phases 2 and 3, and also between phases 4 and 1, which decreases the total lost time for STRAB. Because of these features of STRAB under TSRT control, its cycle lengths for high RT ratio demand conditions are relatively shorter than SIG.

(4) Operational performance comparison

a) Capacity

Since the mechanism of signal control in STRAB is similar within SIG, the models for estimating capacity and delay are also similar. Capacity of TH and LT vehicles are calculated by Equation (19)$^{10)}$. However, the capacity for RT vehicles is constrained by capacity of storage area on circulatory roadways, as shown in Equation (20).

$$c_j = S_j \frac{G_j}{C_{opt}} \tag{19}$$

$$c_k^{rt} = min(S_k^{rt} \frac{G_k^{rt}}{C_{opt}}, CAP_i * \frac{3600}{C_{opt}}) \tag{20}$$

Where, c_j: capacity of TH or LT (veh/h); S_j: SFR (veh/h/ln); c_k^{rt}: capacity of RT (veh/h), k is the identifier of legs, k = 1, 2, 3, 4; S_k^{rt}: SFR of RT (veh/h/ln) and G_k^{rt}: allocated effective green time to RT (sec).

The capacity of both SIG and STRAB are shown in **Fig.7**.

i) When both major and minor are given 1000 veh/h

As shown in **Fig.7(a)**, LT and TH movements in STRAB have larger capacity than in SIG under all given RT ratios. This is because compared with protected RT phasing used in SIG, STRAB can offer storage area for RT vehicles, which allows RT vehicles to enter the roundabout together with TH vehicles and to wait before the second stop lines. Besides, RT vehicles can use both two circulatory roadways to circulate out the roundabout, which doubles the disspate speed of RT vehicles. Therefore, compared with in SIG, less time is assigned to RT movement and capacities of LT and TH movements are larger.

Table 2 Signal timing plans for SIG with permitted RT

Scenario number	Clearance lost time	Phase 1	Phase 2	Cycle length
1	10	28	28	66
2	10	20	20	50
3	10	45	45	100
4	10	212	212	434
5	10	19	19	48
6	10	21	19	50
7	10	21	19	50
8	10	25	19	54
9	10	38	19	67
10	10	47	20	77
11	10	19	19	48
12	10	19	19	48
13	10	19	19	48
14	10	19	19	48
15	10	19	19	48

Table 3 Signal timing plans for SIG with protected RT

Scenario number	Clearance lost time	Phase 1	Phase 2	Phase 3	Phase 4	Cycle length
1	14	53	8	53	8	138
2	14	48	18	48	18	146
3	14	36	33	36	33	154
4	14	28	28	28	28	126
5	14	-	-	-	-	-
8	14	49	50	28	20	160
9	14	49	62	52	25	202
10	14	50	71	76	28	239

Table 4 Signal timing plans for STRAB

Scenario number	Clearance lost time	Phase 1	Phase 2	Phase 3	Phase 4	Cycle length
1	10	60	8	60	8	147
2	10	42	8	42	8	110
3	10	27	10	27	10	83
4	10	78	10	78	10	186
5	10	107	11	107	11	246
6	10	53	8	21	8	100
7	10	52	8	21	8	99
8	10	51	8	27	8	104
9	10	53	8	25	8	104
10	10	54	9	24	8	105
11	10	20	8	20	8	67
12	10	20	8	20	8	66
13	10	20	8	20	8	66
14	10	20	8	20	8	66
15	10	20	8	20	8	67

ii) When major: 1000 veh/h and minor: 400 veh/h

As illustrated in **Fig.7(b)** and **Fig.7(c)**, for both major and minor approaches, STRAB always has larger RT movement capacity than SIG. When the TH:RT ratios are 7:1 and 6:2, which means RT ratio is low, LT and TH movements in SIG have slight larger capacity compared with STRAB. This is because SIG is under permitted RT phasing under low RT ratio, and the lost time is decerased. Because both TH and RT movements are in low demands, it is easy for RT vehicles to find a gap to cross. While in STRAB, RT vehicles still requires extra phases to allow them circulate out the roundabout, which results in a less time assigned to TH and LT movements.

