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REPRINT

Performance of roundabouts under heavy demand conditions

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NOTE:

This paper is related to the intersection analysis methodology used in the SIDRA INTERSECTION software. Since the publication of this paper, many related aspects of the traffic model have been further developed in later versions of SIDRA INTERSECTION. Though some aspects of this paper may be outdated, this reprint is provided as a record of important aspects of the SIDRA INTERSECTION software, and in order to promote software assessment and further research.

Performance of roundabouts under heavy demand conditions

R. Akçelik, E. Chung and M. Besley

Abstract

The changes introduced in SIDRA 4.1 for improved prediction of capacity and performance of roundabouts under heavy demand conditions are described. The new method, developed in response to problems observed at real-life roundabouts, predicts generally less optimistic results compared with the current AUSTROADS roundabout guide, particularly for multi-lane roundabouts with high circulating flow rates and unbalanced flow patterns.

The new method takes into account the effects of the origin-destination pattern, lane usage and queueing characteristics of approach flows. As such, it is the first analytical method that models interactions among approach flows, rather than treating the roundabout as a series of independent T-junctions. Various other changes have been introduced to the modelling of critical gap and follow-up headways to prevent overestimation of capacities. A further and significant change is to decrease the follow-up headway in the case of heavy entry flows against low circulating flows.

The implications of the new method in terms of the capacity and performance of roundabouts are discussed. The application of the new method to a case study from the AUSTROADS roundabout guide is also presented.

The roundabout capacity analysis method described in ARRB Special Report SR 45 (Troutbeck 1989) was incorporated into the Australian roundabout design guide, *Guide to Traffic Engineering Practice, Part 6 - Roundabouts* (AUSTROADS 1993) with some minor modifications (Troutbeck 1992). The method has been in use in practice through the SIDRA 4.07 package (Akçelik and Troutbeck 1991). The most important features of this capacity estimation method are the dependence of gap-acceptance parameters on roundabout geometry, circulating flows and entry lane flows, and the designation of approach lanes as dominant and subdominant lanes that have different capacity characteristics.

The method in SIDRA 4.07 incorporated some variations and extensions to the SR 45 method. Further significant enhancements based on new research were introduced in SIDRA 4.1 to improve prediction of capacities, particularly under heavy flow conditions (Akçelik, Chung and Besley 1995; Akçelik, Besley *et al.* 1995). An overall summary of the extensions and enhancements introduced in SIDRA is given in *Table 1*.

The most important enhancement to the capacity estimation method introduced in SIDRA 4.1 is allowance for the effects of origin-destination pattern of entry flows, amount of queueing on approach roads, and approach lane use. This contrasts with the traditional method of roundabout modelling that treats the roundabout as a series of independent *T-junctions* with no interactions among approach flows. While the traditional method has been adequate for low to medium flow conditions, the method introduced in SIDRA 4.1 improves the prediction of capacities under heavy flow conditions, especially at multi-lane roundabouts with unbalanced entry flows. This helps to avoid capacity overprediction under such conditions as observed at many real-life intersections, which was a concern expressed by many practitioners.

The feedback received from SIDRA users reporting real-life problems indicated that the capacities were substantially overestimated for multi-lane roundabouts with high circulating flows (over about 1,000 veh/h). To a great extent, this is corrected through the new method for the O-D pattern and approach queueing characteristics of the circulating flow. However, a significant number of cases indicated that this was not sufficient to predict the oversaturation (low capacity, long delays and queues) observed in real-life situations. The specific roundabout cases where the capacity estimation method failed included:

- Mickleham Road – Broadmeadows Road (Melbourne) before installation of part-time metering signals. This case is described in the AUSTROADS (1993) roundabout guide;

- Fitzsimons Lane – Porter Street (Melbourne). A Royal Automobile Club of Victoria survey indicated that this was the second-most hated intersection in Melbourne. It is now being enlarged to a three-lane roundabout;

- Panmure Highway – Lagoon Drive (Auckland, New Zealand). Surveys were carried out and a lot of effort went into calibrating the SR 45 method without success;

- Parkes Way – Kings Avenue – Moreshead Drive (Canberra). Marking of entry lanes with a single through lane on one approach road (for safety reasons) resulted in very long queues, whereas the SR 45 method predicted satisfactory operation for this design;

- various intersections in Melbourne studied by Stan Chang (1993) in the context of the unbalanced flow problem; and

- various intersections in Melbourne studied by Andrew O'Brien and Associates (O'Brien 1995).

In all these cases, the SR 45 method predicted good operating conditions, whereas long delays and queues were observed on one or more approaches. SIDRA analysis results are available for the first four cases. Detailed results for the first case are given in this paper.

Table 1

Enhancements to roundabout analysis method introduced in SIDRA

- An iterative method is used to calculate:

    (i)   the circulating flow (for entry lanes) and the exiting flow (for slip lanes) for each approach; and

    (ii) the proportion of heavy vehicles, proportion of queued vehicles from the dominant approach, and proportions of vehicles from single or multi-lane approach streams for each circulating and exiting flow.

- *Capacity constraint* for oversaturated approaches is applied in determining circulating and exiting flow characteristics.

- Origin-Destination (O-D) pattern, approach queueing and approach lane usage affect entry lane capacities (roundabout is *not* analysed as a series of independent T-junctions).

- Gap acceptance parameters (critical gap and follow-up headway) are adjusted for heavy entry flows against low circulating flows.

- Various limits are applied to the values of gap acceptance parameters.

- Different critical gap and follow-up headways can be specified for different turns (left, through, right) from the same approach.

- A proportion of exiting flow can be added to the circulating flow.

- Entry lane flow estimation as a function of lane capacities: Iterative calculations are performed due to the dependence of the follow-up headway on dominant-subdominant lane flow ratios.

- Lane underutilisation for entry lanes: Unequal approach lane utilisation is allowed for.

- Short lane model is fully applicable through the use of back of queue formulation (*excess flow* is assigned to adjacent lanes when the average back of queue exceeds the available storage space in the short lane).

- Slip lanes are modelled by treating the exiting flow as the opposing stream.

- Detailed lane-by-lane modelling of capacity and performance is applied (including fuel consumption, operating cost and pollutant emissions).

- Time-dependent performance formulae are used for application to oversaturated cases.

