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Capacity Increase through connectivity for the i-Roundabout and i-Turbo roundabout

L.G.H. (Bertus) Fortuijn[1] and A. Maria Salomons[2]

Abstract— **Is a roundabout still a good solution in the era where 'intelligent' intersection control using vehicle connection (i-TLC), is in upswing? To answer this question, the capacity of 'i-roundabouts', where the infrastructure communicates with the vehicles (I2V), is determined analytically. The roundabouts considered are single-lane roundabouts and turbo roundabouts (a spiral multi-lane roundabout with reduced number of conflicts). A macroscopic approach explores the capacity gain that can be achieved by taking into account the necessary safety margins with regard to headways and gaps. Furthermore, it is assumed that by using I2V the speed, headway, and also the driving curve of the vehicles can be controlled.**

For roundabouts with speeds lower than 36 km/h, the conclusions are that:

- **On a single lane roundabout, roughly a doubling of the capacity can be achieved.**
- **On a turbo roundabout the capacity gain can be surprisingly much higher (about a factor 2.5). This is due to the possibility of gap synchronization on the double-lane segments.**

I. INTRODUCTION

The perspective of connected controlled vehicles is in the spotlight. The car industry is mainly aiming on the aspect that scores high among consumers, namely comfort enhancement. From a traffic-related point of view, in addition to the safety aspect, the possible gain in capacity is also interesting. For intersections 'intelligent traffic light controllers', i-TLC, are topic of research [1]. In a much earlier study [2] the first author introduced automatic vehicle guidance (abbreviated to *AVG*) , which assumes it is possible to control the speed and movement for each individual vehicle approaching the intersection. With current communication possibilities that arise using i-TLC and I2V, automatic vehicle guidance seems to be feasible in future. In this earlier study, assuming automatic vehicle guidance and using a macroscopic approach, it was determined that in theory a capacity gain of at least 50% can be achieved on motorways, and that for intersections the capacity can be doubled compared to a traditional traffic signal, provided that vehicles are clustered (and do not intersect individually).

Macroscopic approach and type of connectivity (*AVG*) is used in this contribution as well, focusing on the capacity gain that can be achieved at single-lane roundabouts and the turbo roundabouts. The turbo-roundabout is a multi-lane roundabout where through its spiral design the number of conflicts are reduced when compared to a common multi-lane roundabouts [3]. Turbo roundabouts can have multiple shapes, to fit the capacity to the demand pattern at the location. The capacity (and the gain using *AVG*) is determined by macroscopic capacity models based on gap acceptance. In this paper also a small-scale analysis at vehicle level is done in order to analyse the validity of the parameters that are used in the capacity model.

In this paper, in section II the difference between modes of conflict handling are explained, in section III the principles of *AVG* are explained, that are applicable both to single-lane and turbo roundabouts, in section IV these principles are applied to single-lane roundabouts, in V, VI and VII the *AVG* on turbo roundabouts is expounded. In section VIII the conclusions and recommendations are given.

II. MODES OF CONFLICT HANDLING: CLUSTERING OR ZIPPING

When conflicts are considered, both (time) headways and gaps between crossing flows must be considered. In this paper 'headway' and 'gap' denote the gross time headway and the gross time gap, so including the vehicle length; the word 'net' is added if the time gap between vehicles is meant. Analysis of the traffic flow shows that the (time) headways (i.e. the time gap between passing the rear sides of vehicles in the same flow) are smaller than the (time) gaps needed for conflict handling of vehicles in different flows, because in case of crossing not only the vehicle lengths, but also the vehicle widths play a role, see Figure 1. The capacity gain that can be achieved with *AVG* is based on the fact that greater precision in control handling can be obtained with the aid of automation. As a result, both the gaps between vehicles of conflicting flows and the headways of vehicles in the same flow can be shorter than a person as driver needs, for a driver can respond less accurately than an automatic guided vehicle.

