

Robustness of Roundabout Metering Systems (RMS)

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Abstract

A simple explorative study shows that roundabouts are too small to be equipped with permanently operating traffic lights. The conclusion of a recent, more detailed study was not fundamentally different to this: at a small two-lane roundabout with four legs and with leg-by-leg control the shortest green time is 11 to 13 seconds, irrespective of the volume of traffic on the least busy leg. This results in a great deal of unnecessary waiting time. Leg-by-leg control at a four-lane roundabout is therefore not regarded as a robust solution. In view of this, at small roundabouts incidental metering signals are used.

At single lane roundabouts, metering signals provide a more balanced distribution of the waiting time, whereas at two-lane roundabouts, the metering signals also have the potential to improve traffic flow. This was shown as early as 2003, in research conducted in collaboration with the author. This article explains the theoretical background to the research. In addition, general design principles for roundabout metering signals (RMS) are deduced.

In 2011, research carried out as part of a Master's thesis supervised by the author studied the robustness of RMS for various traffic loads and roundabout types. Two types of roundabout were studied:

- a standard turbo roundabout and
- a spiral roundabout.

A simulation model was used that underestimated rather than overestimated the effect of an RMS.

The results show that, even under less than optimum conditions, traffic performance of the whole roundabout was improved by approximately 10 %. Traffic performance in the relevant (saturated) leg improved by more than this, namely by 15-45 %.

The reduction of time loss at all legs taken together is even greater: -20 % to -50 % in total, and as much as -70 % for the saturated leg. Notably, altering a dominant load pattern can even reduce waiting time in the leg with the metering light.

Keywords: Increase in capacity, Leg-by-leg control, Micro simulation, Reduction of delay, Roundabout capacity, Roundabout metering signal, Roundabout metering system, Single-lane roundabout, Signalized Roundabout, Turbo roundabout, Two-lane Roundabout

1. POSSIBILITIES FOR TRAFFIC SIGNALS AT SMALL ROUNDABOUTS

This article deals with the question how to increase the capacity of small roundabouts by signalization (outer diameter up to approx. 60 - 70 m)¹. It is evident, that if a roundabout has a small diameter, traffic cannot queue on the roundabout itself because the roundabout segments are too short. In such cases, with substantial left turning traffic volumes, only the following traffic-control methods can be used:

- full signalization with leg-by-leg control;
- roundabout metering signals in the approach lanes.

2. FULL SIGNALISATION

If full signalization is used, both traffic lights at the approach streams as on the roundabout segments are necessary. If leg-by-leg control (split phasing system), is used, the traffic lights on the roundabout segments are necessary to intercept 'stray' cars so that they do not cause a collision.

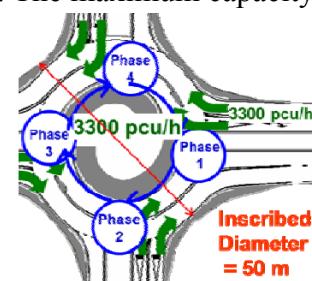
The property of leg-by-leg control is that only one leg at a time can have a green light. The saturation flow of all entries together will generally be the same as the capacity of one entry when there is no traffic on the roundabout. For one lane, this is 1650 pcu/h to 1800 pcu/h². If the control operates in a clockwise direction, the internal loss³ is minimal. Depending on the roundabout diameter, it may be 0 seconds, provided the green and yellow time of the approach directions overlap⁴. This means that the capacity of a single-lane roundabout with leg-by-leg control is approximately 1800 pcu/h. This is much lower than for a single-lane roundabout without traffic signals (approx. 2500 pcu/h).

Consequently, the capacity of a single-lane roundabout will decrease if it is signalized.

On a two-lane roundabout, leg-by-leg control is also the only possibility unless the diameter is increased. In his PhD thesis, the author used a global approach for calculating capacity gain, on the assumption that the internal loss will be hardly less than 0 seconds in the case of clockwise control (Fortuijn, 2013). The maximum capacity of a signalized roundabout with two lanes is therefore barely higher than $2 \times 1650 = 3300$ pcu/h. This is approximately the same as for an unsignalized double-lane roundabout. The principle is shown in Figure 1.

Figure 1 Representative capacity of a signalized turbo roundabout with leg-by-leg control

This has since been researched in greater detail for a Master's thesis. (Hoek, 2013). This research showed that, at a roundabout with a diameter of



¹ In AE signalized roundabouts with larger diameters are called Signalized Traffic Circles.

² The capacity of an entry to an unsignalized roundabout is 1650 pcu/h. It is possible that traffic participants keep to a shorter follow-on-time if they can be certain there is no traffic on the roundabout. It is very much the question by how much traffic lights will reduce the follow-on-time in the case of a two-lane entry.

³ The internal lost time is the sum of the transition times between successive conflicting streams. The transition time consist of a part of the yellow time (after the yellow use time), the clearance time needed to clear the conflict area, and the start-up delay (the start lag of the following green phase). In the following approach the used part of the yellow time and the start-up delay are regarded as equal.

⁴ It has to be noticed, that in this approach only the transition times of the traffic control between the entries has been stated, and not the control of the individual conflict areas.

52 m (with a 3-second yellow phase) the green phase overlap could be 0.8 s, whereas it can be 1.3 s for a diameter of 64 m. Therefore, the capacity of a fully signalized roundabout would increase if the length of the phases is as short as possible.