- Geometric delay method is consistent for all intersection types. The SIDRA method differs from the AUSTROADS (1993) method in applying the geometric delays to stopped and unstopped vehicles, and using different equations for geometric delays.

- New performance functions are used in SIDRA 4.1 for delay (total delay, stopped delay, idling time and geometric delay), back of queue and cycle-average queue length (mean, and 90th, 95th and 98th percentile values), queue move-up rate, effective stop rate, proportion queued and queue clearance time.

- Consistency of capacity and performance analysis methods for roundabouts, other unsignalised intersections and signalised intersections is achieved through the use of an integrated modelling framework.

Given the evidence of real-life cases and simulation studies (Akçelik, Chung and Besley 1995), it was concluded that the overestimation of capacity for high circulating flows, especially at multi-lane roundabouts, by the SR 45 method was a systematic error that could not be explained away by statistical variation or unusual geometries. Further changes were introduced in order to achieve satisfactory prediction of capacities for the roundabouts listed. These changes, coupled with the method for O-D pattern and queueing characteristics of the circulating stream, meant a substantial change to the SR 45/ AUSTROADS method. The changes are discussed in the following sections. For detailed descriptions and formulae, refer to Akçelik, Chung and Besley (1995) and Akçelik, Besley *et al.* (1995).

EFFECTS OF ORIGIN-DESTINATION PATTERN AND APPROACH QUEUEING

A major enhancement to the roundabout capacity estimation method introduced in SIDRA 4.1 is to allow for the effects of the origin-destination (O-D) pattern and approach queueing characteristics of traffic that constitute the circulating stream (Akçelik, Chung and Besley 1995). The effect of this method is to reduce the capacity, especially in the case of heavy flow conditions with unbalanced flow patterns. The reduction in capacity increases as the proportion of the total circulating stream flow that originated from and were queued on the *dominant approach* increases. The dominant approach is determined by SIDRA as the approach that contributes the highest proportion of the queued traffic in the circulating flow.

This is the first analytical method that takes roundabout analysis beyond the treatment of entry points as a series of independent T-junctions, which is particularly useful for analysing the cases of unbalanced flow patterns and heavy flow levels. The method is also applied to slip lane movements that give way to exiting flows.

The basis of the model for estimating the capacity of a roundabout entry lane (Q_e) is to use a factor (f_{od}) to reduce the basic gap-acceptance capacity (Q_g) to allow for the effects of the origin-destination pattern and approach queueing characteristics of traffic that constitute the circulating stream. The two variables in the factor (f_{od}) to reduce the basic gap-acceptance capacity are:

(i) the proportion of the total circulating stream flow that originated from the *dominant approach* $(p_{cd} = q_{cd} / q_c)$; and

(ii) the proportion queued for that part of the circulating stream that originated from the *dominant approach* (p_{qd}).

The dominant approach is determined as the approach that has the highest value of $(p_{qd}\, p_{cd})$ considering all approaches that contribute to the circulating flow. The product of the two variables $(p_{qd}\, p_{cd})$ give the proportion of the total circulating stream flow that originated from and were queued on the dominant approach. Any *exiting flow* effect that is included in the circulating flow is also included in the calculation of $(p_{qd}\, p_{cd})$. For multi-lane approach roads that contribute to the circulating flow, the value of $(p_{qd}\, p_{cd})$ is calculated as a flow-weighted average of individual lane values considering the lanes used by the relevant movements and using contributing flow rates in passenger car units per hour (pcu/h), to allow for heavy vehicles in relevant traffic streams.

The factor f_{od} decreases (therefore the entry capacity decreases) as the proportion of the total circulating stream flow that originated from and were queued on the dominant approach increases. The amount of reduction also increases with increasing flow levels and is in the range 4% to 55%.

One difficulty with oversaturated roundabout cases is the lack of information on demand flows. In such cases, the arrival flows should be observed upstream of the back of the queue rather than using the stop-line counts which give capacity flows. The method for O-D effects uses approach entry flows (less than demand flows when oversaturated, i.e. subject to capacity constraint).

EFFECT OF APPROACH LANE USE ON CIRCULATING STREAM CHARACTERISTICS

The linear model used in SR 45/AUSTROADS (1993) to estimate the proportion of free (i.e. unbunched) vehicles in the circulating flow was replaced by an exponential relationship (Akçelik and Chung 1994). The values predicted by the new model are higher

for low flows (less bunched) and lower for high flows (more bunched). For very high flows, the new model gives non-zero values, which are higher than the linear model predictions.

For each subject approach, SIDRA 4.1 determines the circulating stream as *single-lane* or *multi-lane* by inspecting the *effective approach lane use* of the flows that constitute the circulating stream, irrespective of the actual number of circulating lanes (see *Fig. 1*). Where several O-D streams differ in being single-lane and multi-lane, a flow-weighted average of the intra-bunch headway is used, with flows in pcu/h. Therefore, circulating streams in multi-lane circulating roads will not have a clear-cut description as *single-lane* or *multi-lane*.

In SIDRA 4.1, a *minimum* intra-bunch headway of 1.2 s is used for multi-lane circulating streams and 2.0 s for single-lane streams. Therefore, the value of intra-bunch headway may be in the range 1.2 to 2.0 s depending on the effective lane use of the O-D streams that constitute the circulating stream. This contrasts with the use of an intra-bunch headway of 1.0 s for all multi-lane circulating road cases in the SR 45 / AUSTROADS (1993) method. It was only by

increasing the multi-lane minimum intra-bunch headway value from 1.0 s to 1.2 s, and establishing effective lane usage of the circulating roadway (*Fig. 1*), that the authors were able to predict capacities close to those observed in real-life for the roundabout cases listed at the start of this paper.

CHANGES TO CRITICAL GAPS AND FOLLOW-UP HEADWAYS

Concern was expressed by practitioners that the SR 45/AUSTROADS (1993) method underestimates capacities at low flows due to very high values of critical gaps and follow-up headways. In SIDRA 4.07, lower limits were introduced on critical gap and follow-up headway values predicted by the SR 45 method. Furthermore, the inscribed diameter* value used in the formula for calculating the dominant lane follow-up headway was limited to a maximum of 80 m, to prevent the prediction of very low follow-up headways. These were adopted in AUSTROADS (1993).

