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Synchronous Roundabouts with Rotating Priority Sectors (SYROPS) : High Capacity and Safety for Conventional and Autonomous Vehicles

Guillermo Ibanez*, Tobias Meuser**, Miguel A. Lopez-Carmona*, Diego Lopez-Pajares*
* Departamento de Automática, University of Alcalá, Alcalá de Henares (Madrid), Spain.
** Multimedia Communications Lab (KOM), Technische Universit at Darmstadt, Darmstadt, Germany.
Email: guillermo.ibanez@uah.es,tobias.meuser@kom.tu-darmstadt.de,miguelangel.lopez@uah.es,diego.lopezp@uah.es.

Roundabouts need capacity and safety improvements compatible with manual-driven, not only with autonomous vehicles. The signaling and control of roundabouts must evolve and incorporate current technologies. For that, we approach roundabouts as *synchronous switches of vehicles*. This paper describes Synchronous Roundabouts with Rotating Priorities, a roundabout control system based on vehicle platoons arriving at the roundabout at speed identical to the roundabout and within the time slot assigned to their entry, avoiding conflicts and stops, thus increasing roundabout capacity and safety. Signaling is visual for human drivers and also wireless for connected and autonomous vehicles. We evaluate analytically and with simulations roundabouts of different radius for several values of the average distance between vehicles. Average delays are 28,7 % lower, with negligible dispersion. The capacity improvements depend on design parameters: in our set is moderate for small roundabouts but goes up to 70-100 % for short distances and medium and large roundabouts.

***Index Terms*—Roundabouts, traffic engineering, Rotary priority, Spatio-temporal technique, Synchronization, Protocols, Intelligent Transport Systems, Connected Vehicles, Traffic Safety**

I. Introduction

The first roundabout in history is considered to be the Circus in Bath [1], but modern roundabouts with the priority rule were first made mandatory in the United Kingdom in 1966. Roundabouts of this type have been widely adopted because they provide a great reduction in the number of accidents with injuries and fatalities when compared with intersections [2] [3] and old traffic circles where the vehicles entering had the priority. Modern roundabouts provide more safety and lower delay than signalled intersections for traffic not too intense [4]. Their performance is very dependent on drivers behaviour, specially the duration of the critical headway and the follow-up headway [5].

Although different improvements in the design of roundabouts have been adopted, including turbo-roundabouts [6] and the so-called "Magic Roundabout" [7], the basic rule of absolute priority to the vehicles inside the roundabout has been kept because it provides increased safety and prevents blocking in most circumstances (not all). But this priority mechanism limits the capacity due to the frequent stops at the entrance of the roundabout caused by the lack of priority of the incoming traffic, and the internal conflicts between vehicles willing to leave the roundabout and vehicles continuing their traversal. It is surprising that, whilst the physical design of roundabouts has improved in the past decades, their signalling and control have not evolved accordingly. Besides this, most proposals for more efficient roundabouts and intersections are based in full automation and are not applicable to human-driven vehicles, making the transition problematic.

In our approach, we look at roundabouts as synchronous, time-division switches or multiplexers of vehicles, taking into account the non-negligible transmission (displacement) delays inside the roundabout.

This paper describes the Synchronous Rotating Priority Sectors (SYROPS) roundabouts, a new roundabout traffic signalling and control system compatible with both human-driven and autonomous vehicles.Signaling is visual for human driven vehicles and also wireless for connected and autonomous vehicles. Most current advances in car safety (anticollision systems, lane control, cruise control, signal reading, etc) are compatible and helpful with the system, and new ones could be devised to understand SYROPS signaling. The basic idea is to divide the roundabout circle in sectors and assign each sector for exclusive use of an access. These sectors rotate at the same speed than the vehicles in the roundabout. By forming compact platoons of vehicles that arrive at the roundabout at a speed equal to the linear speed of the roundabout and within the time of the passage of the rotating sector by the access, thus avoiding conflicts and subsequent stops, increasing the roundabout capacity and safety. An example of a revolving roundabout with rotary priorities is shown in figure 1, in which signalling is visual for human drivers and wireless for autonomous vehicles. We evaluate analytically and with Sumo simulations the capacities of roundabouts with 2 rotary 180° sectors alternatively assigned to North-South and East-West every 270° rotation. Results for roundabouts of different radius and various assumptions for distances between vehicles are provided and compared with substantial advantage them with current capacity models published at Highway Capacity Manuals [5] [8] by the US Transportation Research Board and with excellent delay results, thus providing highest levels of service.

The paper is structured as follows: Section II provides

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an overview of the system, while Section III describes in detail an example of signalling and vehicle accesses sequence. Section IV contains the evaluation and discussion about the applicability and implementation of static and dynamic signalling variants, Section V presents the related work and Section VI the future work. Finally, Section VII collects the conclusion.

II. Overview

We describe the basis of a new system for signaling and control of roundabouts for both connected vehicles and manually driven vehicles. The capacity of any roundabout is, roughly speaking, directly proportional to the average vehicle speed and inversely to the average inter-vehicle distance. If we increase the first and reduce the second, capacity increases. Roundabouts are currently limited in capacity and safety by conflict points. Roundabouts have multiple points of conflict between vehicles, more precisely 24 conflict points for a double lane roundabout and 14 for a turbo-roundabout, as shown in figure 2 The conflict points often provoke stops at the roundabout entrances, thus reducing average speed and increasing the inter-vehicle gap needed by a vehicle to enter the roundabout safely. The stops also increase vehicle distances (follow-up) and lower the capacity of the roundabout. The basis of our proposal is that, by making the traffic regular and predictable at accesses, with constant speeds and controlled delays, conflict points at the entries and inside the roundabout are eliminated and the subsequent stops and decelerations. Capacity and safety increase.

The priority of the vehicles inside the roundabout is no longer permanent, it is dynamically assigned to rotating sectors associated with the different entries.

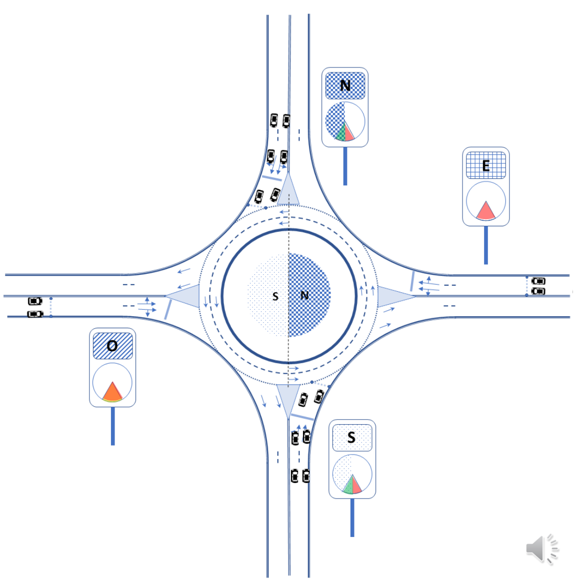

Fig. 1: Example of a synchronous revolving roundabout with rotating priorities and staggered platoons.

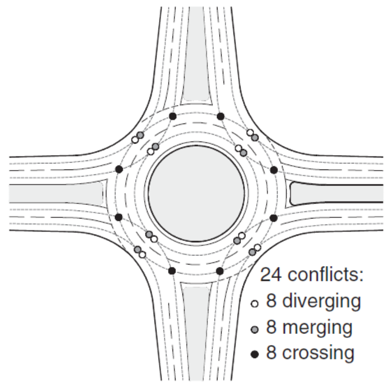

Fig. 2: Conflict points in a standard roundabout [6]

A. Working principle of roundabout

To maximize lane's occupancy and avoid stops, the vehicles from each access are grouped into platoons. The arrival times of the platoons of the two perpendicular directions are staggered to avoid access conflicts. The capacity is optimized by the just-in-time, centrally controlled, the arrival of the platoons to the roundabout. The synchronization of arrivals is based on the staggering of orthogonal platoons and platoon formation and control. Maximum smoothness is obtained by equating the vehicle circulation speed at accesses with the linear speed inside the roundabout.