The difference between headway and gap is the base of the capacity gain that can be achieved by clustering cars using traffic control. Even in an automated traffic flow, the (gross) gap for conflicting flows must be greater than two times the (gross) headway of vehicles in the same flow. Also the variation in the transverse position of the vehicles (which has not yet been taken into account in Figure 1) has to be considered. When the speeds of the conflicting vehicles differ, also the translation from distance to time of the two components of the (deviation of) the swept paths differs. The contribution to the gap enlargement for each of

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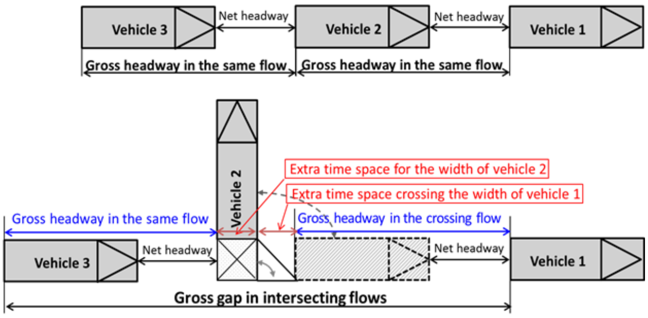


Fig. 1. The difference in distance between vehicle 1 and 3 for the same flow (upper figure, 2x the gross headway) and for an intersecting flow (lower figure, the gross gap). The lower figure shows the clearance time, expressed in distance, between two identical conflicting vehicles that move over the same conflict area with the same speed.

the two components consists of the widened swept path of the conflicting party divided by its own speed. If the vehicle is guided to decrease this variation of the transverse position, the gap enlargement will reduce.

The capacity advantage of roundabouts with respect to (uncontrolled) intersections is based on a combination of two factors: lower speeds will simplify estimating the required gap, while the conflict handling is separated spatially so that vehicles from conflicting directions can enter the roundabout (almost) simultaneously. Therefore, clustering of traffic by means of traffic control does not yield any gain on single-lane roundabouts. In general, on roundabouts clustered conflict handling initiates capacity loss, so the optimum conflict handling on roundabouts is based on zipping [2]. The capacity can be increased if the arrivals at the roundabout entrance can be automatically adjusted in a way that the distribution of the headways is optimum for zipping.

To avoid long waiting times on a side direction of a roundabout, the roundabout metering signal (RMS) has been introduced. On a single-lane roundabout RMS does not yield a capacity gain, but this is different for multi-lane roundabouts, because the clustered gaps are (implicitly) synchronised in parallel roundabout flows [4]. So when vehicles are guided on a turbo roundabout, this synchronising should be added explicitly to increase the gain.

Summarizing, with *AVG*:

- due to greater driving precision, the headways and gaps can be reduced;
- course guidance will also lead to a reduction of the headways;
- the conflict handling is based on zipping, the optimum distribution of headways can be done by automatically adjusting the arrivals;
- for turbo roundabouts, the synchronization of gaps on parallel roundabout-lanes can yield extra profit;

The capacity gain, using the opportunities of *AVG* mentioned above, are explored in this paper.

III. PRINCIPLES OF AUTOMATIC VEHICLE GUIDANCE (*AVG*) AT ROUNDABOUTS

Research at the end of the 90s has already shown that automatic vehicle guidance only yields capacity if the cars do not only drive autonomously, but also drive connected. The lead author also assumed this in [2], based on findings in [6]. This electronic connection is now called V2V (information exchange between vehicles), I2V (communication between infrastructure and vehicle in both directions) [5], [7]. Connectivity in the combination of V2V and I2V is the condition for achieving the goals of *AVG* set in II. For *AVG* control is assumed that the infrastructure can communicate to the vehicle the desired course in lateral and longitudinal position and the desired speed. The management by connectivity is referred to as cooperative traffic management [7].