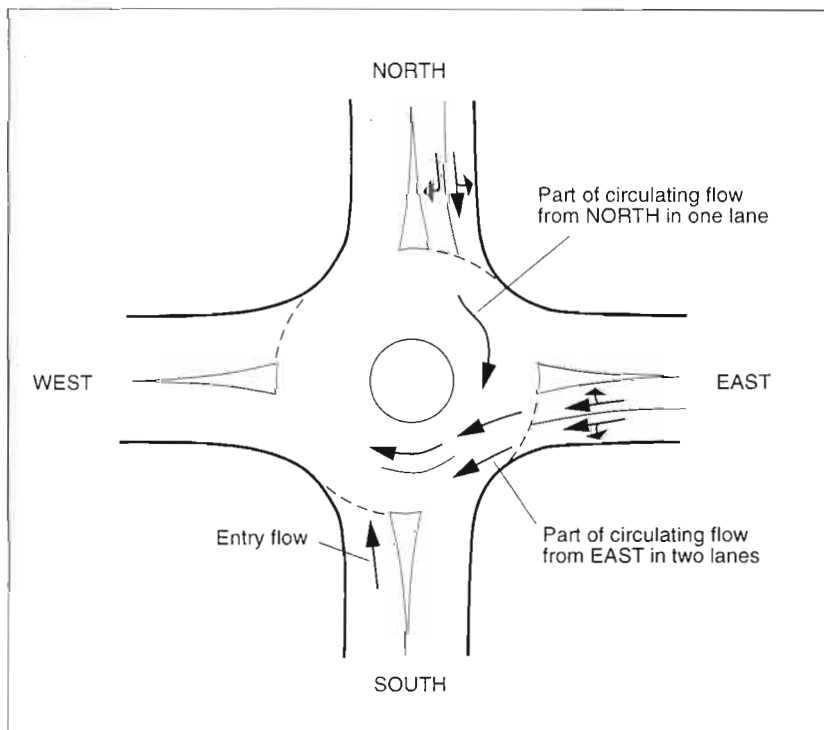The minimum critical gap and follow-up headway values were further increased in SIDRA 4.1 as shown in *Table 2*.

Figure 1
Approach lane use effect on circulating stream characteristics at a multi-lane roundabout

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* The inscribed diameter is measured from the give-way line of the subject approach, and includes the central island and the circulating lanes on both sides of the central island.

Table 2
Minimum values of critical gap and follow-up headway used in SIDRA

	Minimum critical gap (s)	Minimum follow-up headway (s)
SIDRA 4.07	2.1 (single-lane circul.) 1.5 (multi-lane circul.)	0.8
SIDRA 4.1	2.2 (all)	1.2

The increased limits have been chosen conservatively with due consideration given to the range of data listed in SR 45. In Tables B1 to B3 of SR 45, there are only a few data points with values less than the minimum values used in SIDRA 4.1. This can be seen from *Figs 2a* and *2b* based on data given in SR 45 (critical gaps *used in regression* and the corresponding follow-up headways listed in Table B3).

A further, and significant, modification is in the formula for calculating the critical gap. The SR 45 method predicts that the ratio of the critical gap to the follow-up headway keeps decreasing with increased circulating flow (Equation 4 of SR 45). However, it is observed from Fig. 6 of SR 45 that this ratio increases as the circulating flow increases beyond about 1,200 pcu/h. This observation could be explained by the difficulty of accepting gaps in circulating streams with high flow rates but the more efficient use of the accepted gaps (smaller follow-up headways). A limited survey at a roundabout in Auckland, New Zealand, indicated that follow-up headways decreased with increasing circulating flows in the range 1,000 to 2,400 pcu/h (the measured values were close to the SR 45 values), but the critical gaps increased with increasing circulating flows. As seen in *Fig. 2a* based on SR 45 data, critical gaps are fairly constant for circulating flows above 1200 veh/h. Without redeveloping the SR 45 regression equation, the linear reduction in the ratio of the critical gap to the follow-up headway with increasing circulating flow rate has been limited to flow rates below 1,200 pcu/h.

In SIDRA 4.07, a maximum follow-up headway of 4.0 s (applied to dominant lanes only) and a maximum critical gap of 10.0 s (applied to all lanes) were used. Furthermore, the inscribed diameter value used in the formula for calculating the dominant lane follow-up headway was limited to a minimum of 20 m in order to prevent the prediction of very large follow-up headway values (therefore, large critical gap values).

In SIDRA 4.1, the maximum critical gap was reduced to 8.0 s, and the maximum follow-up headway of 4.0 s was applied to all lanes. These maximum values may still be large, but underestimation of capacity at low circulating flows is not as serious a problem as the overestimation at high circulating flows.

ADJUSTMENT FOR THE EFFECT OF HEAVY ENTRY FLOWS AGAINST LOW CIRCULATING FLOWS

A significant change introduced in SIDRA 4.1 in order to avoid underestimation of capacities at low flows is to allow for the effect of heavy entry flows against low circulating flows. Troutbeck (1992) suggested that:

> designers should reduce the dominant stream follow on times by say 20% if there is a high entry flow and a low circulating flow. Under these conditions it would be better to use the same critical acceptance gaps.