The system uses vertical visual signaling in the form of circular light sectors (and optionally traffic lights) to indicate the assignment of access priorities. The platoons of vehicles are formed and compacted using moving luminous signs at the head of the platoon located on the sides of the entrances and/or transversely on the floor of the entrances or by other procedures, including wireless signaling for connected/autonomous vehicles. These platoon head signs (e.g. North and South accesses) approach the roundabout at a constant speed, synchronizing the entrance to the roundabout of the platoons of vehicles of each two accesses from opposite directions. The perpendicular direction signs (e.g. East and West accesses) have a spatial and temporal offset adjusted to match the arrival of vehicles from the pair of accesses to the roundabout with the start of their access priority, thus avoiding most stops at the roundabout entrance. Besides this, the placement of the stop lines at a certain distance before the roundabout allows the vehicles, in the event of a stop, to enter the roundabout at the same speed of the rotating priority sector.

B. System description and operation

Figure 3 shows a roundabout equipped with vertical light signalling devices (12, 13, 16, 17 and 18) located at the entrances to the roundabout and on the central island (10). Around the central island (10) there is a light ring (11) formed by a set of programmable color lights showing colored circular sectors, which rotate at a speed similar to the average speed of vehicles in the roundabout. The vertical panels serve to show, in an analog form, the position of the sectors of the central

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light ring to the vehicles of each access. The panels contain a circle (14) in which the same colored circular sectors (15) are shown, replicating vertically the position of the sectors of the ring, as seen from the vehicles that reach the roundabout through each access, as it would be if the ring (11) was placed vertically perpendicular to each of the accesses. Figure 4 shows a block diagram of the system, comprising a processing unit that communicates with the camcorder control, wireless communication with connected vehicles, TV cameras, and image interpretation software, vertical light panels, and vehicle sensors. The mobile light signals that mark the start of platoons at the accesses are also controlled by the processing unit and indicate at all times the forward limit of the vehicle platoon not to be exceeded to maintain the synchronism of the platoon arrival with its assigned priority sector.

The processing unit obtains the characteristics of the traffic from the sensors and camcorders: intensity, average speed and degree of grouping, and depending on these, it modifies or not the movement speed of each approach light signal, the absolute and relative duration of the sectors, and the speed of rotation of the sectors in the panels and the central light ring. The maximum width of the sectors is, by default, 180 degrees, and the processing unit extends or decreases its duration depending on the traffic detected by the sensors and camcorders and the programmed traffic policies. When the sensors and / or cameras detect the start of the formation of a queue in some access, the size of the corresponding access sector is increased to facilitate the elimination of the queue, preventing the stops of the platoons at the accesses with more traffic. The far platoons of competing accesses (perpendicular) can be slowed down slightly to compensate for this increase, or the platoon size reduced by the sector duration reduction. As indicated in the vertical and horizontal signals, vehicles turning 90 degrees to the right must access the roundabout in the right lane. Vehicles going straight (second exit, 180 degrees) may use the right or left lane of access. Vehicles that are going to turn 270 degrees (turn left), must necessarily take the left lane of access. In this implementation variant, the 360-degree turn (change of direction) in the roundabout is not contemplated, but it is feasible, increasing the distances between platoons of

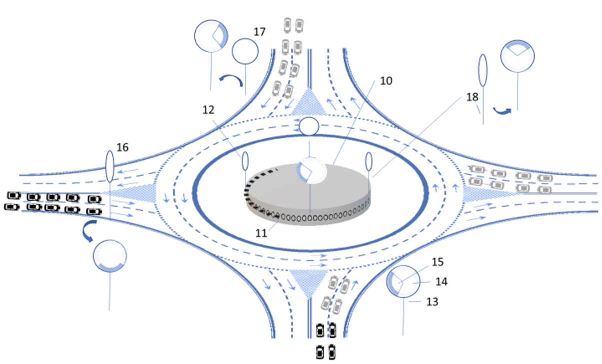

Fig. 3: SYROPS Roundabout signalling arrangement.

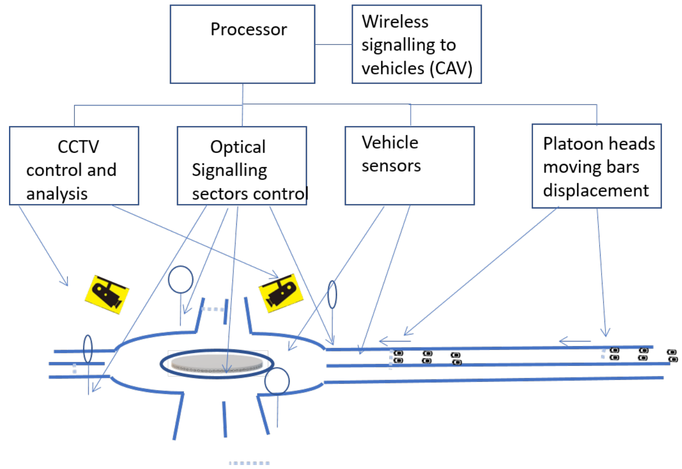

Fig. 4: Block diagram of roundabout control.

vehicles. In this implementation variant, if a vehicle remains in the roundabout after its 270 degrees of rotation, it loses its priority and must yield to those who access the roundabout. The same would happen at 360 degrees if the 360-degree turn was allowed. This restriction of the entrance lane to be used by vehicles according to their exit, together with the zoning of the priorities in the roundabout, avoids conflicts between vehicles to exit the roundabout [6]. These conflicts are quite common in standard roundabouts when, while passing access, the vehicle on the outer lane of the roundabout wishes to continue in the roundabout and the vehicle on the inner lane wishes to exit through the nearby access, crossing the paths of both vehicles and forcing the deceleration of one of them. The vertical light panels at each entry show the same information as the central light ring in the way that is most relevant for vehicle drivers: the color and pattern univocally associated with that entry, the turning position of the sector that gives the priority to the entry, showing the total size of this sector when it is fully deployed, and a fixed circular sector of about 60 degrees (the lower sector of the vertical circle), which visualizes the status of the priority of that access through the conventional colors of green, flashing yellow, or red. When the light sector of that access enters this lower 60 sector, the shared surface (i.e. the geometrical intersection) to both sectors is shown in green color (v), to provide an analog visualization of its priority sector position and priority time remaining.

Figure 5 shows a suggested traffic signal (EU style) to inform about the proximity of a rotating priorities roundabout.

Figure 4 shows the luminous platoon head mobile signs (32), located on the sides of the access and the ground. The ground signs light up sequentially in the direction of travel at the recommended speed of access to the roundabout, indicating the position of the front line of the platoon of vehicles.

To form the platoons of vehicles of the appropriate size (e.g. from two rows of four vehicles), the dynamic platoon header lines are initially at the beginning of the platoon circulation area delimited by the signals like figure 6 and

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figure 7 and controlled by the central processing unit. This distance between platoon heads is, for the variant described, a distance equivalent to 1.5 times the length of the central circumference of the roundabout (the line separating the two lanes). The maximum number of consecutive vehicles per row of the platoon depends on the dimensions of the roundabout. Drivers are informed in the sign of figure 6 of the maximum platoon length in the number of consecutive cars (C) and trucks (T), and the minimum but recommended distance to keep with the preceding platoon. The stop lines at the accesses, only used in case of congestion, are located at a distance from the roundabout that is sufficient to reach the speed of the rotating sectors to keep the smoothness of operation.

C. Platooning

The two key aspects of SYROPS roundabouts are the platooning of vehicles at each entry and their adequate orthogonal staggering to arrive just-in-time to the roundabout access when the access gets the rotating priority. To achieve it, the platoons must be first formed and then maintained while circulating at the mandatory speed.