When the RT ratio increased, protected RT phasing are required to serve RT vehicles, which decreases the green time assigned to LT and TH movements. Therefore, STRAB has larger capacity for LT and TH than SIG.

iii) When both major and minor are given 400 veh/h

As shown in **Fig.7(d)**, SIG is under permitted RT phasing control, because of the same reason explained before, SIG has larger capacity for LT and TH movements. However, because there is no conflicts between RT vehicles and opposing TH vehicles in STRAB, the SFRs of RT movements in STRAB are much larger than in SIG, so that capacity of RT are still larger in STRAB.

iv) Difference in total capacity

To clearly find the conditions that STRAB has larger total capacity compared with SIG, values of difference on capacity are calculated by Equation (21).

$$\Delta Total\ capacity = c_{STRAB} - c_{SIG} \qquad (21)$$

Where, c_{STRAB}: total capacity of STRAB; c_{SIG}: total capacity of SIG.

The values of capacity difference between SIG and STRAB are drawn in **Fig.8**. Positive values mean STRAB has larger total capacity than SIG under the same traffic demand pattern. Therefore, under the high entry demands for both major and minor, STRAB always has much larger capacity than SIG. When major approaches have high demand and minor approaches have low demand, SIG has larger capacity than STRAB when the RT ratios are low; and STRAB has larger capacity than SIG when the RT ratios are high. When both major and minor are given low entry demands, the difference on capacity are not obvious and overall, SIG has slightly larger capacity than STRAB.

b) Average delay of vehicles

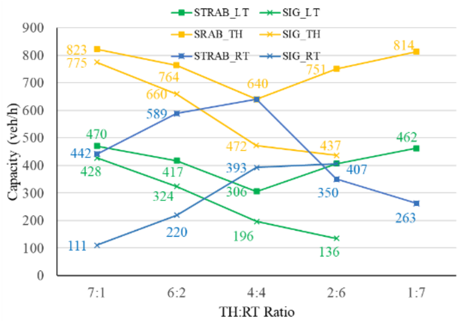
For average control delay in SIG and delay at the first stop liness d_1 in STRAB, uniform delay and incremental delay are considered (Equation (22)$^{10)}$). For average delay at the second stop lines in STRAB, only RT vehicles suffer an extra delay, which is calculated by Equation (23).

$$d_1 = \frac{0.5C\left(1-\frac{G}{C}\right)^2}{1-\left[\min(1,X)\frac{G}{C}\right]} + 900T\left[X-1+\sqrt{(X-1)^2+\frac{8kIX}{cT}}\right] \qquad (22)$$

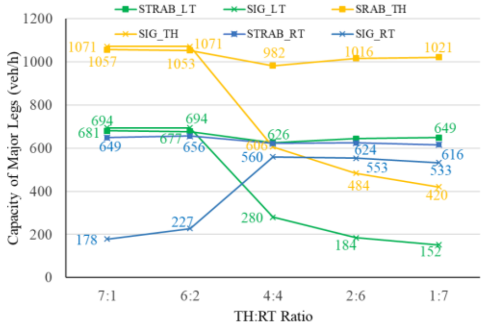
$$d_2 = offset - \frac{L_{12}}{v_1} \qquad (23)$$

Where, d_1: average delay at the first stop lines (sec); G: length of green time (sec); C: length of cycle length (sec); X: degree of saturation; d_2: average delay at the second stop lines (sec); *offset*: offset of green time between phase 1 and phase 2 and L_{12} (sec): length of trajectory between the first and second stop line (m).

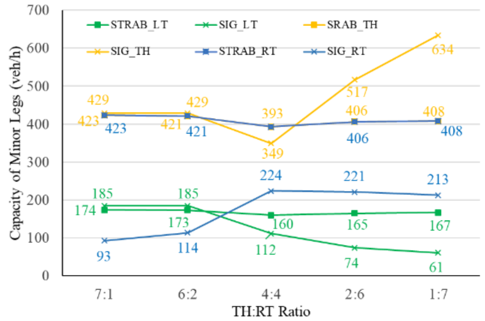
Besides, geometric delay caused by layout of the roundabout should be considered. Geometric delay is calculated by vehicle's average travel time for driving through roundabout minus travel time for the same movement in SIG.