The method used in SIDRA 4.1 is to decrease the follow-up headway of the dominant entry lane as a function of the ratio of entry flow to circulating flow. The adjustment of the follow-up headway from the SR 45 method is carried out in a continuous way down to a nominated minimum value, and for circulating flows up to a nominated maximum value. This results in increased capacities for all entry lanes. Entry lane capacities as a function of the ratio of entry flow to circulating flow (q_e/q_c) are shown in *Fig. 3* for a single-lane roundabout example.
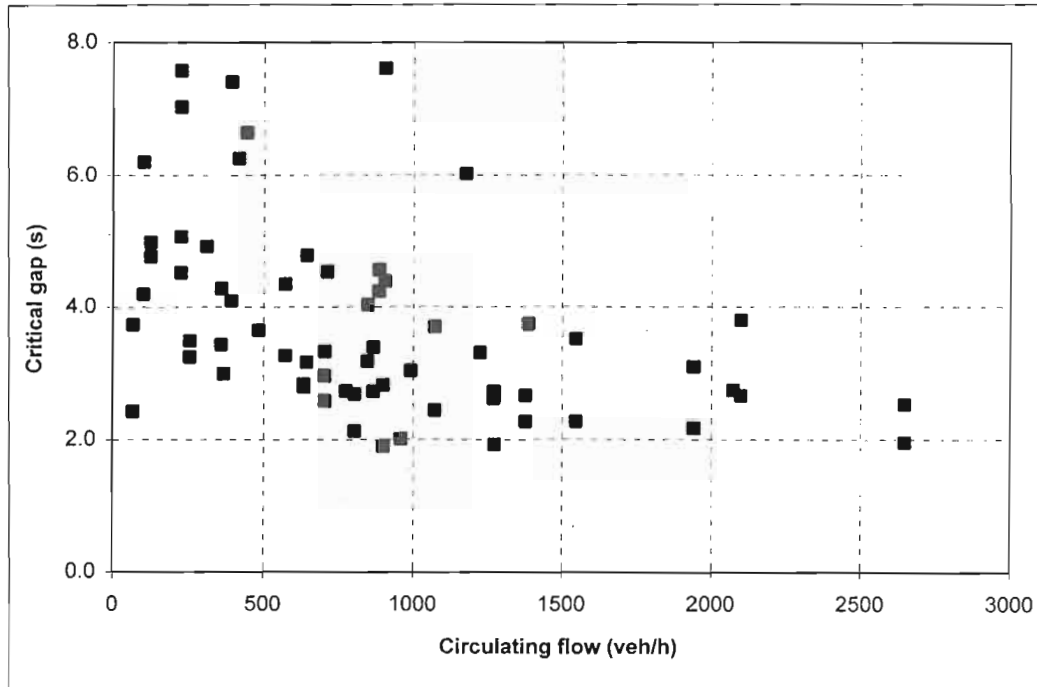
*Figure 2a
Observed critical
gaps as a function
of the circulating
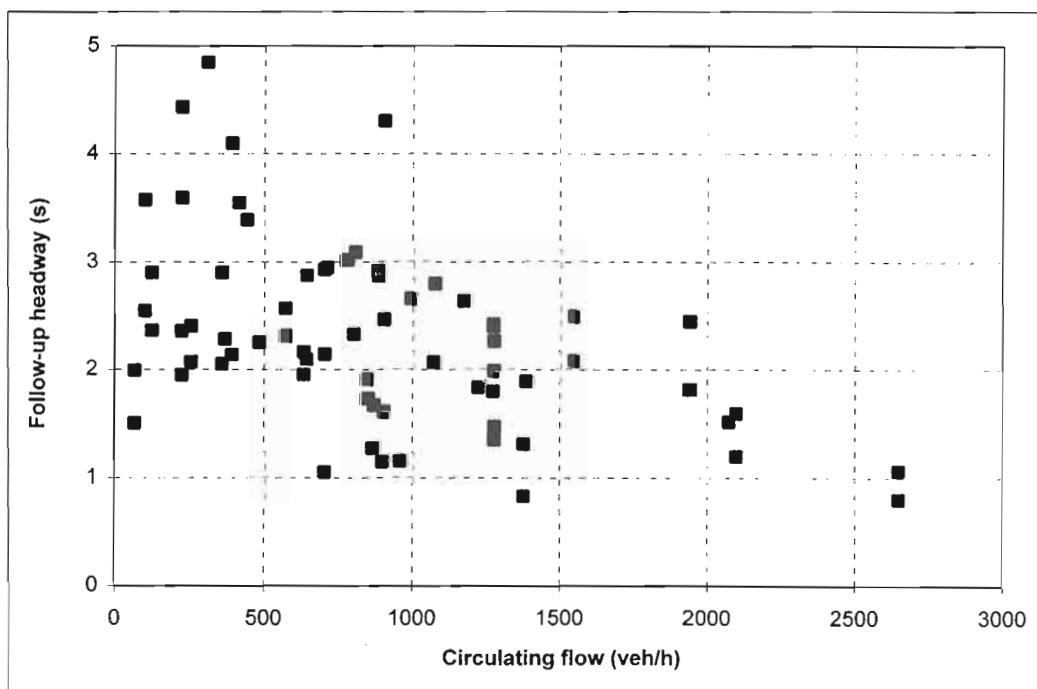flow (based on data
given in Table B3
of SR 45)*

*Figure 2b
Observed follow-
up headways as a
function of the
circulating flow
(based on data
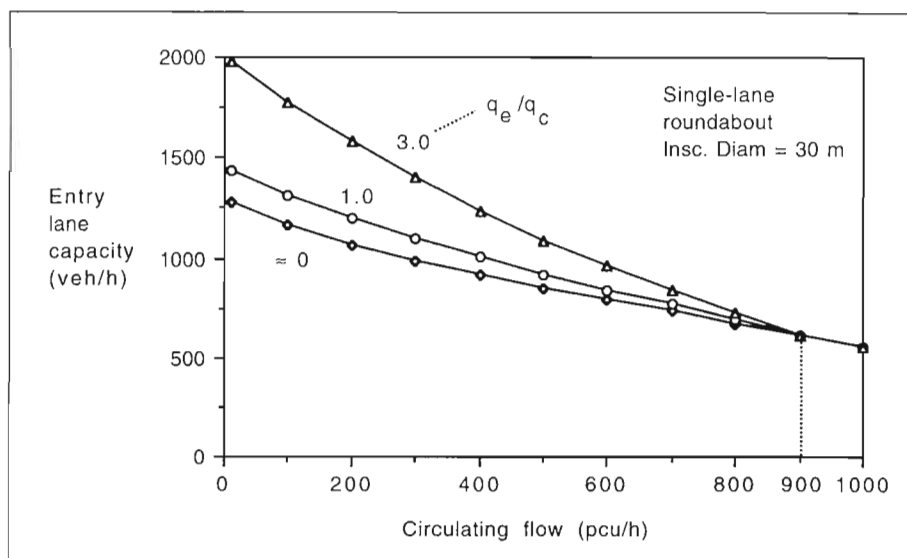given in Table B3
of SR 45)*

Figure 3
Entry lane capacities as a function of circulating flow for various q_e/q_c values (ratio of entry flow to circulating flow)

DISCUSSION ON ROUNDABOUT CAPACITY

A discussion of the comparison of capacity estimates from SIDRA 4.1 and previous versions, (and therefore from the SR 45/AUSTROADS (1993) method, is given in this section.