However, analysis of leg-by-leg control at a roundabout has shown that there should always be a minimum green time, see Figure 2 (Hoek, 2013). Traffic turning left from the east leg, for example, must pass the conflict area with the opposite west leg before the green phase can begin for the entry from the west leg. At a four-leg roundabout with a diameter of 52 m, the distance between the stop lines for the relevant conflict areas is 55 m, which is travelled in 8 seconds. Without green phase overlap, the minimum green time would be 11 s with a minimum cycle time of $4 \times (3 + 8) = 44$ seconds (in the case of equal traffic volumes from all directions). With green phase overlap, the minimum green time is $(0.8 + 3 + 8 + 0.8) = 12.6$ s. The shortest cycle time is then $4 \times (12.6 - 0.8) = 47.2$ s. The gain from the phase overlap is $(4 \times 0.8) / 47.2 = 6.8\%$.

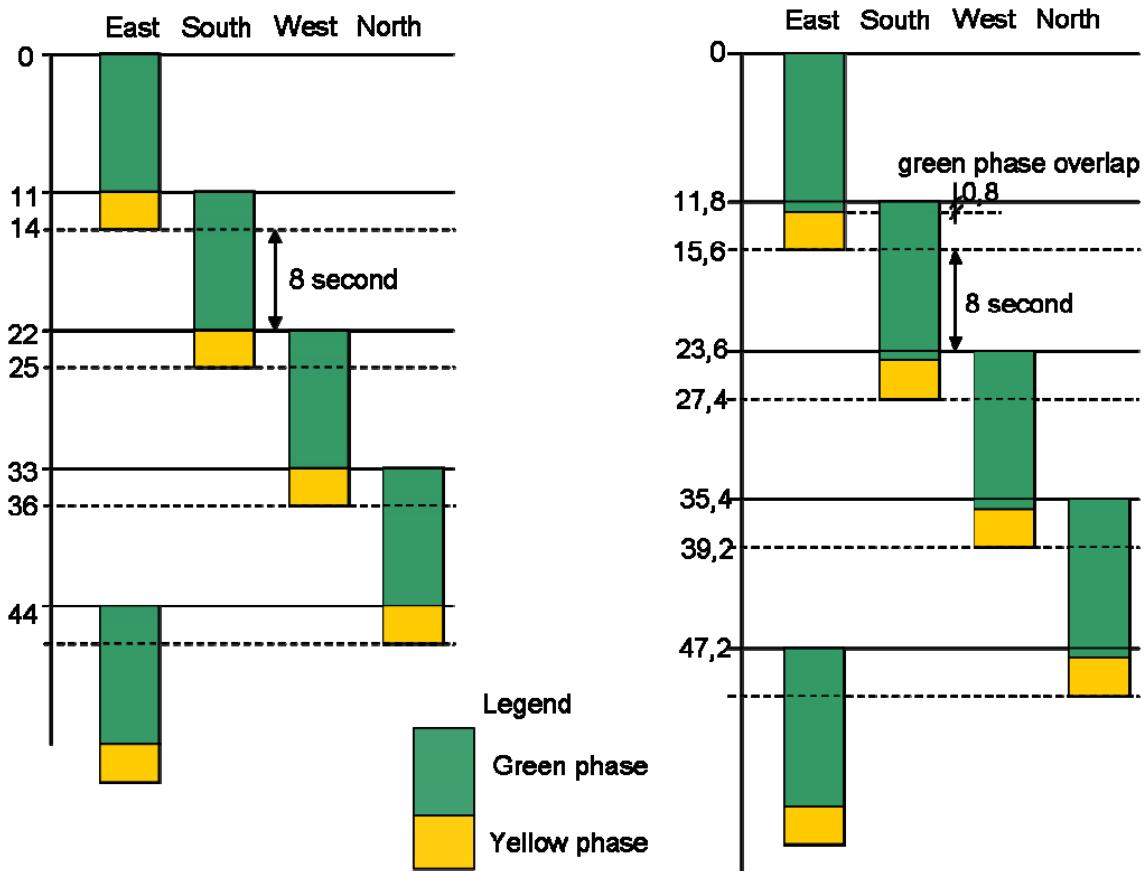


Figure 2 Phase diagrams of the approach flows without and with green phase overlap for a rotor roundabout $\varnothing 52$ m with equal traffic volumes from all legs

If the diameter is 64 m, a vehicle turning left has to travel a distance of 82 m between the stop lines, which take 12 seconds. With a green phase overlap of 1.3 s, the minimum green time is 17.6 s with a cycle time of $4 \times (17.6 - 1.3) = 65.2$ s, also with equal traffic volumes from all directions. In this case, the gain from the phase overlap is $5.2 / 65.2 = 8\%$. Clearly, the capacity gain depends to a large extent on the balance between the traffic volumes of the legs. In the aforementioned study, the ratio of the loads was 60 : 60 : 80 : 100 for all variants. At a rotor roundabout with a diameter of 52 m, the optimum cycle time is then $(12.6 + 12.6 + 16.8 + 21) - 3.2 = 59.8$ s and the gain from the phase overlap falls to $5.2 / 59.8 = 5.4\%$. In the case of a rotor roundabout with a diameter of 64 m, the

cycle time is then 82.8 s, with a gain of 6.3 % from phase overlap. If one of the legs has a very small traffic load (e.g. 20 %), the potential gain is negligible (approx. 2 %).