Another complementary or alternative methods to form the platoons are the following:

- horizontal signals on the roads (aka known as "chevrons"). The platoon heads should keep at least two chevrons distance with the preceding platoon.
- moving horizontal traversal lights and/or lateral lights at both sides of the access that indicate the start of the platoon head. These light move at the same linear speed that the middle radius of the roundabout.
- wireless signaling infrastructure for connected autonomous vehicles.
- optical and acoustic signals to drivers from a smartphone app.
- vehicles with semi-autonomous capabilities (like collision avoidance systems) might be enabled for automatic platoon following.

D. Exception handling

Handling of exceptions at the roundabout (like a vehicle staying at the roundabout after his priority has elapsed, stopped vehicle, etc), must be designed ad-hoc based on simulation and real environment experiments. The general principles are based on safety and traffic fluidity and go in the direction of

Fig. 5: Synchronous Rotating Priority Sectors Roundabout (SYROPS) signal.

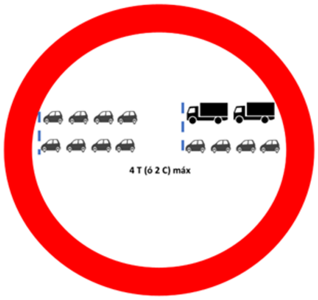

Fig. 6: Platoon start signal with platoon size.

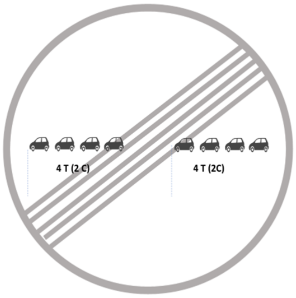

Fig. 7: End of platoon zone signal.

switching back to conventional roundabout operation with all lights in flashing yellow and priority to the vehicles inside the roundabout. If the exception can be handled by the system just by delaying some sectors' priorities or extending existing ones, it is done in this way. In the evaluation section, the "U-turn allowed" paragraph describes an example of 90 void sector usage during the transition from N-S to E-W sectors.

III. Sequence Example

Figure 8) shows schematically the signaling at the instant when the ring and the illuminated panels indicate the immediate beginning of the access priority for the North and South accesses, given that their respective semicircular sectors N and S begin to cross the access associated to its respective sector. Vehicles at the North and South entrances may, therefore, begin to exceed their stop line. The stop lines are placed at a certain distance from the roundabout (backstops), so that, in the event of forced arrest due to not having priority, vehicles can reach the speed of movement in the roundabout upon reaching it. Figure 8 b) shows the lower sector with its green left part (v), informing the vehicles of the North and South accesses that they have access priority. This lower sector

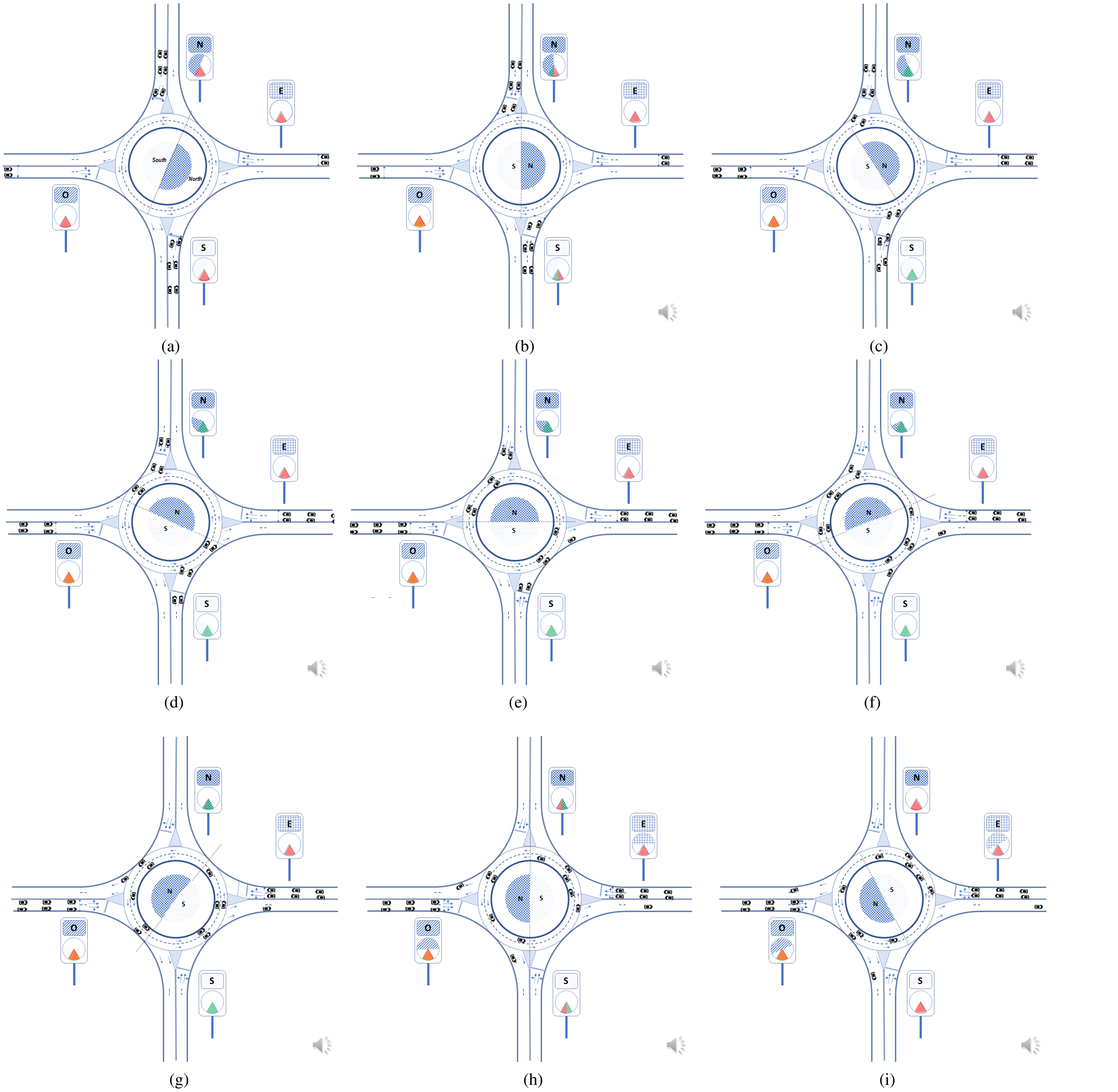

Fig. 8: Roundabout sequence I

continues to be shown in green until figure 8 h), in which it is close to disappearing, as the semicircular sectors of North and South priority pass through their respective entrances.