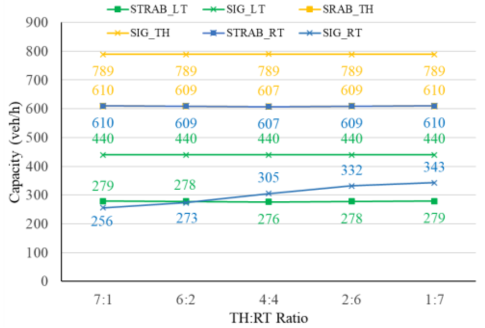
(a) Capacity when both major and minor are 1000veh/h.



(b) Capacity of major when major:1000 and minor: 400veh/h.



(c) Capacity of minor when major:1000 and minor: 400veh/h.



(d) Capacity when both major and minor are 400veh/h.

Fig.7 Capacity of SIG and STRAB

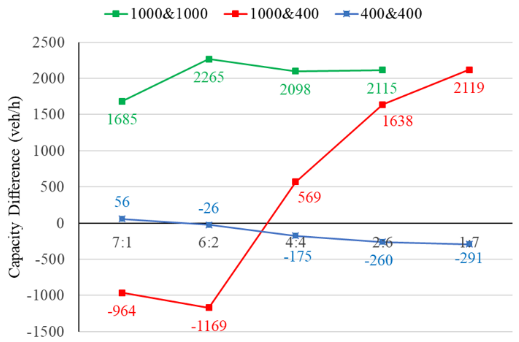


Fig.8 Capacity difference between STRAB and SIG

Table 5 Degree of saturation of SIG and STRAB

Scenario number		LT		TH		RT	
		STRAB	SIG	STRAB	SIG	STRAB	SIG
1		0.43	0.47	0.85	0.90	0.23	0.90
2		0.48	0.62	0.79	0.91	0.34	0.91
3		0.65	0.37	0.63	0.44	0.63	1.53
4		0.49	0.32	0.27	0.20	1.71	1.43
5		0.43	0.45	0.12	0.13	2.66	2.15
6	Major	0.29	0.29	0.66	0.65	0.15	0.56
	Minor	0.46	0.43	0.66	0.65	0.09	0.43
7	Major	0.30	0.29	0.57	0.56	0.30	0.88
	Minor	0.46	0.43	0.57	0.56	0.19	0.70
8	Major	0.32	0.71	0.41	0.66	0.64	0.71
	Minor	0.50	0.71	0.41	0.46	0.41	0.71
9	Major	0.31	0.25	0.20	0.17	0.96	1.15
	Minor	0.48	0.38	0.20	0.16	0.59	1.22
10	Major	0.31	0.25	0.10	0.09	1.14	1.22
	Minor	0.48	0.32	0.10	0.07	0.69	1.24
11		0.29	0.18	0.46	0.35	0.07	0.16
12		0.29	0.18	0.39	0.30	0.13	0.29
13		0.29	0.18	0.26	0.20	0.26	0.52
14		0.29	0.18	0.13	0.10	0.39	0.72
15		0.29	0.18	0.07	0.05	0.46	0.82

The degree of saturation for each movement in SIG and STRAB are listed in **Table 5**. Values in red are larger than 1, which means oversaturated conditions happen. When the entry volumes and RT ratios are high, RT movements in both SIG and STRAB experience oversaturated. Therefore, either the scale of STRAB should be enlarged or the number of RT lanes should be added to solve the problem. Average delay of both SIG and STRAB are shown in **Fig.9**.

i) When both major and minor are given 1000 veh/h

As shown in **Fig.9(a)**, LT and TH movements in STRAB have smaller average delay than in SIG under all given RT ratios. Because SIG is under protected RT phasing control for these scenarios. STRAB can dissipate the RT vehicles much quicker than SIG. Therefore, in STRAB, LT and TH vehicles wait less time than in SIG, which results in a shorter delay.