It is only necessary to lengthen the green phases in the event of a heavy volume of traffic at the roundabout. If this is not the case, the green time for almost every leg will usually remain limited to the minimum green time of 12.6 s and 17.6 s respectively. This will lead to unnecessary waiting, however. A roundabout with full leg-by-leg control is therefore not a robust solution.

3. ROUNDABOUT METERING SIGNALS (RMS, also referred to as 'interception signals')

3.1 Principle

RMS systems in one or more approach legs are an alternative to leg-by-leg control. They are used to briefly interrupt the traffic flow in the leg with a dominant traffic stream, so that waiting traffic streams that conflict with this dominant traffic stream temporarily perceive no conflict and can enter the roundabout. To enter the roundabout at the end of red, priority rules have to be obeyed. Since the system operates only on a part-time basis, two-color signals are used, i.e. red and yellow. No green, while green suggests right of way.

It should be noted that RMS systems function on a completely different principle to ramp metering. The purpose of ramp metering is to increase the gaps between the vehicles (de-clustering of traffic approaching the motorway) in order to prevent a situation in which the merging of vehicles that have to yield causes a tailback onto the motorway – the road on which the traffic has priority. An RMS system has the opposite purpose, i.e. to cluster the traffic on the priority road, i.e. the roundabout. This is done by interrupting the traffic stream on a dominant approach leg. This results in the grouping of the vehicles as well as the gaps on the roundabout. That is why they are also called 'interception signals'.

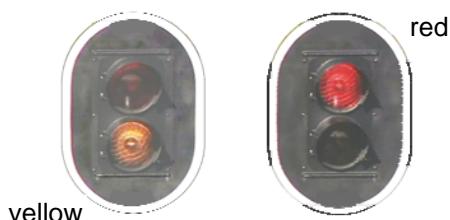


Figure 3 Two-color metering signal

In the Netherlands, the yellow light must first flash for 3 seconds if the approach leg does not have a speed limit of 50 km/h (DGP, 2001). Because this can cause unnecessary time loss, in the Netherlands it is useful to introduce a speed limit on such approach roads outside urban areas. A 3-second yellow phase is then sufficient.

3.2 Position of two-color signal

Because the drivers themselves are to be subject to the normal priority rule, the signals have to be located at some distance before the entry. From the point of view of traffic flow, the distance between the metering signals and the roundabout should be as short as possible. The minimum distance is determined in accordance with road-safety

considerations. If there is a pedestrian and/or cycle crossing point without priority, the distance must be such that pedestrians and cyclists can complete their crossing before an accelerating car reaches them. The distance should therefore be between 30 and 45 m, based on the assumption that pedestrians move more slowly than cyclists, but notice more quickly that a car is starting to move. If there is no crossing for slow traffic without priority, the driver's reaction time is the determining factor. At the end of the red phase, the driver decides to proceed. It is important that he is not then immediately confronted with a yield situation. Assuming an orientation and response time of 6 to 8 seconds, and an acceleration speed of 1.5 m/s^2 , a distance of 30 to 45 m is acceptable.

3.3 Position and function of detectors

A distinction is made between the following:

- the demand detector on the minor leg, i.e. the connecting leg that has a low entry capacity due to dominant traffic streams;
- The delay detector in the major leg, i.e. the connecting leg from which the dominant traffic stream travels.

When a queue forms in the minor leg, the demand detector activates the red metering signal in the major leg, whereas the delay detector postpones activation when queuing in the major leg exceeds a specified limit.

The waiting time at the relevant connecting leg is the determining factor in both cases. The relationship between waiting time and queue length now depends on exit capacity. Based on the Pollaczek-Khinchine M/M/1 waiting-time formula, this can be expressed as a simple relationship (Fortuin and De Leeuw, 2009):

$$d_E = \frac{3600}{C_E - Q_E} \quad [\text{s / pcu}] \quad (1) \quad \text{and} \quad N_E = \frac{C_E}{C_E - Q_E} \quad [\#] \quad (2)$$

$$\text{From (1) and (2) it follows: } N_E = \frac{C_E \cdot d_E}{3600} \quad (3)$$

$$\text{and length of the queue (when } L_v = 6 \text{ m): } L_E = \frac{L_v \cdot C_E \cdot d_E}{3600} = \frac{C_E \cdot d_E}{600} \quad [\text{m}] \quad (4)$$

Where:

d_E : mean waiting time in the roundabout entry lane [s/pcu]

C_E : capacity of the entry lane for the given roundabout load [pcu/h]

Q_E : volume approach lane [pcu/h]

N_E : mean number of vehicles queuing in the roundabout entry lane [#]

L_v : mean distance (measured front-to-front) between cars in a queue, taken to be 6 m [m]

L_E : mean queue length in the roundabout entry lane [m]

An average waiting time of ≤ 50 [s/pcu] can be used as a quality criterion, for example.