Assumptions

Two starting points are important for determining the minimum headway time for vehicles at roundabouts:

- the minimum gross headway time may not be less than 0.8 s/pcu. This assumption is within the ranges that are currently mentioned in literature for the net time headway (0.3 à 0.6 s) [8, 9,10]. This implicitly means that at speeds above 36 km/h the net headway time increases with the speed [2].
- considered are roundabouts at which the speeds are lower than 36 km/h. For the determination of the minimum headway time, the minimum (spatial) distance to be maintained between the vehicles is important. In this study it is assumed that drivers accept a distance of 3 m between each other at such low speeds, as long as they still have to keep their course. If the course guidance is also automated, the minimum distance in the calculation is lowered to 2.70 m.

For the roundabouts the assumptions for the headways have been adjusted because of additional requirements. An important aspect here is that roundabout-lanes are wide and that the trajectories of the vehicles could differ from one another: one driver can follow the outer part of the roundabout-lane while the other follows the inner side. Because the car is always driven in a curve, one car can covers a greater distance than the other. As a result, the headways will constantly change. This means that minimum headways are determined by both the variation in the course, and preventing uncomfortable accelerations. The starting point is a driving curve with a radius R_D, and the deviation of the course is ΔR_D. In [2] is deduced that the initial distance between the two vehicles ($A_{initial}$) driving with speed v_0 and accepting a comfort acceleration $a_{comfort}$, starting from a minimum mutual vehicle distance (A_{min}) must satisfy the condition:

$$A_{initial} > A_{min} + \frac{v_0^2}{a_{comfort}} \left(\frac{\Delta R_D}{R_D}\right)^2 . \qquad (1)$$

At a roundabout with an outer radius of 18 m and an inner radius of 12.75 m, depending on the *AVG* variant,

R_D = 15.38 m (manual steering) or 16.42 m (with path guidance). The driving curves on roundabouts are generally more spacious, but for safety reasons this radius is used for calculating the space for accommodating the variations in the driving course. Furthermore, the value a = 1.5 m/s^2 is used as a comfortable acceleration and deceleration.

The minimum headway t_M for circulatory traffic follows from:

$$t_M = \frac{A_{initial} + L_{veh}}{v_0}, \tag{2}$$

where v_0 is the speed on the inner lane and L_{veh} is the vehicle length. For the sake of simplicity, this study only considers private cars with a length of 5 m (in Dutch Guidelines 4.88 m [8]).

As already stated in section II, the traffic flow on a modern single-lane roundabout is comparable to a 'zipper model' at low speed. Even though the flows approach each other almost perpendicularly, they do not intersect. On a turbo roundabout, traffic to the inner roundabout lane must cross the outer roundabout lane. In this case the gap extension does play a role (see Table I and section VII).

IV. *AVG* AT SINGLE LANE ROUNDABOUTS: THE SINGLE-LANE i-ROUNDABOUT

Capacity gain

From Eq. 1 can be determined that $A_{initial}$ will be about 3.4 m. If the zipper system is used for small single lane roundabouts, this will lead to a headway of t_M= 1.12 s/pcu when assuming a realistic speed of v=7.5 m/s (Eq. 2). For the conflict area opposite the entrance, the capacity will be 3600/t_M=3200 pcu/h. On a single lane roundabout, the conflict capacity without *AVG* is 1650 to 1700 pcu/h [10]. In [2] on the basis of this, it was estimated that the capacity gain on a single lane roundabout was roughly a factor 2 (3000/1650).

It is also possible to use a gap acceptance model. When there is no automatic vehicle guidance, stochastic processes determine the distribution of headways. Tanner [9] has derived a useful approach for this, taking into account clustering that occurs because cars have to maintain a minimum mutual distance. Troutbeck [12] later modified the Tanner model, taking into account additional clustering. This leads to higher capacities.

The Troutbeck model can be written as:

$$C_E = \rho q_R (1 - t_M q_R) \frac{e^{-\rho q_R (t_C - t_M)}}{1 - e^{-\rho q_R t_F}}, \tag{3}$$

where the following applies:

C_E:	capacity of the entrance	[pcu/s];
q_R :	volume of roundabout traffic	[pcu/s];
ρ:	cluster factor;	
t_M:	minimum headway circulatory traffic	[s/pcu];
t_C:	critical gap in the circulatory flow for access from the entrance;	[s/pcu];
t_F:	follow-up time from the entrance	[s/pcu].