The vehicles of North and South accesses reach the edge of the roundabout and in figures it is shown how they freely circulate through it during the duration of their sector, having finished their access priority in figure 8 g) thus ceasing to access to the roundabout. Figure 8 i) shows the starting time of the priority for the accesses with the appearance of the East and West sectors when the East and West sectors reach the lower sectors of the East and West accesses, respectively, in the vertical light panels. In figures 9 a) to g) it can be seen how the lower sector in the East and West panels lights up green starting from the left side 9 b), coinciding with the passage of the East sector through the lower sector and ending on its right side figure 9 h). In the central circle, the most advanced radius in the direction of rotation of the South and North sector is then fixed in the West and East direction, respectively, stopping its rotation. However, the most backward radius of the North and South sector continues to rotate, thus

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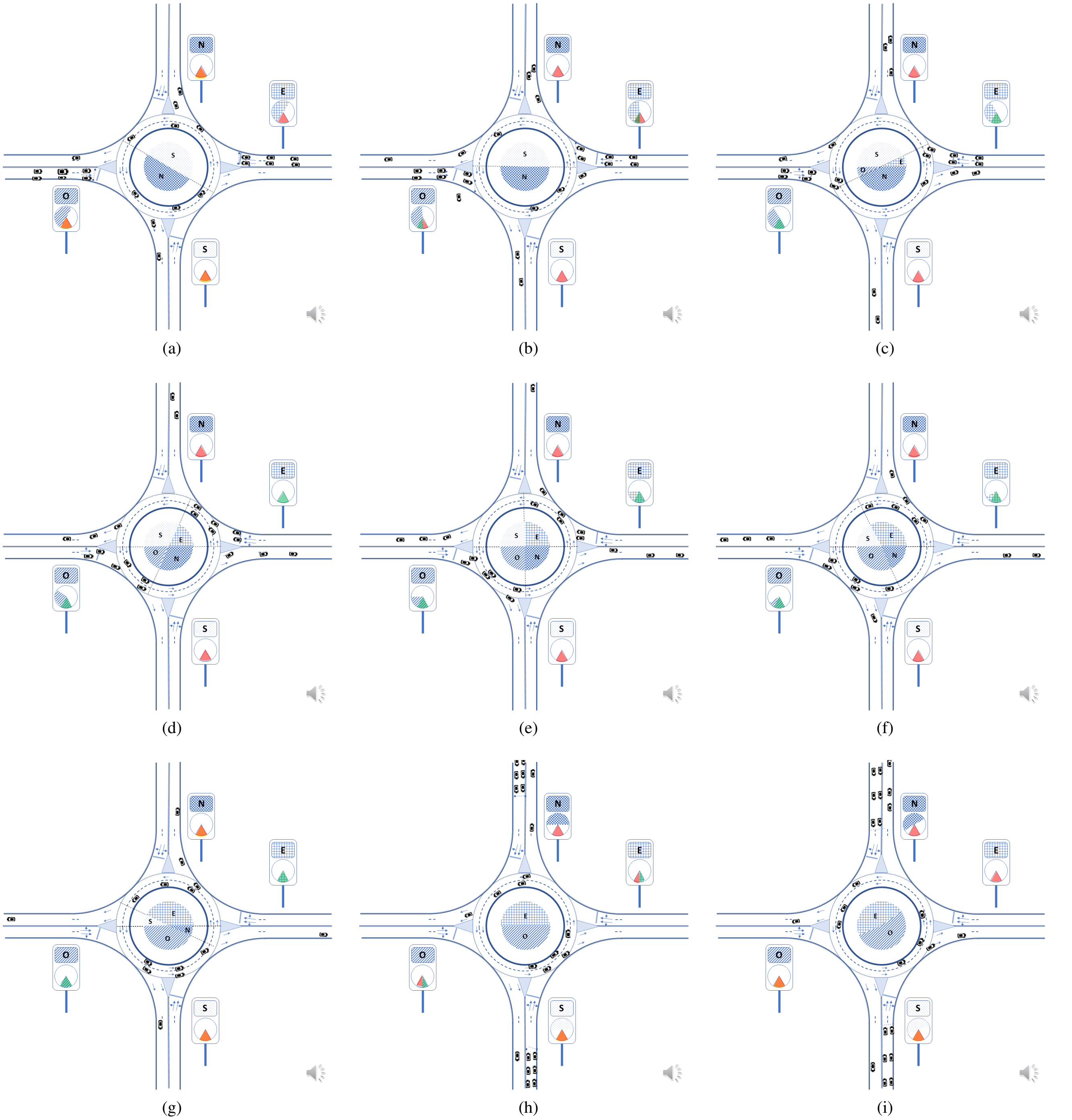

(a) (b) (c) (d) (e) (f) (g) (h) (i)

Fig. 9: Roundabout sequence II

the amplitude of these sectors begins to decrease. In the space created by this decrease, the East and West sectors appear and grow gradually with the general turn of traffic and to the same extent that the North and South sectors contract. The east and west access vehicles begin to access the roundabout when they have priority, i.e. their priority sector passes in front of their access. In figure 9 i) it can be seen how the last vehicles coming from North and South have already left from the West and the East respectively (the maximum allowed turn is 270, changes of direction are prohibited in this specific roundabout implementation). The East and West light sectors gradually increase until they reach their maximum amplitude (180 in this implementation). Figure 9 i) shows the end of the priority of the East and West accesses and figure 10 a) and figure 10 b) when the North and South vehicles arrive and begin to have the right of way. The cycle repeats indefinitely.

The described sequence provides maximum roundabout utilization but may need some allowance for human failures

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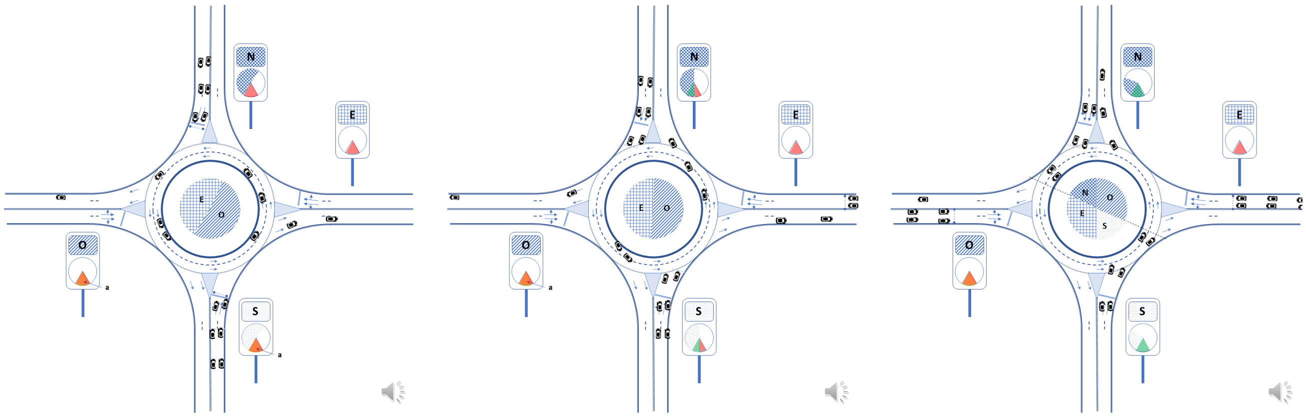

(a) (b) (c)

Fig. 10: Roundabout sequence III

in adapting to the roundabout circulating discipline (i.e. circulate at the recommended speed and to leave the roundabout maximum at 270 turn). Then it seems reasonable, at least when starting to operate a revolving roundabout, to foresee a slack or ”void” sector at the end of the signaling cycle to ensure that all vehicles abandon the roundabout and next cycle starts without disturbances that could affect the circulating speed. An extra phase period of duration between 90-180 would provide a margin for vehicles to leave the roundabout. This would be signaling as a ”mandatory emptying” phase. It would also allow u-turns to vehicles that did not leave the roundabout at the maximum 270 turn allowed. The reduction of capacity for the use of this sector (directly proportional to cycle lengthening) seems acceptable. In the sequence shown, to implement an extra 180 sector it would be necessary to increase accordingly the inter-platoon staggering.

IV. Evaluation

Synchronous roundabouts are much more regular and predictable in operation than conventional ones and do not require driver’s decisions to enter the roundabout. Due to this regularity and predictability we first evaluate roundabout capacities analytically. We evaluate one exemplary and efficient (although specific) implementation, among the many alternative sector sizes, rotation speeds and signalling sequence arrangements possible. For simplicity we assume equal traffic in all accesses and use (except during priority transitions) only two simultaneous sectors of 180 maximum amplitude. Vehicle turns at roundabout are only allowed up to 270.

The important parameters of a roundabout are closely interrelated and affect its capacity: radius, vehicle separation (gap in seconds or distance) and roundabout rotation period and average linear speed of the rotating sectors). We omit the basic equations that link these parameters as they are straightforward.