The queue length and waiting time show a spread pattern. The standard deviation for the queue length is:

$$\text{Std}[N_E] = \frac{\sqrt{\rho}}{(1-\rho)} \quad (5)$$

where the rate of saturation ρ is: $\rho = Q_E/C_E$ (6)

$$\text{Using equation (3) holds: } \text{Std}[N_E] = \frac{d_E \cdot C_E}{3600} \cdot \sqrt{1 - \frac{3600}{d_E \cdot C_E}} \quad (7)$$

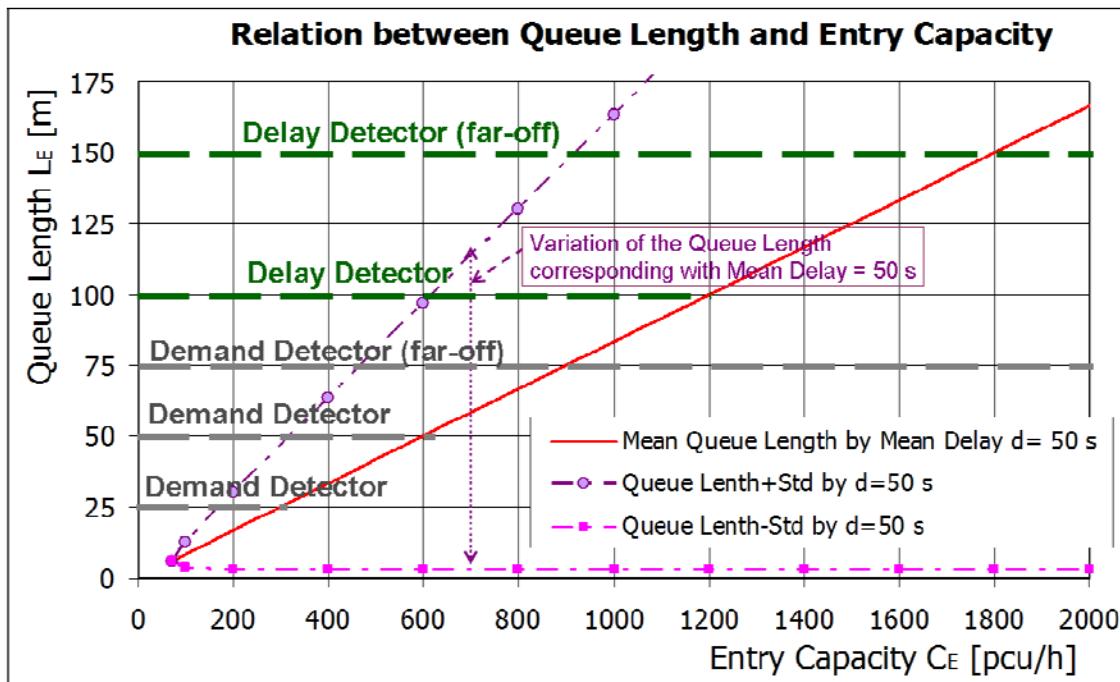


Figure 4 Detector configuration

The values for the queue lengths relating to the mean waiting time of 50 s/pcu are indicated by a red line in Figure 4. From the system of equations it is clear that – given a mean waiting time – there is a linear relationship between the mean queue length and the entry capacity. However, from the related spread it follows that, irrespective of entry capacity, the lower limit of the queue-length spread is one vehicle. Whichever detector configuration is chosen, individual waiting time peaks cannot always be prevented.

It is clear from Figure 4 that it is not feasible to apply one specific detector distance, but that a more advanced detection system is needed in order to achieve optimum results with an interception signal. One option is a combination of an automatic traffic recorder (ATR) at the roundabout approach with three queue loops. Continued occupation of a given occupancy loop may or may not lead to a queue-clearance action; this depends on the number of cars counted by the ATR in the previous 100 seconds. The shortest and longest distances from the occupancy loop to the roundabout are determined by the variation in the predicted (or measured) entry capacity of the relevant leg. The occupancy loops closest to the roundabout do not lead to a queue-clearance action until traffic intensity is below the intensity value measured by the ATR. No limits are configured for the occupancy loop furthest from the roundabout.

3.4 Duration of red phase

In the case of standard traffic signals, the length of the red phase is determined by traffic-flow aspects as well as road safety (clearance times). In the case of an RMS system, the position of the signals is partly determined by traffic-safety considerations. Only the traffic-flow aspect is relevant for the length of the red phase. The determining criterion is the optimum utilization of the intersection area opposite the leg, combined with the waiting-time limits.

Various methods can be used to determine the optimum length of the red phase. The simplest of these involves a fixed red time, which depends on the distance from the demand detector to the roundabout (L_{AD}). The front-to-front distance of standing cars ($L_v = 6$ m) determines the number of cars in the queue when the demand detector is activated. The follow-on-time in the left-hand entry lane of the side leg $t_F = 2.25$ s/pcu (Fortuijn, 2009) determines the time it takes to clear the queue between the demand detector and the roundabout, assuming that the disruptions due to traffic turning left from the opposite leg are negligible. The required duration for the red phase is therefore shorter, because the last car passing the yellow light reaches the conflict area before the first car after the end of the relevant red phase. Assuming a speed on the roundabout of $v_r = 10$ m/s and an acceleration speed $a = 1.5$ m/s², the difference is $t = v_r / a = 10 / 1.5 = 6.7$ seconds. The time for the required gap ($t_C = 4$ s) must be added to this. The settings are as in Table 1 depending on the position of the demand detector.

Table 1 Fixed red phases determined by the position of the demand detector

Formula for fixed red time: $RT_{fixed} = (L_{AD} / L_v) \cdot t_F + t_C - v_r / a_0$	
Distance from demand detector to roundabout (L_{AD})	Fixed red phase
25 m	9.0 s
50 m	18.4 s
75 m	27.8 s

When delays from left-turning traffic from the opposite minor leg have to be taken into account, it is logical to use the 'cancel' signal of the demand loop. TT is the time required between the 'no queue' signal from the occupancy loop and the termination of the red phase (transition time). See the Appendix for the derivations of the formulas. The results are shown in Table 2. These show that it is not possible to optimize the transition time if use is made of the cancel information from a demand detector positioned 25 m from the roundabout.