ii) When major: 1000 veh/h and minor: 400 veh/h

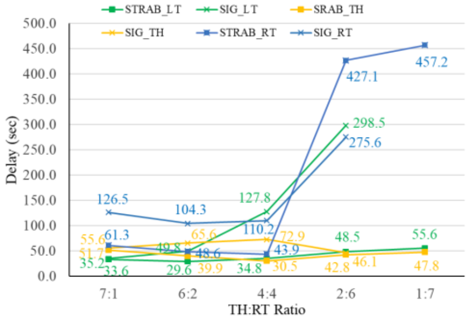
As illustrated in **Fig.9(b)** and **Fig.9(c)**, for both major and minor approaches, STRAB always has smaller RT average delay than SIG. When the TH:RT ratios are 7:1 and 6:2, which means RT ratios are low, LT and TH movements in SIG have slight smaller average delay compared with STRAB. This is because SIG is under permitted RT phasing under low RT ratios, and the lost time is decreased. When the RT ratio increased, protected RT phasing are required to serve RT vehicles, which decreases the green time assigned to LT and TH movements. Therefore, STRAB has smaller delay for LT and TH than SIG.

iii) When both major and minor are given 400 veh/h

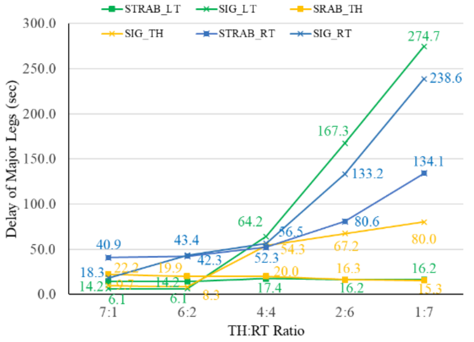
As shown in **Fig.9(d)**, SIG has smaller delay for all movements. Because SIG is under permitted RT phasing control and vehicles in STRAB will suffer large geometric delay.

iv) Difference in average delay

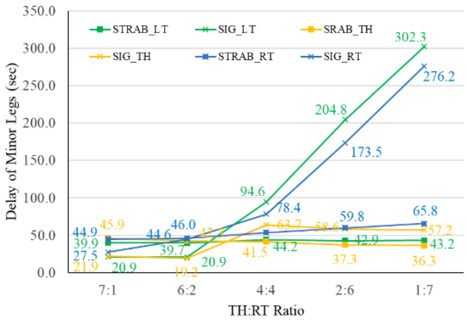
To clearly find the conditions that STRAB has smaller



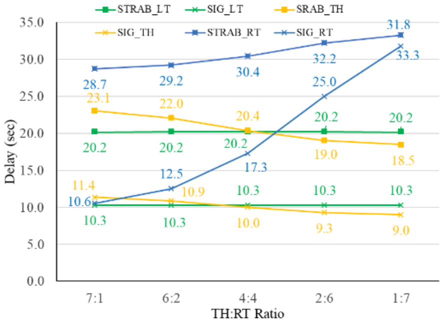
(a) Delay when both major and minor are 1000veh/h.



(b) Delay of major when major:1000 and minor: 400veh/h.



(c) Delay of minor when major:1000 and minor: 400veh/h .



(d) Delay when both major and minor are 400veh/h.

Fig.9 Average delay of SIG and STRAB

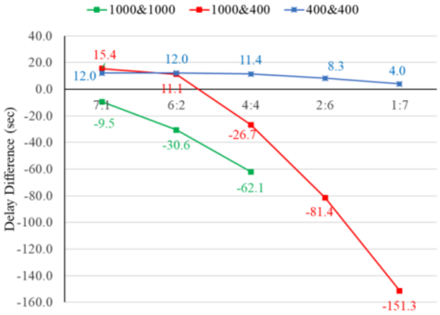


Fig.10 Delay difference between STRAB and SIG

average delay compared with SIG, values of difference on average delay are calculated by Equation (24).

$$\Delta Average\ delay = d_{STRAB} - d_{SIG} \qquad (24)$$

Where, d_{STRAB}: average delay of STRAB; d_{SIG}: average delay of SIG.