The cluster factor ρ indicates to what extent the proportion of clustered traffic on the roundabout deviates from the distribution that Tanner used in his derivation [10]. For ρ = 1 the Troutbeck model is identical to the Tanner model. If $\rho \rightarrow 0$, (almost) all headways equal the minimum headway, or at_M (offering a gap, since $t_C = 2t_M$), where a is an integer, and the relationship between access capacity and roundabout intensity is linear:

$$C_E = \frac{1 - t_M q_R}{t_F}. \tag{4}$$

As long as *AVG* is limited to reducing headways and gaps, the Tanner model is the appropriate method for calculating the effects with $t_F = t_M$ and $t_C = 2t_M$, in this paper this model is indicated as AVG-S1, see in Table I.

The next step in extending *AVG* is to optimize the distribution of headways by adjusting the arrivals via automatic vehicle guidance (here: AVG-S2), this will result in a linear relationship between the access capacity and the circulatory volume at a single-lane roundabout (in the model of Troutbeck $\rho \rightarrow 0$). If both the arrival pattern and the course keeping are improved by the automatic vehicle guidance (here: AVG-S3), a capacity gain of globally a factor of 2 is obtained with a fully applied *AVG* system. The resulting capacities for the human driver and for the *AVG* variants are compared in Figure 2, for the entrance capacity as well as for the capacity of the conflict area. The capacity for human driven vehicles is in [10] compared to field data. In which way the assumptions about the headway reduction and adjusting of the arrival patterns can be applied in practice, has to be tested by means of microsimulation.

V. ANALYSIS OF THE POSSIBILITY OF GAP SYNCHRONIZATION AT A TURBO ROUNDABOUT

On the single-lane roundabout, the capacity gain with automatic vehicle guidance is achieved by reducing the headways and gaps. On roundabouts with more than one lane, an additional capacity gain can be achieved by synchronizing the gaps on the two-lane segments. This section analyzes the options for synchronizing for the most critical case on the basic turbo roundabout. Unlike the single-lane roundabout, the zipper model alone will not suffice for the turbo roundabout. On a turbo roundabout, traffic to the inner roundabout lane must cross the outer roundabout lane, therefore the gap extension will play a role.

In principle, the flows of all legs influence each other, but the segment between the main leg and the minor leg is most critical to properly synchronize gaps. This is the case with two vehicles that enter from the main leg, and a vehicle from the minor leg on the left lane wants to enter the roundabout, see Figure 3. The vehicles from the major leg will use the same gap, but the left vehicle can enter a little earlier than the right vehicle following the outer lane. However, facing the minor leg, the time of arrival must have been shifted in the very opposite direction: the vehicle on the outer lane must arrive earlier than the one on the inner lane to offer a synchronized gap for the entering car at the left lane of the minor leg.