The ranges considered practical and used for this evaluation are as follows:

- Rotation period: 10 to 22 seconds (5 to 11 seconds half-periods)
- Angular rotation: derives directly from the rotation period (6.26 radians per turn): from 0.63 to 0.29 rad./sec
- Radius: from 10 to 50 meters (measured at the separation of the two lanes).
- Linear speeds at roundabouts: 23 to 51 km/h

These ranges are a first approach that would likely evolve over time with the practice of the drivers and other improvements. Some parameter impacts are easy to compute: an increase of 20% in rotation period produces about the same reduction in capacity, excluding platoon lengths truncation effects (although they can be compensated between accesses).

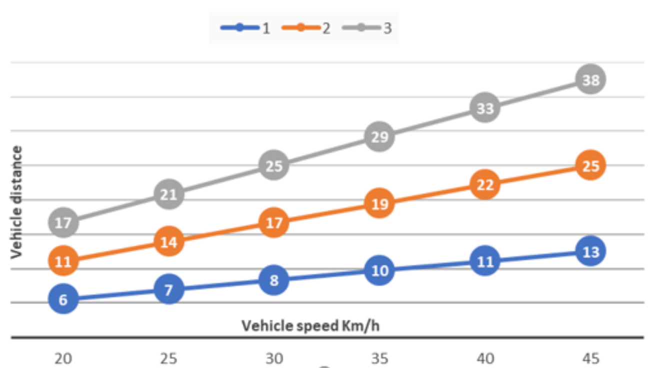

Fig. 11: Inter-vehicle distance vs gap in seconds and speed

The basic time (or maximum transit time) for a platoon crossing is two semi-periods of roundabout signalling rotation: one semi-period is used by the platoon heads located at the entrance of the roundabout to cross completely the roundabout and occupy the full semicircle, and the second is used by the platoon to exit the roundabout. If speed is constant, the lengths should be equal. Some guard time is needed at both ends (specially at the platoon tail) to ensure the smoothness of operation. As an example, if priority period (semicircle rotation) duration is 6 seconds, the first 6 seconds are used

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angular speed	linear speed	linear speed	gap	roundabout radius	semi-circle	platoon length	pl.length rounded	inter platoon distance	-1 lenght	slack	period	shorter plat	*4 max	conservative
rad/seg	m/s	km/h	m	m	m	cars	cars	m		cars	seg	-1 length	total	50%
0,63	6,3	**23**	8	10	31	2,6	***2***	***94***	***1,0***	1,6	**10**	**1920**	**3840**	**1920**
0,57	8,6	**31**	8	15	47	3,9	***3***	***141***	***2,0***	1,9	**11**	**3491**	**5236**	**2618**
0,48	9,7	**35**	8	20	63	5,2	***5***	***188***	***4,0***	1,2	**13**	**5908**	**7385**	**3692**
0,42	10,5	**38**	8	25	79	6,5	***6***	***236***	***5,0***	1,5	**15**	**6400**	**7680**	**3840**
0,35	10,5	**38**	8	30	94	7,9	***7***	***283***	***6,0***	1,9	**18**	**6400**	**7467**	**3733**
0,33	11,6	**42**	8	35	110	9,2	***9***	***330***	***8,0***	1,2	**19**	**8084**	**9095**	**4547**
0,31	12,6	**45**	8	40	126	10,5	***10***	***377***	***9,0***	1,5	**20**	**8640**	**9600**	**4800**
0,30	13,5	**48**	8	45	141	11,8	***11***	***424***	***10,0***	1,8	**21**	**9143**	**10057**	**5029**
0,29	14,3	**51**	8	50	157	13,1	***13***	***471***	***12,0***	1,1	**22**	**10473**	**11345**	**5673**
0,63	6,3	**23**	12	10	31	2,0	***1***	***94***	***1,0***	1,0	**10**	1920	1920	**960**
0,57	8,6	**31**	12	15	47	2,9	***2***	***141***	***1,0***	1,9	**11**	1745	3491	**1745**
0,48	9,7	**35**	12	20	63	3,9	***3***	***188***	***2,0***	1,9	**13**	2954	4431	**2215**
0,42	10,5	**38**	12	25	79	4,9	***4***	***236***	***3,0***	1,9	**15**	3840	5120	**2560**
0,35	10,5	**38**	12	30	94	5,9	***5***	***283***	***4,0***	1,9	**18**	4267	5333	**2667**
0,33	11,6	**42**	12	35	110	6,9	***6***	***330***	***5,0***	1,9	**19**	5053	6063	**3032**
0,31	12,6	**45**	12	40	126	7,9	***7***	***377***	***6,0***	1,9	**20**	5760	6720	**3360**
0,30	13,5	**48**	12	45	141	8,8	***8***	***424***	***7,0***	1,8	**21**	6400	7314	**3657**
0,29	14,3	**51**	12	50	157	9,8	***9***	***471***	***8,0***	1,8	**22**	**6982**	**7855**	**3927**
0,63	6,3	**23**	16	10	31	1,6	***1***	***94***	***1,0***	0,6	**10**	1920	1920	**960**
0,57	8,6	**31**	16	15	47	2,4	***2***	***141***	***1,0***	1,4	**11**	1745	3491	**1745**
0,48	9,7	**35**	16	20	63	3,1	***3***	***188***	***2,0***	1,1	**13**	2954	4431	**2215**
0,42	10,5	**38**	16	25	79	3,9	***3***	***236***	***2,0***	1,9	**15**	2560	3840	**1920**
0,35	10,5	**38**	16	30	94	4,7	***4***	***283***	***3,0***	1,7	**18**	3200	4267	**2133**
0,33	11,6	**42**	16	35	110	5,5	***5***	***330***	***4,0***	1,5	**19**	4042	5053	**2526**
0,31	12,6	**45**	16	40	126	6,3	***6***	***377***	***5,0***	1,3	**20**	4800	5760	**2880**
0,30	13,5	**48**	16	45	141	7,1	***7***	***424***	***6,0***	1,1	**21**	5486	6400	**3200**
0,29	14,3	**51**	16	50	157	7,9	***7***	***471***	***6,0***	1,9	**22**	**5236**	**6109**	**3055**
0,63	6,3	**23**	20	10	31	1,3	***1***	***94***	***1,0***	0,3	**10**	1920	1920	**960**
0,57	8,6	**31**	20	15	47	2,0	***1***	***141***	***1,0***	1,0	**11**	1745	1745	**873**
0,48	9,7	**35**	20	20	63	2,6	***2***	***188***	***1,0***	1,6	**13**	1477	2954	**1477**
0,42	10,5	**38**	20	25	79	3,3	***3***	***236***	***2,0***	1,3	**15**	2560	3840	**1920**
0,35	10,5	**38**	20	30	94	3,9	***3***	***283***	***2,0***	1,9	**18**	2133	3200	**1600**
0,33	11,6	**42**	20	35	110	4,6	***4***	***330***	***3,0***	1,6	**19**	3032	4042	**2021**
0,31	12,6	**45**	20	40	126	5,2	***5***	***377***	***4,0***	1,2	**20**	3840	4800	**2400**
0,30	13,5	**48**	20	45	141	5,9	***5***	***424***	***4,0***	1,9	**21**	3657	4571	**2286**
0,29	14,3	**51**	20	50	157	6,5	***6***	***471***	***5,0***	1,5	**22**	**4364**	**5236**	**2618**

Fig. 12: Roundabout capacities.

by the platoon heads to get close to the exit of the roundabout and the 6 additional seconds will be used by the platoon to leave the roundabout.

A. Calculation of maximum capacity of roundabout

The maximum theoretical capacity of a rotary roundabout is obtained by multiplying the number of cars that can cross the roundabout in one signalling cycle, multiplied by the number of cycles possible in one hour, i.e. 3600 seconds divided by the total (N-S and E-W) signalling period duration in seconds.