Table 2 Calculated values for transition time between the cancel signal from the demand detector and the end of the red phase

Formula for transition time (TT): $TT = T_{ZDS} - T_A - T_{HLS} + t_C$ (see Appendix)		
Distance from demand detector to roundabout	Distance from metering signal to roundabout	
	30 m	45 m
	TT = time between cancel signal and end of red phase	
25 m	-3.1 s	-4.6 s
50 m	1.6 s	0.1 s
75 m	6.3 s	4.8 s

There is always a loss of 3 to 4.5 s, depending on the position of the metering signal. Alternatively, a fixed red time from Table 1 can be applied. In the case of distances of 50 m and above, it is better to use the cancel information, because the red time is better aligned to the time it actually takes for vehicles in the minor leg to reach the roundabout. It is important to set an upper limit for the red time (e.g. 30 to 40 seconds), depending on the values measured by the detector in the major leg.

3.5. RMS systems on single-lane entries

On the basis of theoretical considerations, it cannot be expected that an RMS system will increase the capacity of a single-lane roundabout. For the purpose of clustering is to ensure that, during clustering, at the next leg (where a queue has formed), there will be no circulatory traffic for some time, so that this queue can be cleared. But as Table 3 shows, this creates periods in which the sum of the roundabout intensity and the entry capacity is less than when there is a larger volume of roundabout traffic (based on capacity measurements at an unsignalized roundabout), so the capacity of the conflict area will decrease. Brief clustering's - which increase capacity, according to Troutbeck's model - are excluded from Table 3. It is therefore possible that an RMS system with a very short red phase can increase the capacity of the total roundabout as well.

Table 3 *Trend in the sum of the roundabout intensity and entry capacity of a single-lane roundabout (unsignalized)*

Volume Q_R on a roundabout segment	1000	500	100
Measured C_E capacity on the entry	740	1160	1550
Sum $Q_R + C_E$ [pcu/h]	1740	1670	1650

—————Theoretical Effect Metering Signal—————→

Notwithstanding the supposed capacity decrease RMS systems are used at single-lane roundabouts, albeit not frequently. Figure 5 is an example. The significance of this is the redistribution of waiting times. A dominant traffic stream can sometimes cause extreme waiting times and spillback in the next leg.

Figure 5 *RMS system at the Hoogerheide / Woensdrecht intersection on the A58 (installed in around the year 2000; subsequently replaced with a turbo roundabout)*



The redistribution of waiting times, without an increase in capacity, can mean that the average waiting time is below the 50 s limit in the disadvantaged leg, whereas, in the dominant leg with the two-color signal, it does not exceed this. Traffic flow will improve in this case too.

3.6 RMS systems on double-lane entries

On the basis of theoretical considerations, it can be expected that an RMS system in a two-lane entry can result not only in an improved distribution of waiting times, but that it can also increase the roundabout's capacity. A gap is required in both roundabout lanes to proceed from the entry to the inner lane on the roundabout. If the roundabout traffic is clustered, gaps are forced in both streams simultaneously. This theoretical effect is shown in a graphic in Figure 6 (Fortuijn, 2013). The curve 'Coinciding gaps in both lanes' is obtained by multiplying the values on the horizontal axis of the curve

'Everything in one lane' by a factor 1.8. Theoretically, the factor is equal to 2, but this will never be feasible in practice. That is why the ratio between the values has been selected where the curve 'Evenly distributed over the roundabout lanes' and the curve 'Everything in one lane' cut the x-axis.