Capacity estimates from SIDRA 4.1 and the SR 45 method are plotted in *Figs 4a* and *4b* for two examples corresponding to Figs 15 and 20 of SR 45. *Figure 4a* is for a single-lane roundabout with inscribed diameter of 40 m, circulating road width of 10 m, and 4 m entry lane widths. *Figure 4b* is for a two-lane roundabout with inscribed diameter of 60 m, circulating road width of 10 m, and 4 m entry lane widths. In *Figs 4a* and *4b*, curves A and B show the range of capacity values that SIDRA 4.1 can estimate for the same circulating flow rate, depending on the dominant flow characteristics. Curve A is the basic gap-acceptance capacity, and Curve B is the lowest capacity that can be predicted — with all circulating traffic originating from the dominant approach and all being queued.

For single-lane circulating streams, the basic gap-acceptance capacities predicted by SIDRA 4.1 and the SR 45 method are very similar (Curve A in *Fig. 4a*). For multi-lane circulating streams, the basic gap-acceptance capacities predicted by SIDRA 4.1 (Curve A in *Fig. 4b*) are much lower than the SR 45 method for high circulating flow rates, particularly above 1,500 pcu/h.

Actual capacities predicted by SIDRA 4.1 will be generally lower (values between curves A and B) at medium to high circulating flow rates due to dominant approach effects. However, higher capacities than the SR 45 method will be predicted at low circulating flows. The difference will be significant when the ratio of entry flow to circulating flow is high (see *Fig. 3*).

Maximum flows that a roundabout can handle

High values of the theoretical capacities and circulating flow rates calculated for single stream cases, as seen in *Figs 4a* and *4b*, do not necessarily represent the flow levels that a roundabout can handle. For this purpose, calculations for full roundabout cases are necessary. To give an indication of the highest levels of flow that can be handled by roundabouts, the total intersection capacities and practical capacities* for a four-way roundabout with equal entry flows on all approaches are shown in *Fig. 5*.

Figure 5 has been obtained assuming through movements consisting of cars only. All lane widths are equal (4.0 m). The single-lane roundabout has an inscribed diameter of 40 m and circulating road

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* 'Practical capacity' is the flow that yields a degree of saturation of 0.85, and 'absolute capacity' is the flow that gives a degree of saturation of 1.0.
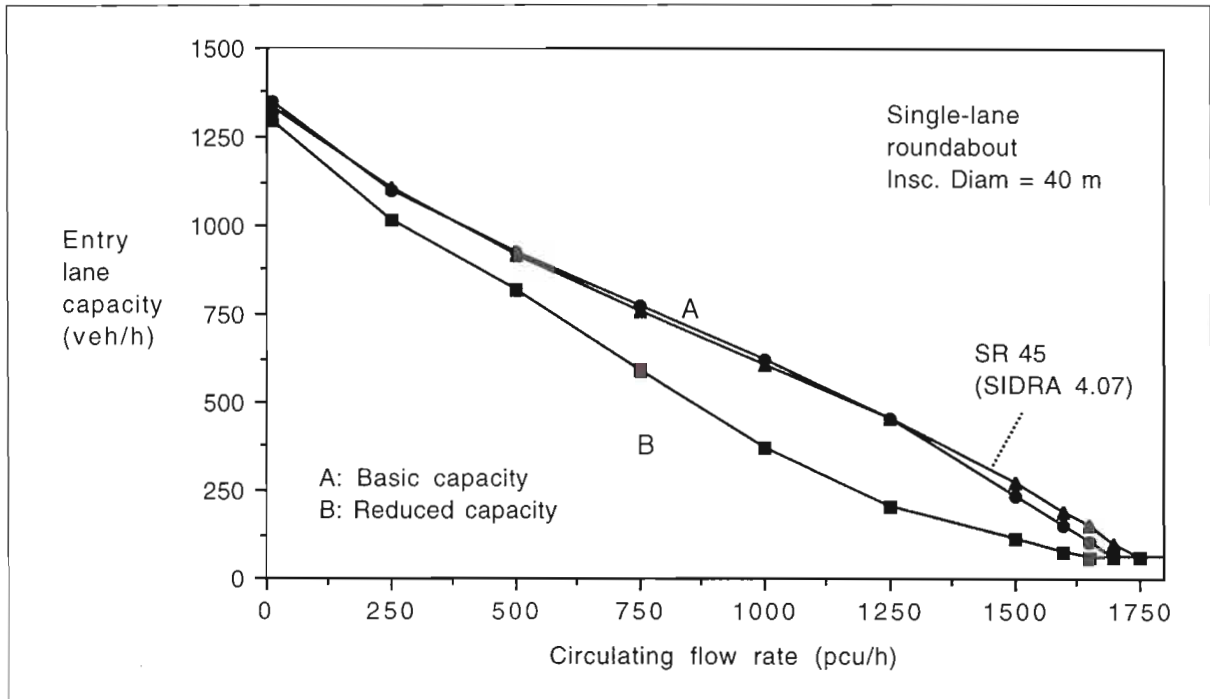
Figure 4a
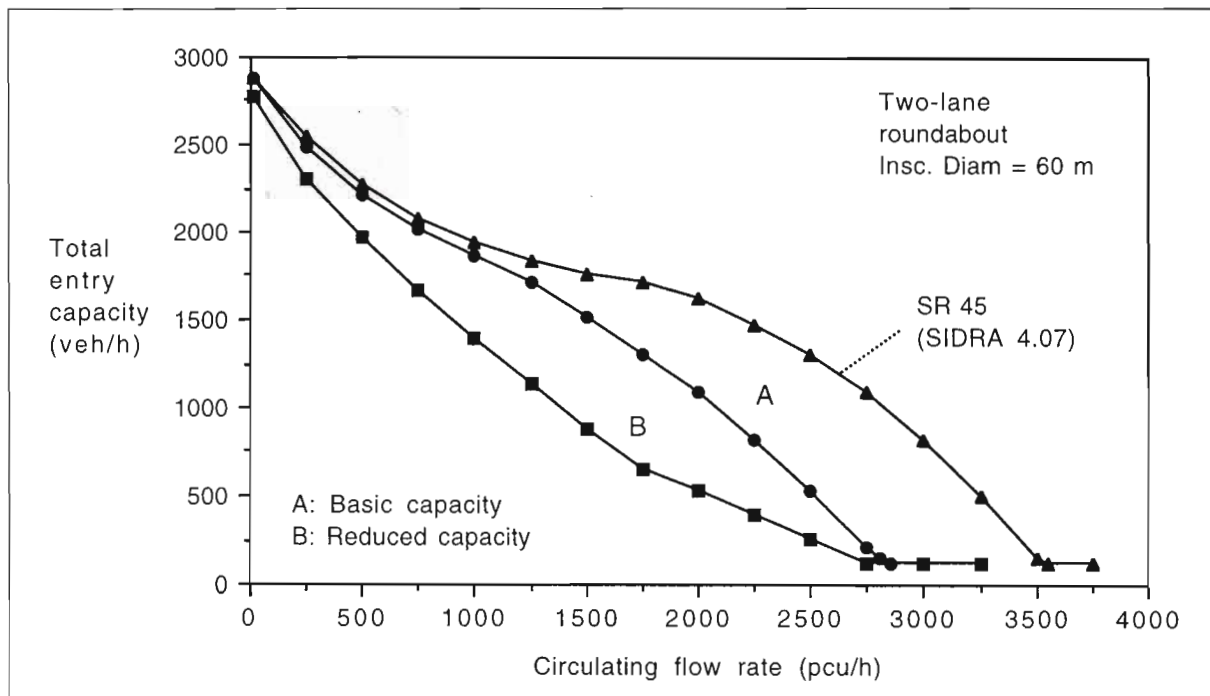*Capacity graphs for a single-lane roundabout (corresponds to Figure 15 of SR 45)*