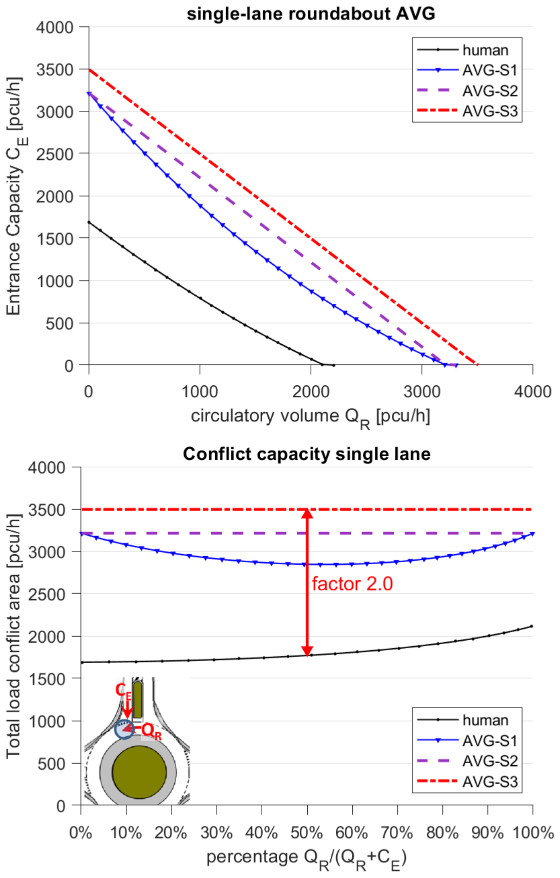


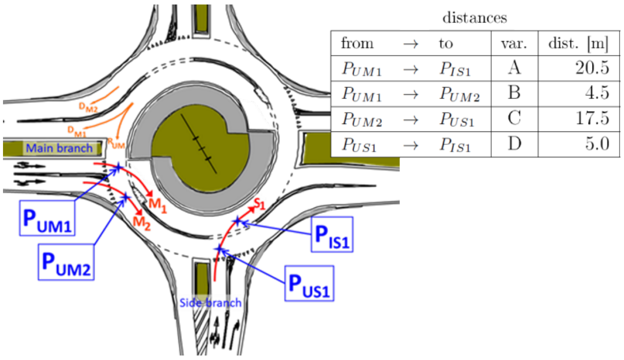
Fig. 2. Single-lane i-roundabout: effect on the capacity using the *AVG* variants. Upper: the entrance capacity as function of the circulatory volume, lower: the conflict capacity. For the explanation of the legends: see Table I.

This has been further analyzed for the basic turbo roundabout with a diameter of 52 m (see guidelines [11]). In Figure 3 the conflict points and traffic flows are indicated. The criterion for synchronization is that the distance from P_{UM1} via the inner roundabout to P_{IS1} (distance A = 20.5 m, see Fig. 3 for the distances) is covered in the same amount of time as over the outer roundabout via P_{UM2} and P_{US1} (distance B + C + D = 4.5 + 17.5 + 5.0 = 27 m). In formula:

$$t_{P_{IS1}} = \frac{A}{v_{M1}} = \frac{B}{v_{RU}} + \frac{C}{v_{M2}} + \frac{D}{v_{S1}} \tag{5}$$

Because the car on the inner roundabout lane should have the lowest speed, the speed v_{M2} of M_2 on the outer roundabout lane is assumed as given. On a turbo roundabout with an inscribed diameter of about 52 m, this is circa 36 km/h (10 m/s). Taking into account some left-turning traffic from the previous side branch that drives slower than 36 km/h, this is his has been reduced to 32 km/h (8.9 m/s). Two variants are considered: Variant ‘a’, the case speed of M_1 and S_1 should be equal after passing PS_1 when they continue the same course: $v_{S1} = v_{M1}$ and $v_{RU} = v_{M2}$. From 5 follows:

$$v_{S1} = \frac{(A-D)}{(B+C)} v_{M2} \tag{6}$$



distances

from	→	to	var.	dist. [m]
P_{UM1}	→	P_{IS1}	A	20.5
P_{UM1}	→	P_{UM2}	B	4.5
P_{UM2}	→	P_{US1}	C	17.5
P_{US1}	→	P_{IS1}	D	5.0

Fig. 3. Definition of flows, conflict points and distances

At v_{M2} = 8.9 m/s = 32 km/h, v_{S1} = 6.26 m/s = 22.5 km/h.

Variant ‘b’, the effects of the speed differences between M_1 and S_1 after passing PS_1 can be absorbed by course guidance when they continue the same course: $v_{RU} = v_{M2}$ and $v_{SI} > v_{M1}$. Using equation 5:

$$v_{M1} = \frac{A}{\frac{B+C}{v_{RU}} + \frac{D}{v_{S1}}} \tag{7}$$

At $v_{RU} = v_{M2}$=32 km/h and v_{S1}=27 km/h, $v_{M1} = v_{RI}$ = 6.35 m/s =23.5 km/h. These speeds lower than 27 km/h lead to higher values for the headway (time); see Table I.