The values of average delay difference between SIG and STRAB are drawn in **Fig.10**. Negative values mean STRAB has smaller average delay than SIG under the same demand patterns. Therefore, under the high entry demands for both major and minor, STRAB always has smaller average intersection delay than SIG and as the RT ratio increases, the STRAB performs much better than SIG. When major approaches have high demand and minor approaches have low demand, SIG has smaller intersection average delay than STRAB when the RT ratios are low; and STRAB has smaller average delay than SIG when the RT ratios are high. When both major and minor are given low entry demands, SIG has smaller intersection average delay than STRAB for all kinds of RT ratio.

4. CONCLUSIONS

This paper introduced three types of phasing design and three types of geometric design of roundabouts. By comparing the features of each type of phasing and layout, STRAB under TSRT phasing control are selected to compare with conventional four-leg SIG. This is because turbo roundabouts can offer more storage area for RT vehicles on circulatory lanes and it is safer for drivers to drive through turbo roundabout. TSRT control can serve unbalanced and high traffic demands more efficiently. To find the specific traffic demand conditions under which STRAB has better performance than SIG, several scenarios of traffic demand patterns have been hypothesized. The total entry volume and RT ratio are changed to observe their influence and the impact of pedestrians on both SIG and STRAB has been considered. Capacity and average delay have been investigated as indexes of operational performance to make a comparison between SIG and STRAB.

A general conclusion can be obtained that STRAB havs larger capacity and smaller average delay than SIG when the entry volume is high and the RT ratio is high. When the major and minor approaches have the same entry volume, the influence of RT ratio is not obvious. When the entry volume is high, STRAB has obvious better performance than SIG. When the entry volume is low, SIG usually has better performance than STRAB. When the entry volume of major and minor approaches are unbalanced, SIG has better performance than STRAB under low RT ratios and has worse performance under high RT ratios. The influence of unbalanced ratio of traffic volume between different legs is small on the difference of operational performance. The critical values of entry volume and RT ratio should be found later. Besides, the building cost and maintenance cost for STRAB is higher than SIG, when making a selection choice, this should also be considered.

In this paper, to simplify the problem, dirctional split ratio is assumed as 0.5. However, in the peak hours at central business district, traffic flows coming from opposing approaches are usually unbalanced. Comparison under more various traffic demand patterns should be conducted. Although the impact of pedestrians are studied, average pedestrian delay can be calculated as another performance index later. Besides, simulation analysis can be conducted to compare the operational performance between signalized roundabouts and SIGs to further verify the results.

REFERENCES

1) Alternative Types of Roundabouts: An Informational Guide. Tollazzi, T. ed., Springer Tracts on Transportation and Traffic, 2015.
2) Akçelik, R.: A roundabout case study comparing capacity estimates from alternative analytical models. In: the 2nd Urban Street Symposium, Anaheim, California, USA, 2003.
3) Shawaly, E., Li, C., Ashworth, R.: Effects of entry signals on the capacity of roundabout entries: a case-study of Moore street roundabout in Sheffield. Traffic Engineering and Control 32 (6), 297–301, 1991.
4) Yang, X., Li, X., and Xue, K.: A new traffic-signal control for modern roundabouts: method and application. Intelligent Transportation Systems, IEEE Transactions, pp. 282–287, 2004.
5) Ma, W., Liu, Y., Head, L., and Yang, X.: Integrated optimization of lane markings and timings for signalized roundabouts. Transportation Research Part C, pp. 307-323, 2013.
6) Tracz, M., Chodur, J.: Performance and safety roundabouts with traffic signals. Procedia-Soc. Beh. Sci., pp. 788-799, 2012.
7) Fortuijn, L.G.H., Salomons A.M. Signalized Turbo Circle; design and performance. Paper 15-2987 for Annual Meeting, Transportation Research Board, 2015.
8) NCHRP Report 672, Roundabouts: A Informational Guide, Second Edition, Federal Highway Administration, 2010.
9) Fortuijn, L. G. H.: Turbo Roundabouts: Design Principles and Safety Performance. Transportation Research Record, 2096(1), 16–24, 2009.
10) Highway Capacity Manual (HCM) 6th edition, Transportation Research Board, 2016.
11) Manual on Traffic Signal Control, Revised Edition, Japan Society of Traffic Engineers, 2006. (in Japanese)

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