Figure 4b
Capacity graphs for a two-lane roundabout (corresponds to Figure 20 of SR 45)
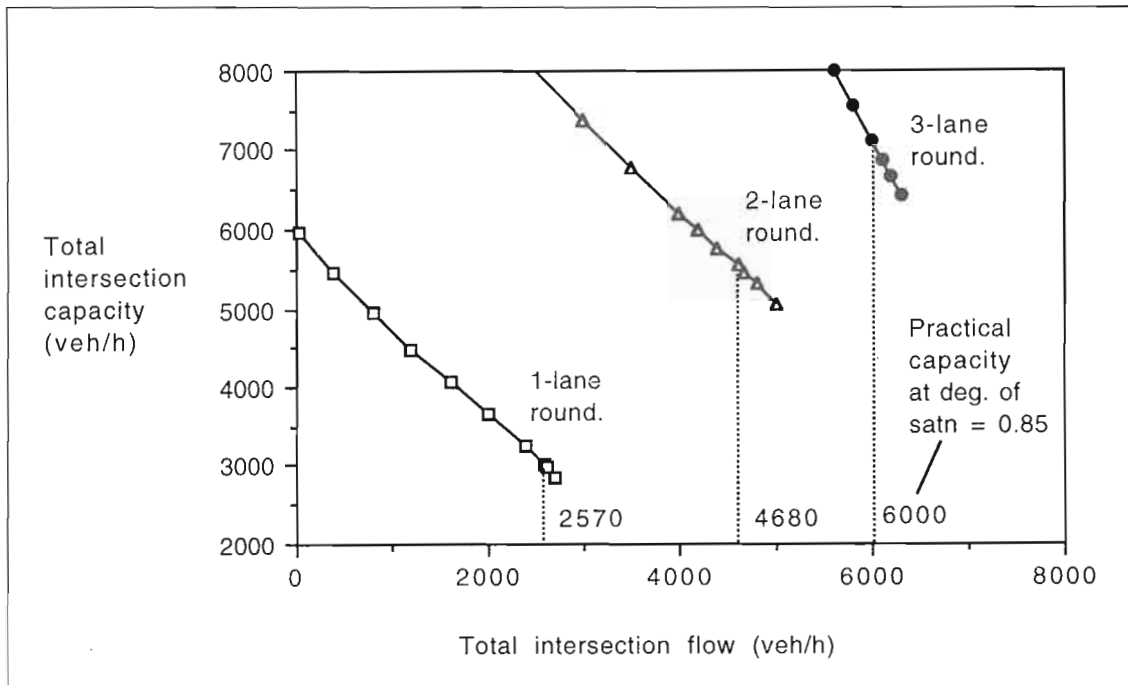
Figure 5
Total intersection capacity and practical capacities for a four-way roundabout with equal entry flows on all approaches

width 10 m; the two-lane roundabout has an inscribed diameter of 60 m and circulating road width 10 m; and the three-lane roundabout has an inscribed diameter of 80 m and circulating road width 15 m. SIDRA 4.1 indicates that:

- the single-lane roundabout can handle total flows of around 2,570 to 2,800 veh/h (approximately 640 to 700 veh/h per approach);

- the two-lane roundabout can handle total flows around 4,680 to 5,000 veh/h (1,170 to 1,250 veh/h per approach); and

- the three-lane roundabout can handle total flows around 6,000 to 6,320 veh/h (1,500 to 1,580 veh/h per approach).

In these ranges, the low value is the *practical* capacity and the high value is the *absolute* capacity.

In more realistic cases of multi-lane roundabouts with turning flows, lower capacities are obtained due to the effect of single-lane turning flows in the circulating stream. For example, the following *practical capacities* are obtained for the same roundabouts with equal flows on all legs but assuming 20% left-turn, 60% through and 20% right-turn flow on each leg. Lane disciplines are assumed

to be LT, TR for the two-lane roundabout, and LT, T ('through' traffic), TR for the three-lane roundabout):

Single-lane roundabout	2,600 veh/h
	(650 veh/h per approach)
Two-lane roundabout	4,560 veh/h
	(1,140 veh/h per approach)
Three-lane roundabout	5,840 veh/h
	(1,460 veh/h per approach)

A very small increase in the capacity of the single-lane roundabout is observed; this is because the dominant approach contributes a smaller (80%) flow to the circulating stream. The main reason for decreased capacities for multi-lane roundabouts is the effect of the single-lane right-turn flow in the circulating stream. For the same reason, even lower capacities will be predicted for the multi-lane roundabouts when exclusive lanes are used, or when the single-lane right-turn flow rates are higher.