VI. GAP EXTENSION BY CROSSING THE OUTER ROUNDABOUT-LANE

As stated in section II, crossing traffic causes gap enlargement. Not only the physical width of the vehicles plays a role in this, but also the uncertainty in the swept path. For variants without course guidance, the starting point is that a car uses the whole lane width between the lines. For the variant with course guidance, of the driving curve variation of 0.25 m on both sides is assumed. Together with a width of 1.77 m for a passenger car, the variation of the swept path is 2.27 m, both on the entrance and on the roundabout-lane. It must be taken into account that the critical gap (including extension) consists of two components:

- the gross headway of the entering traffic + extra time space crossing the vehicle that passed on the roundabout;
- the theoretical possible reduced gross headway at the outer roundabout lane + extra time space required for the entering vehicle.

Because the speeds in the outer lane are higher than of the entering vehicle, the values of these two parts of t_C also differ. Combined with two assumptions for the deviation of the driving curve, the incidental minimum following distance A_{min} and the speeds, this leads to different possible *AVG* variants characterized by different values for t_M, t_C and t_F. The parameters of the *AVG*-strategies investigated are shown in Table I.

VII. *AVG* ON TURBO ROUNDABOUTS:

TABLE I: Assumptions and parameters used in the *AVG*-variants

Human Single-lane	Tanner model
AVG-S1 Single-lane *AVG* simplified	Tanner model
AVG-S2 Single-lane *AVG* + headways optimized	Linear model
AVG-S3 Single-lane *AVG* + headways optimized + path guidance	Linear model
Human Turbo roundabout	Fisk model
AVG-T1 Turbo roundabout *AVG* simplified	Fisk model
AVG-T2 Turbo roundabout *AVG* + gap synchronisation	Tanner model
AVG-T3 Turbo roundabout *AVG* + gap synchronisation + headways optimized	Kinked Linear model
AVG-T4 Turbo roundabout *AVG* + gap synchronisation + headways optimized + path guidance	Linear model

		Single-lane roundabout				Turbo roundabout				
variable		Human	AVG-S1	AVG-S2	AVG-S3	Human	AVG-T1	AVG-T2	AVG-T3	AVG-T4
v_{RI} speed inner lane	[km/h]	n/a	27	27	27	n/a	26.0	22.5	22.5	23.5
v_{S1} speed entrance	[km/h]	n/a	27	27	27	n/a	26.0	22.5	22.5	27.0
v_{RU} speed outer lane	[km/h]	–	–	–	–	n/a	32.0	32.0	32.0	32.0
Radius driving curve										
R_{DI} entrance inner lane	[m]	n/a	15.38	15.38	16.42	n/a	14.58	14.58	14.58	15.82
R_{DU} outer lane	[m]	–	–	–	–	n/a	19.95	19.95	19.95	20.87
Deviation driving curve										
ΔR_{DI} entrance inner lane	[m]	n/a	1.55	1.55	0.25	n/a	1.63	1.63	1.63	0.25
ΔR_{DU} outer lane	[m]	–	–	–	–	n/a	1.43	1.43	1.43	0.25
Following Distance										
A_{min} minimum	[m]	n/a	3.00	3.00	2.70	n/a	3.00	3.00	3.00	2.70
$A_{initial}$ inititial	[m]	n/a	3.38	3.38	2.71	n/a	3.43	3.33	3.33	2.71
t_M min. headway circ.traf.	[s/pcu]	1.70	1.12	1.12	1.03	1.70	1.17	1.32	1.32	1.18
t_{CI} critical gap inner lane	[s/pcu]	3.15	2.24	2.24	2.06	3.70	2.34	2.79	2.79	2.36
t_{CU} critical gap outer lane	[s/pcu]	–	–	–	–	3.80	2.79	2.79	2.79	2.36
t_F follow-on time	[s/pcu]	2.13	1.12	1.12	1.03	2.25	1.17	1.32	1.32	1.18
ρ cluster factor		1	1	$\rightarrow 0$	$\rightarrow 0$	1	1	1	n/a	$\rightarrow 0$