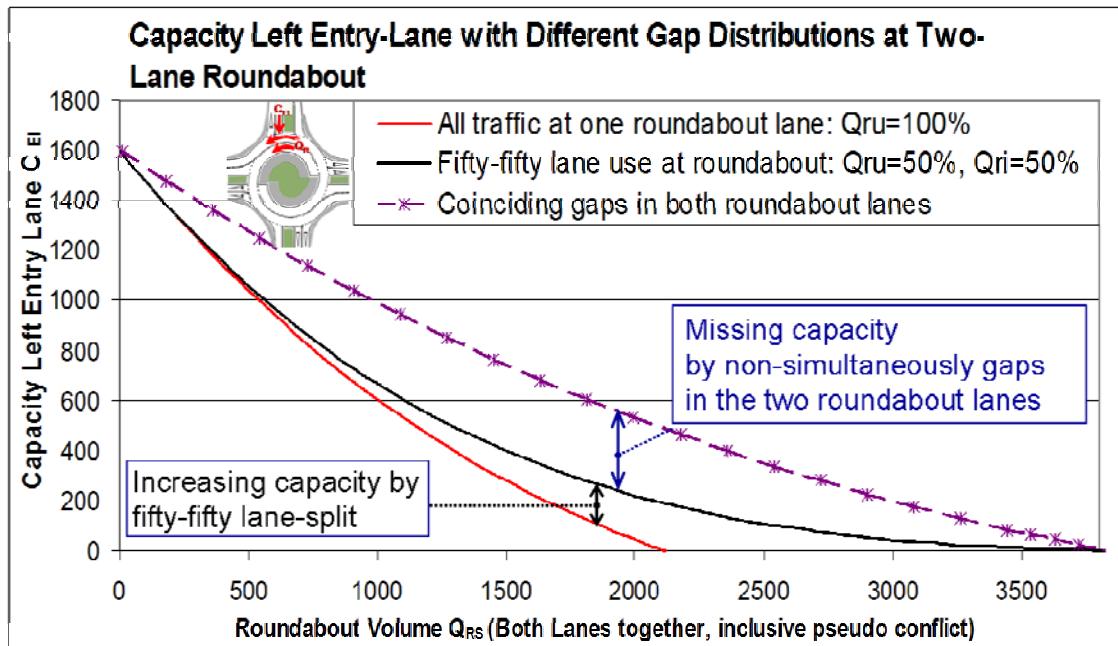


Figure 6 Effect of gap distribution on two roundabout lanes

4. RESULTS OF A SIMULATION UNDER OPTIMUM CONDITIONS

The conclusion from the previous section is that further investigation of the possibilities of RMS systems is worthwhile. A microscopic simulation tool is a suitable instrument for this purpose; in the studies at hand the Vissim simulation tool was used. The first studies were carried out in 2003 by A.M. de Leeuw (Fortuijn, 2003), focused on one conflict area: the left entry-lane of the North leg of Figure 7. The RMS system in the major leg is positioned 45 m before the roundabout and has a fixed red time of 20 s; the demand detector in the minor leg is positioned 50 m before the roundabout. The red phase will then be 20 s, unless the delay detector at 95 m is occupied. The limits for the delay time for this detector in the major leg were not studied; no limits were necessary for the approach intensities used. The simulation was based on an uneven traffic-volume pattern, see Table 4. The volumes 1 and 2 (as indicated in figure 7) were used as input and were also able to enter the roundabout.

The differences in the table are due to the random process used in Vissim. In terms of input into Vissim, volumes for directions 11 and 12 were so heavy that without RMS there was a continuous congestion in this side leg, but this could be cleared by RMS with acceptable waiting times.

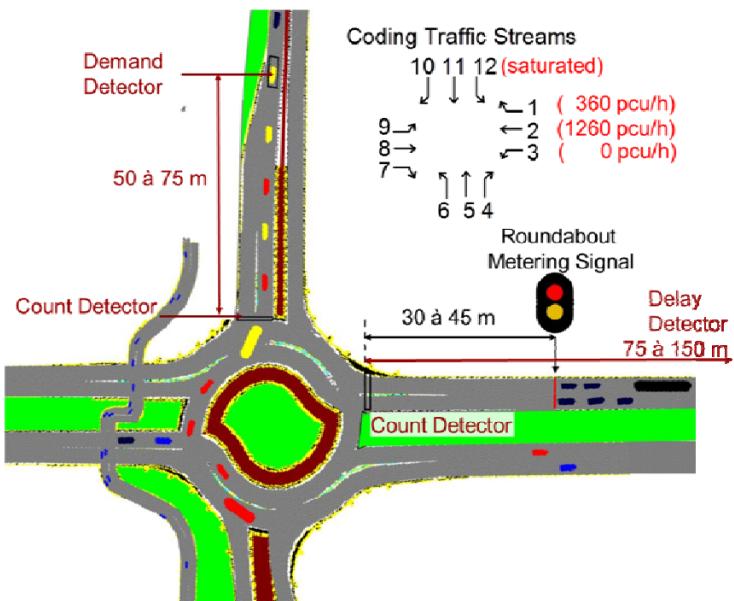


Figure 7 Roundabout metering signal (RMS) at a two-lane entry to a turbo roundabout

Table 4 shows that if the traffic volume in the major leg is around 1280 pcu/h (1350 pcu/h including pseudo-conflict), with an RMS system the capacity of the minor leg increases by 86 % from 476 pcu/h to 884 pcu/h.

Table 4 Simulation input and results for RMS at Hogendorpweg

Conflicting volumes level with a side leg on a turbo roundabout.	Turbo roundabout without RMS	Turbo roundabout with RMS
Intensity in inner roundabout lane (part dir.2)	727 pcu/h	752 pcu/h
Intensity in outer roundabout lane (part dir.2 and dir.3)	532 pcu/h	536 pcu/h
Intensity of traffic turning towards the same leg (dir.1)	360 pcu/h	436 pcu/h
Intensity of lateral traffic in the roundabout (dir. 5+6+9)	0 pcu/h	0 pcu/h
Left-hand lane capacity in North minor leg (dir. 11+12)	476 pcu/h	884 pcu/h

This corresponds to the diagram in Figure 6. It is obvious that, with this input, on the major leg the same amount of traffic could enter as without RMS. This means that the total traffic performance of the relevant conflict area (comprising two roundabout lanes and one entry lane) increases from 1736 to 2172 pcu/h. That is a total increase of 25 %.

5. EFFECTS OF RM S UNDER SUB-OPTIMUM CONDITIONS

The traffic-volume pattern in Table 4 does not include the effect of other conflicting traffic flows. It is to be expected that, above all, the roundabout traffic that crosses the minor leg while the RMS is operating (direction 6) will reduce the effectiveness of the RMS. The ultimate effect will also be influenced by the roundabout traffic that is crossing the major leg (directions 5, 6 and 9); the higher that volume the lower the positive effect on the minor leg, but also the negative effect on the major leg at the end of a phase. Yet studies with various volume patterns show that an RMS system has positive effects. Akçelik (2008) reports reduced queue lengths.