A more comprehensive study of various flow, geometry and approach lane discipline combinations could be carried out using SIDRA 4.1 to establish the practical capacity ranges for roundabouts. The results (as in *Fig. 5*) should be used in lieu of Fig. 3.3 of AUSTROADS (1993), which indicates higher practical capacities then those given here.

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DISCUSSION ON ROUNDABOUT PERFORMANCE

The full set of formulae used in SIDRA 4.1 for estimating roundabout performance (delay, queue length, proportion queued, queue move-up rate and stop rate) are given in Akçelik, Chung and Besley (1995) and Akçelik, Besley et al. (1995). These formulae are substantially different from those used in SIDRA 4.07. The new models are based on an integrated modelling framework developed for consistency among different statistics and among models for different intersection types. The models have the traditional two-term form with additional calibration factors introduced for each term of each model. The additional factors help to allow for the effects of variations in arrival flow rates and cycle capacities (which vary as a function of acceptable gaps in the circulating stream).

The models for roundabouts and other unsignalised intersections were developed by converting the block and unblock periods in traditional gap-acceptance modelling to effective red and green periods by analogy to traffic signal operations (Akçelik 1994). This enabled the modelling of the average back of queue, proportion queued and queue move-up rates in a manner consistent with models for signalised intersections. Models were derived using a bunched exponential model of arrival headway distributions in a modified version of the microscopic simulation model MODELC (Chung 1993; Chung, Young and Akçelik 1992).

Peak demand considerations

The models for delay, queue length, queue move-up rate and stop rate are *time-dependent*, i.e. the values of these statistics depend on the duration of the *peak flow period*, and the models are applicable to oversaturated conditions. In the derivation of the time-dependent formulae, a zero initial queue and a constant demand rate throughout the peak flow period are assumed.

The work reported by Akçelik and Rouphail (1993) and Rouphail and Akçelik (1992) showed that a single-period analysis with a constant demand rate is adequate provided that it is applied to a peak flow period which is determined with due attention to the peaking profile in the *total flow period*. The method for specifying the related flow parameters (total flow period, peak flow period and peak flow factor) has been improved in SIDRA 4.1 with this in mind, and a peak flow period of 30 min, total flow period of 60 min and a peak flow factor of 90% have been adopted as SIDRA standard default values. The Highway Capacity Manual (TRB 1994) version uses a peak flow period of 15 minutes. Refer to Akçelik, Besley et al. (1995) for a detailed discussion of this subject.

A CASE STUDY

Chapter 12 of AUSTROADS (1993) provides a good real-life example of unbalanced flows. This is the intersection of Mickleham Road and Broadmeadows Road. The intersection geometry and morning peak traffic flows are shown in *Figs 6* and *7*. Note that the right-turn flow of 3 veh/h from the North approach represents U-turns, and the right-turn flow of 1,397 veh/h from the South approach includes 34 U-turns. The circulating flows for the Northeast and South approaches are less than those implied by demand flows (617 rather than 919, and 82 rather than 83) due to the capacity constraint on flows departing from the North approach.

The problem of unbalanced flows at this roundabout is caused by the heavy right-turn flow from the South. The capacity of the North leg was very low, and 'extreme queuing (500 m to 600 m) occurred regularly during the morning peak' (AUSTROADS 1993). To improve the conditions for traffic on the North approach, part-time metering signals were installed on the South approach, actuated by the queue of vehicles extending back along the North approach onto detectors 90 m upstream of the give-way line. The example given here relates to the conditions *before the installation of part-time metering signals*.

Table 3 presents a comparison of the estimates of delay and degree of saturation using SIDRA 4.1 and the SR 45/AUSTROADS (1993) method obtained using the older SIDRA version 4.07. The delays in *Table 2* do not include geometric delays. The queue length estimate from SIDRA 4.1 (95th percentile back of queue) represents the longest queue in any lane. The SR 45/AUSTROADS (1993) method fails to indicate that there is a problem at this intersection. The capacity problem for the North approach is largely caused by the right-turn movement from South, which operates effectively as a single-lane movement due to a de facto exclusive right-turn lane
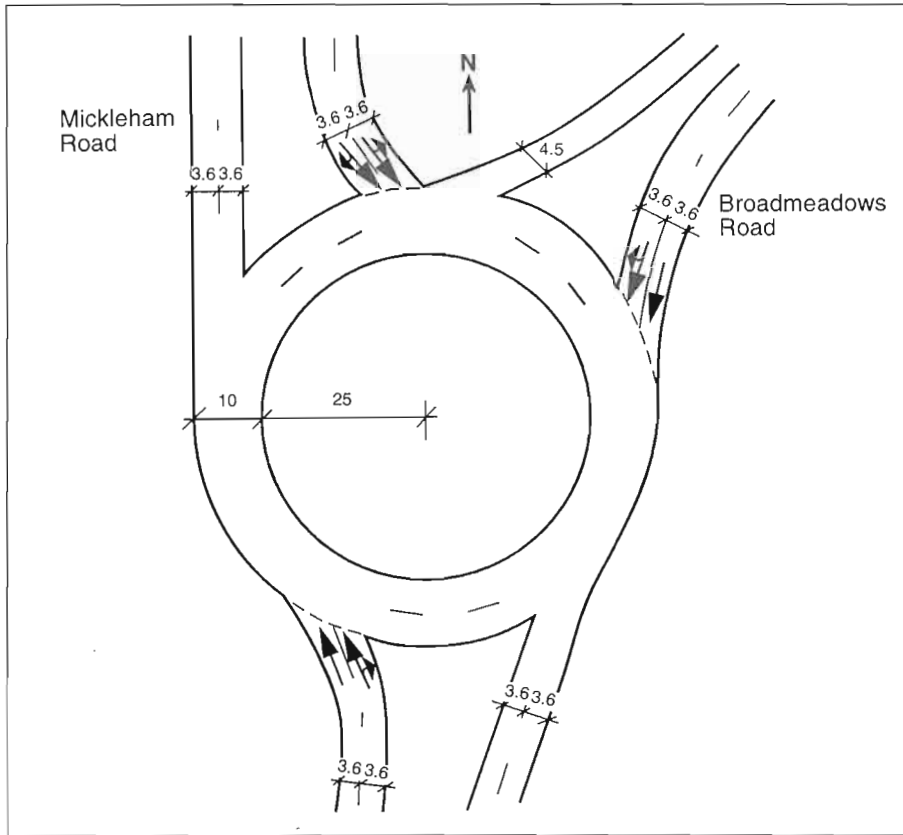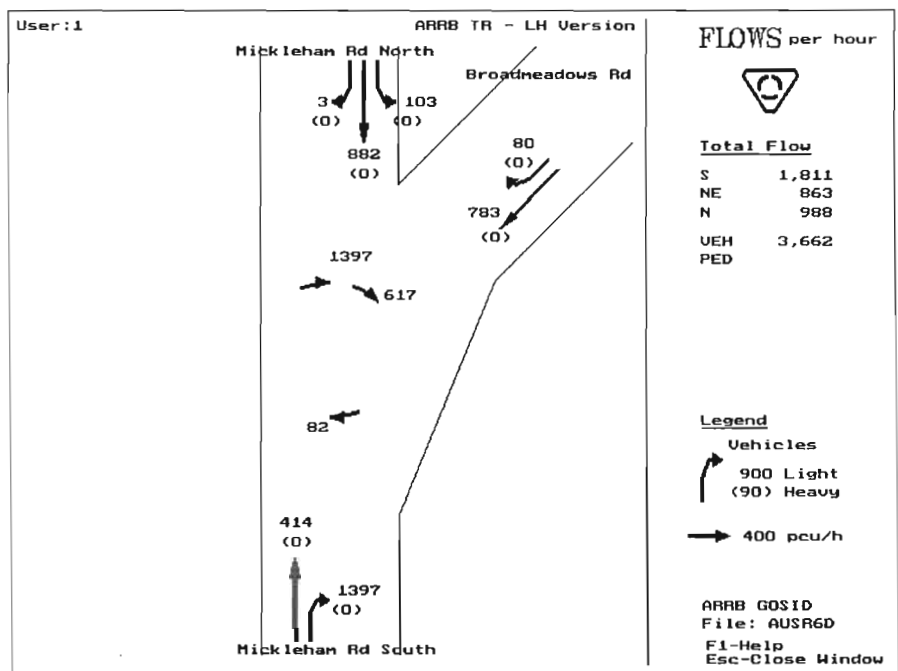
Figure 6
Real-life example for
*unbalanced flows: Intersection*
geometry (AUSTROADS
1993, Fig. 12.1)