B. Inter-vehicle distance

More precisely, for the implementation described above, every three fourths of a turn, two accesses fill and then empty their semicircle sectors, and so two platoons cross the roundabout. Afterwards, the orthogonal pair of accesses does the same. During the 4th cycle the orthogonal pair of accesses starts entering the roundabout, thus requiring in total 1.5 turns per complete signalling cycle of the roundabout. All vehicles in platoons cross the roundabout in one and a half rotation period. For a four-accesses two lanes per access roundabout, the formula for maximum capacity is:

$$C = 4 * 2 * L/1.5 * Tpce/h$$

Where C is the capacity in passenger car equivalents per hour, L is the platoon length in number of vehicles and T is the signalling rotation period. The platoon length is obtained by dividing the semicircle length modulo the sum of vehicle length (4 m.) plus inter-vehicular (gap) distance.

The key aspect impacting capacity of roundabouts is the distance between vehicles (follow-up headway in seconds or meters). In conventional roundabouts this distance is big because the follow-up time (tf = 2.7 seconds) includes the delays involved in human reaction to follow the preceeding car when it starts. If, by avoiding stops and speed changes, we reduce tf in one second, the corresponding intervehicle distance may be reduced. Figure 11 shows typical values for inter-vehicle distances versus time gaps in seconds. In [5] the follow-up headway (time between passing) vehicles in standard roundabouts has been recently reduced to aprox. 2.6 seconds. This includes the length of the first vehicle, which takes about 0.5 seconds to pass.

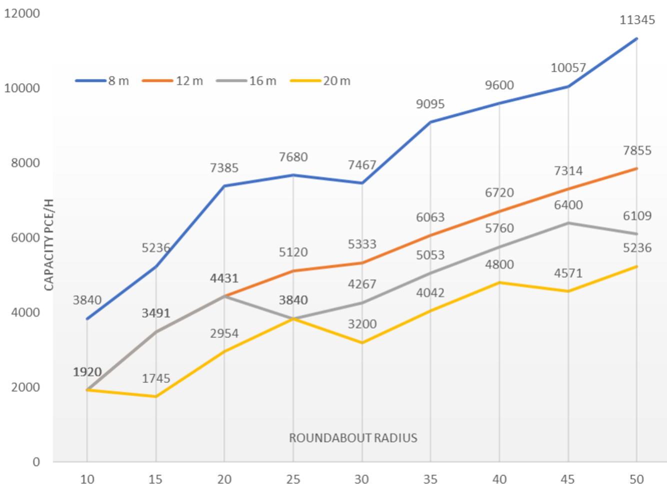

Fig. 13: Maximum roundabout capacities vs vehicle distances and roundabout radius.

In synchronous roundabouts, the uniform speed in accesses and inside the roundabout gives the drivers big confidence on the safety of the mutual approach (a quasi stationary scenario), and gaps can be significantly reduced. Besides this, the driver must only maintain the platoon speed and distance, much easier than entering conventional roundabouts, that require a gap estimation based on other vehicles speeds and distances. Gaps of 1-1.5 seconds between vehicles seem realistic to achieve as the relative speed between platoon vehicles entering the roundabout is very small. In line with this assumption, we select distances from 8 m (equivalent to two car lengths) to 20 m (equivalent to five car lengths) for the capacity calculations.

Figure 12 shows the capacities calculated for combinations of roundabout radius, inter-vehicle distances and linear speed. Rotating periods are adapted to roundabout radius to obtain a suitable linear speed for its radius.

The rotation periods of the roundabout have been chosen to result in a linear speed in line with a realistic linear arrival speed at accesses depending on their diameter (25 to 45 km/h). Increasing the rotation period reduces the capacity in the same proportion.

The three capacity columns are computed as follows: the maximum capacity column (center) is obtained assuming full platoons of spaced vehicles at the distance gap selected (8, 12, 16 or 20 m) with the maximum length allowed physically.

The left column is more conservative and assumes that the length of the platoons is one unit less than the maximum possible (if maximum length is equal or greater than 2), to take into account multiple factors preventing platoon optimization, and the right column is the most conservative approach: it assumes that the practical capacity is half of the maximum capacity calculated.

Figure 13 represents the maximum capacities results from previous table (middle) for different roundabout radius and inter-vehicle distances.

The coincidences in capacity values are a result of the granularity introduced by the fixed platoons length (equal in all accesses), when the platoon length is the same for two inter-vehicle distances. Being the rotation period for the bigger roundabouts, the capacity is lower than of the smaller radius roundabout. The steps in performance are significant because an increase of just one vehicle in the length of platoons means 2*4 = 8 more vehicles crossing in 1.5 roundabout period (e.g. 24 seconds) 1200 pce/h theoretical maximum. In real roundabouts traffic is not equal in all accesses and sector duration may be adapted to traffic intensities. These cases are subject for future work.

C. Simulative evaluation

In addition to our numerical analysis, we implemented our approach in the traffic simulator SUMO [9] to compare it with a non-controlled roundabout with four entries and exits under realistic traffic conditions. The results of this comparison regarding the number of vehicles that can traverse the roundabout in one hour are shown in Figure 14. We can clearly see that the improvement of our approach compared to a standard roundabout is comparably small for small roundabouts, and increases drastically for large roundabout. This behavior is caused by the smaller number of vehicles in small roundabouts, which decrease the number of potential conflicts. Additionally, we can observe that the capacity of the roundabout generally increases with increasing size of the roundabout due to the increased speed of the vehicles. Thus, the number of vehicles is relatively constant between $35m$ and $50m$, which differs from our analytical results. This difference is justified by the vehicle behavior in SUMO, which prevents vehicles from entering the roundabout if another vehicle with priority is nearby. We can also observe that the capacity of the roundabout decreases with increasing inter-vehicle distance, which is expected as less vehicles will be driving in a platoon and, thus, can traverse the roundabout per cycle.

In addition, the time a vehicle spends in the roundabout of $35m$ is shown in Figure 15. In this figure, we differentiate the different turn types, where right turn refers to the vehicle taking the first exit, straight to the second, and left turn to the third. We can clearly observe the drastic improve in vehicle passing time for all of the three turn types. An interesting prospect is that the improvement achieved for the right turn is smaller than for straight and left turn, as the number of potential conflicts are very low and the path is very short for vehicles making a right turn. Thus, the median time spent in the roundabout is not improved, while only the 75^{th} percentile is improved by 19.1%. When looking at straight, we also observe an improvement of 17.3% of the 75^{th} percentile, but additionally a small improvement in the median by 9.0%, which is caused by the increased number of possible conflicts.

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These conflicts are prevented by SYROPS and, thus, do not influence. Thus, the time spent in the roundabout becomes very predictable and has little fluctuation, which is good for having a constant and accident-free traffic flow. For the left turn, the improvement is very drastic, as the number of possible conflicts is the highest among all directions. Thus, we can see an improvement of 8.4% in the median time, and an decrease of 80.0% reduce in the worst case. The overall average time spent of a vehicle in the roundabout independent of the direction is improved by 28.7%.

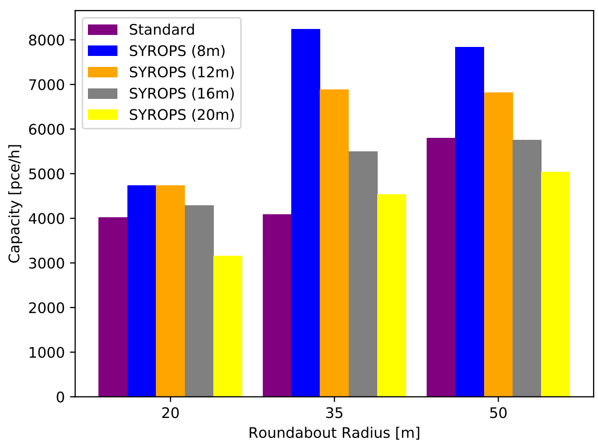

Fig. 14: Roundabout capacity in vehicles per hour.