Granneman (2011) carried out simulations (Vissim) with volume patterns in which the amount of traffic in the leg opposite the busiest major leg was 90 %, of which 60 % was travelling straight ahead and 20 % was turning right and left respectively. Both directions were equally busy, with 33 % turning right and left, respectively. For various ratios between the major legs and minor legs, the volumes were increased until the limit of a mean waiting time of 50 seconds was reached. For those volumes, an RMS system reduced waiting times by 15 % to 50 %, see Figure 8. In all cases, the volumes could be increased further: all legs together by 5 % to 10 % and the minor legs by 15 % to 45 %. See Figure 9. The theoretical gain in Figure 6 and Table 4 appears to be sufficiently large to still lead to a positive result in situations where conditions are less than optimum.

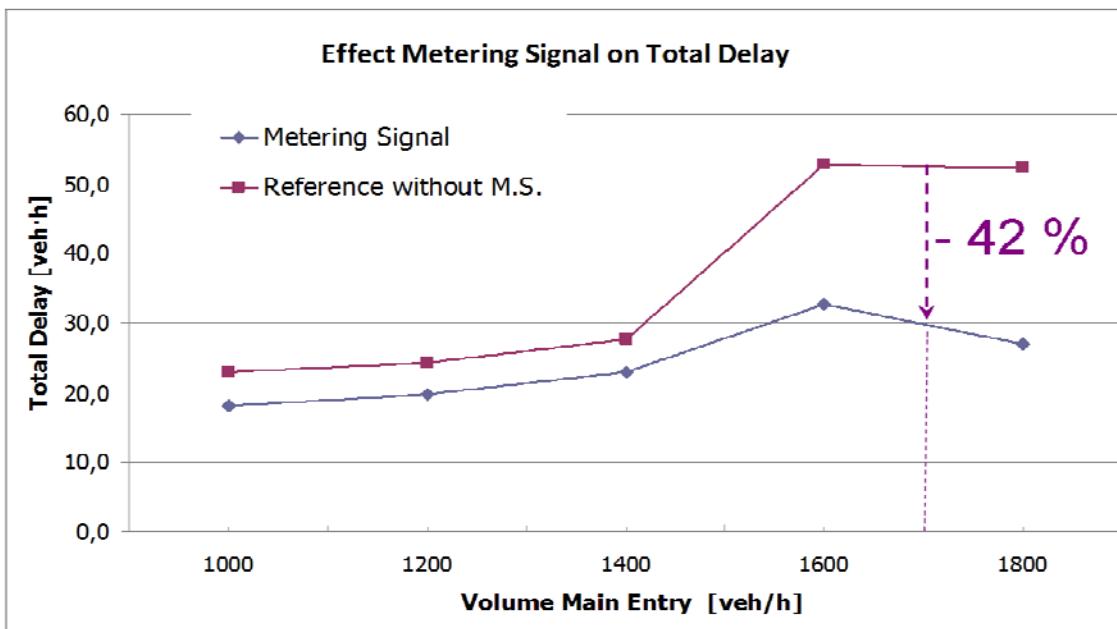


Figure 8 Decrease total delay turbo roundabout

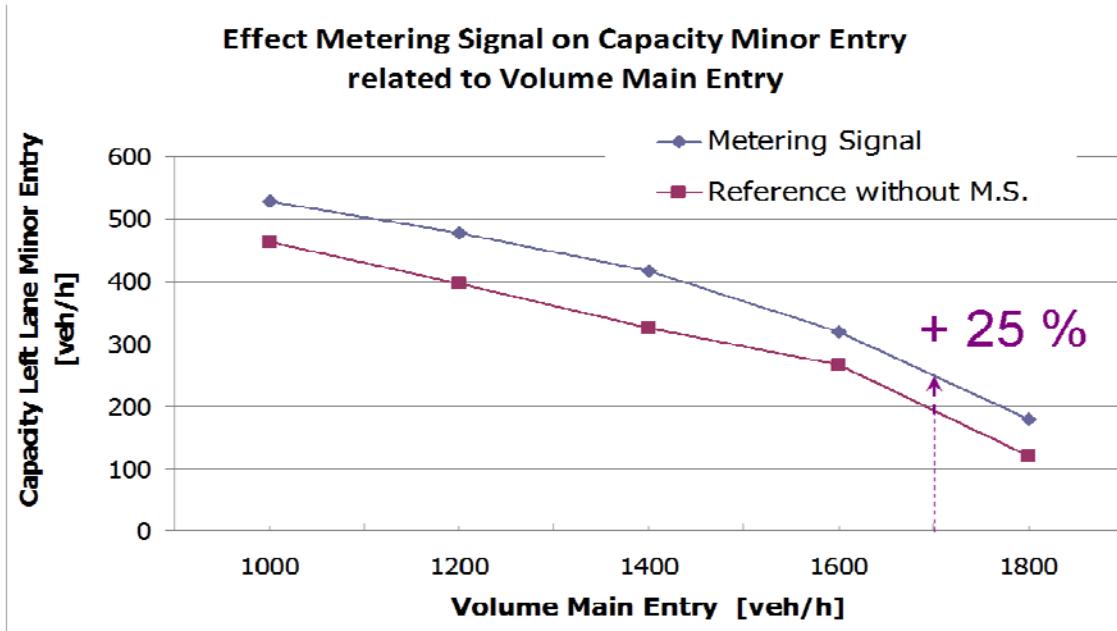


Figure 9 Increase capacity left lane minor entry turbo roundabout

Remarkably, in some cases, the loss time in the leg with the RMS also decreases. This is because a cluster of vehicles from the demanding leg briefly blocks entry from the two following entry legs. These are the legs that, in turn, usually (without the blocking) cause the waiting times in the relevant major leg. Due to the brief blocking, the waiting time from the major leg after the red light is extremely short, so that ultimately there is also a time gain in that leg.