THE i-TURBO ROUNDABOUT

For situations in which stochastic processes determine the distribution of headway times, Fisk [13] has expanded the Tanner model. That model can be used for a human driver and if the *AVG* system is limited to reducing headways and gaps (*Simplified AVG*). Hagring [14] has generalized the Troutbeck model for multi-lane roundabouts. For a two-lane roundabout, that model can be represented as:

$$C_{EL} = \rho q_R (1 - t_M q_{RI})(1 - t_M q_{RU}) \frac{e^{-\rho(q_{RI}(t_{CI}-t_M)+q_{RU}(t_{CU}-t_M))}}{1 - e^{-\rho(q_{RI}+q_{RU})t_F}} \tag{8}$$

This is in addition to equation 3:

t_{CI}	critical gap	s
C_{EL}:	capacity of the left turn lane	[pcu/s];
q_{RI}:	traffic volume, inner roundabout-lane	[pcu/s];
q_{RU}:	traffic volume, outer roundabout-lane	[pcu/s];

The same applies to the indices of the critical gap. If $\rho = 1$, the Hagring model is identical to the Fisk model [10].

For the *AVG simplified* variant, AVG-T1, the same assumptions as for the single lane roundabout can be used for the minimum headway t_M, the follow-on time t_F and for the critical gap t_{CI} for the inner lane. For the outer roundabout-lane, the value t_{CU} must be increased because of crossing each other (see Figure 1 and for the values Table I).

For *AVG+ gap synchronization*, AVG-T2, the gap acceptance model must be changed: the flows on the two circulatory lanes can be considered as one. In this case the models of Tanner can be applied, by halving the circulatory volume. Since the entering vehicle has an equal gap on the outer and inner roundabout-lane, the critical gaps for both lanes become the same as that of the outer lane: $t_{CI} = t_{CU}$.

AVG+gap synchronization+headway optimized, AVG-T3: *AVG* cannot only reduce the headway time but also optimize it, with the discrete values t_M and $t_C + at_F$, where a is an integer. A kinked linear capacity function can be derived for this. The moment the intersecting flows on a conflict area are of the same size ($C_{EL} = 0.5Q_R$), and two cars come alternately from the roundabout lane and from the entrance lane, the headway time in each flow will be $t_h = (t_M + t_C + t_F)/2$ so with $t_M = t_F$: $t_h = (t_C + 2t_M)/2$, while the volume on the both roundabout lanes is $Q_R = 4/(t_C + 2t_M)$ and the capacity on the entrance lane is $C_{EL} = 2/(t_C + 2t_M)$ (in pcu/s). Assuming the distribution of the successive headways to be inversely proportional to the volumes, the capacity can be approximated via a kinked linear function, for which the following applies for $t_F = t_M$:

$$C_{EL} = \begin{cases} \frac{n-0.5(t_C+(n-2)t_M)Q_R}{nt_M} & \text{se } Q_R \leq \frac{2n}{t_c+(2n-1)t_M} \\ \frac{n-0.5\,n\,t_M\,Q_R}{t_C+(n-2)t_M} & \text{se } Q_R > \frac{2n}{t_c+(2n-1)t_M} \end{cases} \tag{9}$$

with C_{EL} and Q_R in pcu/s and n the number of cars in a cluster at the moment $C_{EL} = 0.5Q_R$, so the number of cars in a cluster varies in proportion to the volume.

Clustering with $n = 2$ looks realizable. It is also possible to use a more clustered distribution, but that can lead to more loss time, while the capacity gain (depending on the ratio of t_C and t_F), is often limited. With $t_C = 2t_F = 2t_M$, the kinked linear function changes to a straight linear function.