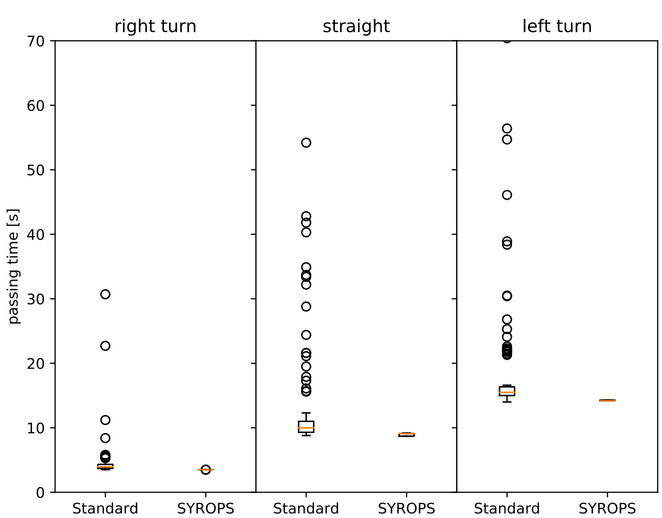

Fig. 15: Roundabout delay per direction of travel for a roundabout radius of $35m$.

D. Allowing U-turns

An important signalling variant allows u-turns (i.e. 360 degrees turns maximum allowed instead of 270), at the cost of increasing the phase duration by an additional 90 sector rotation per access (360 instead of 270) to complete the turn, plus another 90 inactive sector where no entrances are allowed. This sector adds safety to the roundabout and gives way for distracted drivers exceeding U-turns to leave compulsively the roundabout at next 90 turn if presence is sensed in this 90 sector. The total cycle time for the roundabout would be now 28/8 turns, a maximum of 3.5 rotation periods instead of 1.5 period. But There are six 1/8 rotations that are void (no vehicle entrance), if the signalling skips this time, the period would be 22/8 = 2.75 periods. The sequence is shown at Figure 16. Observe that North and South sectors reach North and South and afterwards no traffic is allowed, part of this time can be used as safeguard to empty the roundabout.

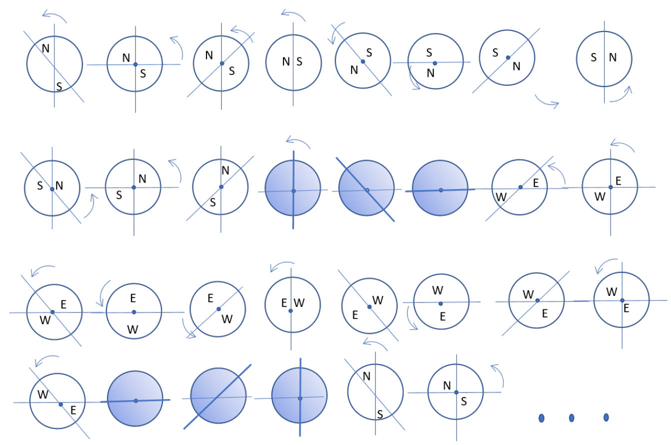

Fig. 16: Signalling sequence for U-turn allowed variant (360) with void sector.

This increase in cycle time would decrease proportionally the capacity of the roundabout, multiplying it by a factor of 1.5/2.75 = 0.54, a 46% reduction.

If higher capacity is needed, the 90 void sector may be skipped (or sped up) and the entrance to E-W signalled just after North and South closing. This should be signalled smoothly and carefully in order to prevent drivers' surprise. This signalling sequence seems recommended for new deployments until the drivers get familiar with the revolving roundabouts procedures.

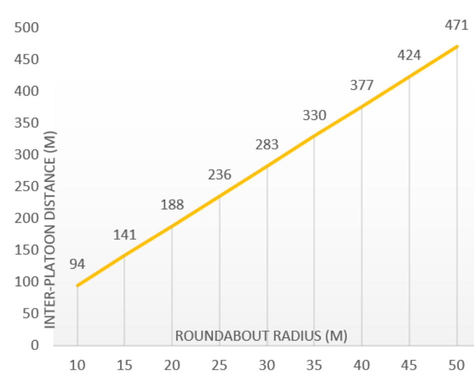

Fig. 17: Inter platoon distances versus roundabout radius.

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E. Inter-platooning distances

The distance between platoons is, assuming constant speed, the linear speed of the roundabout multiplied by duration the signalling cycle. Figure 17 shows the inter-platoon distances to be maintained by the moving platoon head signals.

F. Signalling dynamics and variants for unbalanced traffic

Other signalling variants might adapt the duration of sectors to different traffic intensities at the accesses, and use either different platoon lengths or just signalling two platoons in consecutive phases (e.g. two phases of N-S sectors per one phase E-W).

The use case of unequal traffic intensities at accesses is very common and important in practice, because in many roundabouts there exists a dominant traffic direction and a daily change oscillation of the dominant traffics (e.g. commuters going and returning from work or shopping).

G. Traffic overloads

Synchronous revolving roundabouts prevent congestion through admission control. The platoon headers act as limiters of vehicle flow flowing through the roundabout accesses. Then, the potential queues will appear far from the roundabout. In case of transient excess of traffic, vehicles will accumulate in the road before the platooning zone of priority extended for the accesses. This aspect must be taken into account in the design.

H. Pedestrians traffic

Pedestrian traffic has usually significant impact on roundabout performance and safety and a multiplying coefficient factor is used [10]. For SYROPS roundabouts, pedestrian can cross safely the incoming access just after a platoon has passed and pedestrian signals should adapt to it. The crossing of the outgoing access requires detailed design, in order to use time-slots of the signalling cycle with low traffic probability, e.g. transitions between exiting traffics from different accesses. The dimensioning of sectors duration may also take this into account to create these gaps.

I. Roundabout Capacities at HCM 6th edition

The USA Highway Capacity Manual includes a section for roundabout capacity estimation [5]. The model can be viewed both as an empirical (exponential regression) model and a gap-acceptance model.

The final equation for capacity recommended at HCM2016 section A.2.3 [5], using the recommended values for headway and follow-up is:

$$Qe = 2424 - 0.7159Qc$$

Where Qe is capacity in pce/h passenger vehicles per hour and Qc the conflicting traffic. Assuming uniform traffic in the four accesses, we can estimate the maximum capacity of a rotary roundabout (with maximum permitted rotation of 270) as follows. For an uniformly distributed traffic, Figure 1 of [10] gives a total of 800+700 = 1500 pce/h maximum But application of this value to all entries simultaneously is questionable, as the examples in table 4 of do not consider perfectly balanced traffics [10] and the simulation scenarios (section 4.3) with a total absolute maximum capacity of 1830 pce/h. [11]. If we compare this value with our analytical results, it would correspond to midsize roundabouts with 20 m inter-vehicle distance, quite in the low range of capacities. A key point to be further studied is that in the HCM model, the levels of service will likely degrade much earlier with increasing conflicting traffic than in SYROPS.

V. Related Work

Current practice on roundabout design and evaluation is documented with many empirical studies and usually incorporated in state of the art recommendations from official bodies like HCM [5] in USA and other countries [12].The second edition (2010) of the Roundabouts Informational Guide is a complete guide on the subject [13].

The use of a metering signals and stop lines at accesses of the roundabout to create gaps that improve its performance is a proven technique [4], [14].

Various roundabout designs are known [15] and also the physical design of turbo-roundabouts [16], which seek to reduce the number of conflict points in roundabouts. Regarding roundabout signalling, the design of [17] for conventional vehicles at roundabouts uses a central ring at the roundabout with two operating modes: either it lights up in sequence, so that the lights (like arrows) move in the direction of rotation of vehicles at the roundabout, or flashes to indicate caution.