6. SUMMARY AND CONCLUSIONS

RMS can be used in situations where on a branch of a roundabout the queue becomes longer than desirable. By using RMS, the waiting times will be distributed more equally over the branches and spillback may be prevented.

There are indications that the capacity of a single-lane roundabout will not increase if RMS is used. If applied on two-lane branches, RMS will enlarge the capacity of the minor entry (by 15 à 45 %) and will decrease waiting time on the whole roundabout in heavy loaded situations (by 20 à 50 %).

When RMS is applied, it is mandatory to use a well-designed detector system.

7. REFERENCES

- Akçelik, Rahmi (2008). An Investigation of the performance of Roundabouts with Metering Signals. Paper presented at *TRB National Roundabout Conference*, Kansas City. MO. USA, 18-21 May 2008.
- DGP (2001) *Regeling Verkeerslichten*, Directoraat-Generaal Personenvervoer, Ministerie van Verkeer en waterstaat, Den Haag.
- Fortuin, L.G.H.(2003). Turbopleinen met verkeerslichten; het geometrisch ontwerp. *Verkeerskundige werkdagen 2003*, CROW, Ede.
- Fortuin, Lambertus G.H (2009). Turbo Roundabouts: Estimation of Capacity, *Transportation Research Record, Journal of the Transportation Research Board*, No 2130, Washington, D.C., 2009, pp 83-92.
- Fortuin, L.G.H. en A.M. de Leeuw, (2009). Eenvoudige wachtrijformules voor een stationair verkeersproces, *Bijdrage 5150808 aan Verkeerskundige werkdag 2009*, CROW, Ede.
- Fortuin, L.G.H (Bertus), 2013. *Turborondondes en turboplein; ontwerp, capaciteit en veiligheid* (Turbo Roundabout and Turbo Circle: Design, capacity and safety). TRAIL Thesis Series T2013/1, the Netherlands, TRAL Research School, Delft, ISBN: 978-90-5584-157-8.
- Granneman, Bob (2011). *Effect van verkeerslichten op turborondondes*. Afstudeerscriptie CiTG ,TU-Delft, mei 2011.
- Hoek, Rogier R.M (2013). Signalized Turbo Roundabouts; A Study into the Applicability of Traffic Signals on Turbo Roundabouts. Master's degree study at Delft University of Technology, July 2013.

APPENDIX

Derivation of formulas for transition time Roundabout Metering System

For the transition time (OT):

$$OT = T_{ZDS} - T_A - T_{HLS} + t_C \quad (8)$$

$$\text{For } T_{ZDS}: T_{ZDS} = (L_{AD} / L_v) \cdot (t_F - t_B) \quad (9)$$

$$\text{And for } T_{HLS} = (v_r / a_{accelerate}) + \{L_L - v_r^2 / (2 \cdot a_{accelerate})\} / v_r + t_R \quad (10)$$

if $\{L_L - v_r^2 / (2 \cdot a_{accelerate})\} > 0$, otherwise $T_{HLS} = \sqrt{(L_L / a)} + t_R$

Where:

OT: transition time RMS, i.e. the time from the moment at which the (last) car at the demand detector moves forward and the moment at which the red phase must end.

L_{AD} : distance between the roundabout and the relevant demand loop.

L_L : distance between the stop line before the RMS signals and the conflict areas on the roundabout opposite the (next) minor leg for which the RMS is operating.

L_v : front-to-front distance between standing cars = 6 m (practice measure).

T_{ZDS} : time between the moment at which the car at the demand detector moves forward and the moment at which it reaches the roundabout.

T_A : detector cancel time, i.e. the time between the moment at which the car moves forward from the detector and the moment at which the detector gives the 'no queue' signal.
 $T_A = 2$ s can be applied as a minimum for this.

T_{HLS} : time between the moment at which the red signal ends and the moment at which the first vehicle in the major leg reaches the conflict area opposite the minor leg.

t_C : critical gap = 4 s

t_F : follow-on-time = 2.25 s

t_B : time between the moments at which vehicles in a queue move forward
 $t_B = 0.5 \cdot t_F$ for 1 s/pcu (practice measure)

t_R : reaction time between end of roundabout metering signal and

v_r : speed on roundabout = 10 m/s.

Delay time

Analogous to the calculations for T_{ZDS} for the detectors in the minor leg, the time T_{HDS} for the detectors in the major leg can also be calculated, whereby the demand for the next red phase from the minor road must be delayed until the relevant detector in the major leg is no longer occupied. Only the current measured follow-on-times (converted or not into q_E on the counter of the major legs) can be used (and not the follow-on time t_F).

$$T_{HDS} = (L_{AD} / L_v) \cdot (1 / q_{EH} - t_B)$$

Where:

T_{ZDS} : time between the moment at which the car by the demand detector moves forward and the moment at which it reaches the roundabout.

q_{EH} : mean number of vehicles per lane counted by the ATRs in the major lane before the roundabout, with the exception of the red phase and T_{HSL} (or whichever method is available) [veh/s].

t_B : The question is what the value of t_B is in the case of a queue length of 100 to 150 m, particularly if the capacity C_E is slightly more restricted due to crossing traffic. If no data is available from field research, more in-depth investigation is recommended, if only in the form of simulations. Until such research becomes available, the approximation $t_B = 0.5/q_E$ can be used.