Finally the most developed *AVG* strategy: the automatic vehicle guidance is extended with course guidance and a smaller minimum mutual correction distance is accepted *AVG+gap synchronization+course guidance+headway optimizing*, AVG-T4. In this variant, the sum of the head-

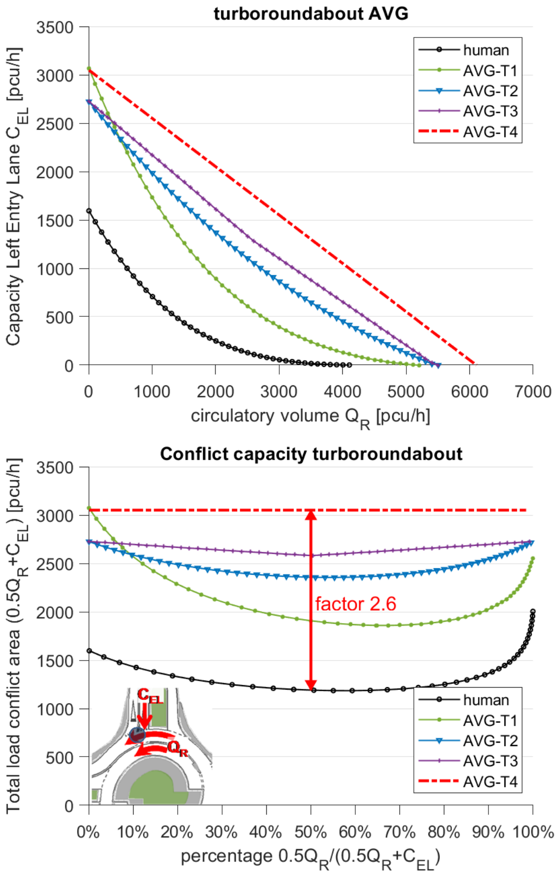


Fig. 4. i-Turbo roundabout: effect on the capacity using the *AVG* variants. Upper: the entrance capacity as function of the circulatory volume, lower: the conflict capacity. For the explanation of the legends: see Table I

ways needed in the two intersecting flows, together with the enlargement of the critical gap for crossing the outer roundabout-lane, happens to be less than twice the minimum headways in the inner roundabout lane. In this case it is relatively easy to optimize the distribution of arrivals (and therefore the headways and gaps), so the adapted linear capacity model can be applied. As can be seen from Figure 4, the capacity increase will be a factor 2.6 if AVG-T4 is compared to a human driver.

The conclusion is that it seems the automation of vehicle handling on i-(turbo) roundabouts will offer high capacity gains. To determine how much exactly for different traffic patterns, it is necessary to develop the *AVG*-algorithms, and to do microsimulation tests using different *AVG* strategies.

VIII. CONCLUSIONS AND RECOMMENDATIONS

The research in this study focused in particular on the possibilities of automatic vehicle guidance for i-roundabouts and i-turbo roundabouts. In a global exploration, based on the headways, it can be concluded that the capacity can double on single-lane roundabouts [2]. In this study, the different levels of development in automatic vehicle guidance have been translated into parameters for capacity models, based on the gap acceptance theory. This indeed shows a substantial capacity gain, a factor 2.

An additional analysis was also carried out for the turbo roundabout into synchronizing the gaps on the two-lane segments. This analysis shows that the i-turbo roundabout offers an even greater capacity gain. Depending on the extent to which automatic vehicle guidance will develop, a capacity gain with a factor of 2.6 appears to be achievable.

The conclusion is, therefore, that i-(turbo)roundabouts in the era of intelligent traffic control can make a significant contribution to capacity gains.

The recommendation is to give the necessary attention to the i-roundabout and i-turbo roundabout in the development of the V2V and I2V communication systems, so that the potential possibilities will actually be utilized. The analytical approach describes the capacity gain in the ideal situation and gives an indication in which way the AVG should be applied, it indicates which parameter settings are of importance. How to reach this ideal situation in reality is to be tested by microsimulation, where the parameters are varied in the full range of optimum settings to realistic settings.

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