Reza Azimi has studied extensively the control of the flow of autonomous and enhanced vehicles at intersections and roundabouts, based on allocating virtual slots to vehicles [18]–[21]. Although the proposals and analysis are solid and the performance improves, the crossing of the intersections and roundabouts may be terrifying for the passengers of the autonomous vehicles. More recent work has evolved Azimi's work to increase safety and passenger's psychological comfort [22].

There are various technologies and standards that try to optimize traffic flow in roundabouts, intersections and other environments through electrical communications between each vehicle and the environment. They are encompassed in the V2X (vehicle to everything) concept [23], which includes both communication between vehicles, vehicles and road infrastructure or vehicles and pedestrians. Mobile technologies such as 3GPP and Vehicular Communication at ITS of ETSI [24], [25] contemplate the electrical communications for these applications.

These autonomous vehicle coordination technologies (automatic driving) are not applicable when driving conventional vehicles with driver, so it is necessary to improve the performance and safety of roundabouts through procedures that are applicable to both driver and autonomous vehicles. The problem of roundabout crossing using virtual platoons of autonomous and manually driven vehicles is studied in [26]. The term virtual platoon applies to vehicles that may circulate at different lanes of the roundabout and coordinate their arrival to the roundabout for safe crossing. An analysis of mixed driven human and CAV vehicles at microscopic level is given is [22].

VI. Future work

Changing roundabout operation is not an easy task: as it happened with current roundabouts, the synchronous rotating priorities roundabout concept requires a learning period by the vehicle drivers and also a signaling design well adapted to human perception. Although the constant speed approach simplifies roundabout crossing, the perceptual aspects must be evaluated together with the traffic dynamics. Simulations and virtual reality platforms offer a excellent set of tools for it.

The simulations performed for the exemplary implementation should be extended to include evaluation dynamic adaptive variants that handle unequal traffic distributions with different sector sizes and sequences varying along the day.

The dynamic hybrid operation of a roundabout, as a revolving roundabout with medium or intense traffic, and as a conventional roundabout with low traffic or anomaly conditions is also worth to study. The capability to operate in both modes alternatively is an important aspect for initial and pilot deployments.

VII. Conclusion

Roundabouts with rotating priorities open a new path for research on roundabout evolution incorporating most technologies available (sensors, V2X, IoT, scene interpretation, Intelligent Infrastructures, Smartphones, CAVs), but preserving compatibility with human-driven vehicles. The analytical evaluation and SUMO simulations show lower delay and very small delay variations as well as higher capacities than conventional roundabouts. By eliminating the conflict points and subsequent speed changes, safety is also improved through driving smoothness. Drivers are only required to follow the platoon or the head of platoon signal and to enter the roundabout in the lane corresponding to their exit. Signalling sequences adapt dynamically to traffic unbalances and daily fluctuations and may alternate between standard operation or synchronous mode. Low delay variation will probably provide high Levels of Service (LOS).

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References

[1] "Circus (bath)," accessed: 2020-05-01. [Online]. Available: https://en.wikipedia.org/wiki/Circus_(Bath)

[2] R. Retting, B. Persaud, P. Garder, D. Lord *et al.*, "Crash and injury reduction following installation of roundabouts in the united states," *American Journal of Public Health*, vol. 91, no. 4, pp. 628–631, 2001.

[3] L. Rodegerdts, *Roundabouts in the United States*. Transportation Research Board, 2007, vol. 572.

[4] R. Akccelik, "Roundabout metering signals: capacity, performance and timing," *Procedia-Social and Behavioral Sciences*, vol. 16, pp. 686–696, 2011.

[5] "Highway capacity manual (hcm)," accessed: 2020-04-28. [Online]. Available: http://www.trb.org/main/blurbs/175169.aspx

[6] L. Vasconcelos, A. B. Silva, lvaro M. Seco, P. Fernandes, and M. C. Coelho, "Turboroundabouts: Multicriterion assessment of intersection capacity, safety, and emissions," *Transportation Research Record*, vol. 2402, no. 1, pp. 28–37, 2014.

[7] W. contributors, "Magic roundabout (swindon). wikipedia," 2020, online; accessed 31-May-2020. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Magic_Roundabout_(Swindon)&oldid=954183430

[8] "Highway capacity manual (hcm)," accessed: 2020-04-28. [Online]. Available: http://www.trb.org/Main/Blurbs/Highway_Capacity_Manual_2010_HCM2010_164718.aspx/

[9] P. A. Lopez, M. Behrisch, L. Bieker-Walz, J. Erdmann, Y.-P. Flötteröd, R. Hilbrich, L. Lücken, J. Rummel, P. Wagner, and E. Wießner, "Microscopic traffic simulation using sumo," in *The 21st IEEE International Conference on Intelligent Transportation Systems*. IEEE, 2018.

[10] R. Akccelik, "An assessment of the highway capacity manual edition 6 roundabout capacity model," *Transportation Research Board: Green Bay, WI, USA*, 2017.

[11] "Highway capacity manual (hcm)," accessed: 2020-04-28. [Online]. Available: http://www.mikeontraffic.com/hcm-6th-edition-roundabout/

[12] R. Akccelik, "Sidra intersection," 2000.

[13] T. R. Board, N. A. of Sciences Engineering, and Medicine, *Roundabouts: An Informational Guide Second Edition*. Washington, DC: The National Academies Press, 2010.

[14] M. Martin-Gasulla, A. Garcia, and A. T. Moreno, "Benefits of metering signals at roundabouts with unbalanced flow: Patterns in spain," *Transportation Research Record*, vol. 2585, no. 1, pp. 20–28, 2016. [Online]. Available: https://doi.org/10.3141/2585-03

[15] "Roundabout," accessed: 2020-05-05. [Online]. Available: https://en.wikipedia.org/wiki/Roundabout

[16] L. G. H. Fortuijn, "Turborotonde en turboplein: ontwerp, capaciteit en veiligheid," *TRAIL Research School*, 2013.

[17] P. Novotnyjan and V. Vochozka, "Traffic lights control for fuel efficiency," 2014, wO2014094693A1.

[18] S. R. A. Upali Priyantha Mudalige, Ragunathan Rajkumar and G. Bhatia, "Efficient intersection autonomous driving protocol," 2015, uS20130304279A1.

[19] R. Azimi, G. Bhatia, R. Rajkumar, and P. Mudalige, "Ballroom intersection protocol: Synchronous autonomous driving at intersections," in *2015 IEEE 21st International Conference on Embedded and Real-Time Computing Systems and Applications*, Aug 2015, pp. 167–175.

[20] R. Azimi, G. Bhatia, R. R. Rajkumar, and P. Mudalige, "Stip: Spatio-temporal intersection protocols for autonomous vehicles," in *2014 ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS)*. IEEE, 2014, pp. 1–12.

[21] R. Azimi, G. Bhatia, R. Rajkumar, and P. Mudalige, "V2v-intersection management at roundabouts," *SAE International Journal of Passenger Cars-Mechanical Systems*, vol. 6, no. 2013-01-0722, pp. 681–690, 2013.

[22] B. Chen, D. Sun, J. Zhou, W. Wong, and Z. Ding, "A future intelligent traffic system with mixed autonomous vehicles and human-driven vehicles," *Information Sciences*, vol. 529, pp. 59 – 72, 2020. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0020025520300736

[23] "Vehicle to everything," accessed: 2020-04-20. [Online]. Available: https://en.wikipedia.org/wiki/Vehicle-to-everything

[24] 3GPP, "Architecture enhancements for v2x services," 2016, technical specification, release 14.

[25] ETSI, "Intelligent transport systems (its); vehicular communications; basic set of applications," 2014, part 2: Specification of Cooperative Awareness Basic Service.

[26] S. Masi, P. Xu, and P. Bonnifait, "Adapting the virtual platooning concept to roundabout crossing," in *2018 IEEE Intelligent Vehicles Symposium (IV)*, 2018, pp. 1366–1372.