Figure 7
Real-life example for unbalanced
flows: Morning peak traffic flows

Table 3
Results for the example in *Figs 6* and *7*

		SR 45/ AUSTROADS (1993)	SIDRA 4.1
Delay (s)	North-Through	6.2	522.7
	North-Left	5.1	519.3
	South-Through	0.6	0.4
	South-Right	3.3	0.6
Degree of saturation	North_Through	0.56	1.52
	North-Left	0.56	1.52
	South-Through	0.40	0.30
	South-Right	0.95	0.77
95% Back of queue (m)	North approach	–	826
	South approach	–	63

Figure 8
Delay estimates from SIDRA 4.1
for the roundabout shown in
Figs. 6 and 7
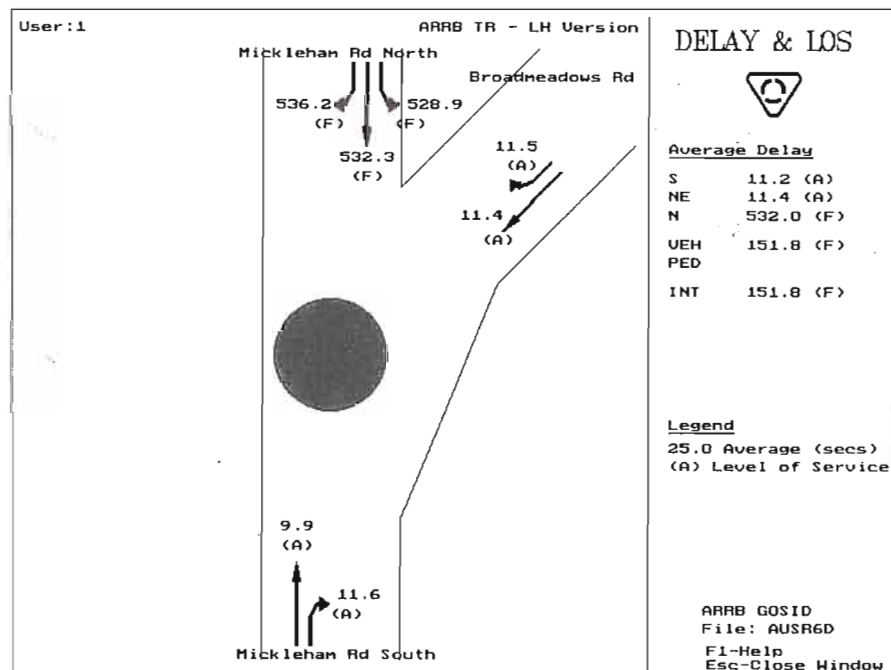
on the South approach and a single exit lane on the Northeast leg. By specifying the number of circulating lanes for the North approach as one, the SIDRA 4.07 predictions were improved substantially and an average delay for the North leg of 121.1 was obtained. SIDRA 4.1 identifies this dominant movement as a single-lane movement automatically.

The delay results from SIDRA 4.1 (including geometric delays) are shown in *Fig. 8*, indicating satisfactory prediction of the performance of this roundabout prior to the introduction of part-time signals (average delay for the North leg is 522.4 s without geometric delays and 532.0 s with geometric delays, average back of queue is 330 m, and 95th percentile back of queue is 826 m).

This case also includes an example of very heavy entry flow (1,397 veh/h in the right-turn lane on the South approach) against a very low circulating flow

(82 veh/h). SIDRA 4.1 finds this movement to be operating under good conditions (degree of saturation is 0.77) due to the adjustment of its follow-up headway (1.82 s). Without the model for follow-up headway adjustment (*Fig. 3*), this movement is predicted as oversaturated, which is not consistent with the introduction of metering signals to control this movement.

CONCLUSIONS AND SUGGESTED RESEARCH

The enhancements described in this paper improve the capacity and performance predictions for roundabouts in general, and for multi-lane roundabouts with high circulating rates and unbalanced flow patterns in particular. However, some of the improvements are of a remedial nature since it was not possible to carry out extensive research into the areas where shortcomings were observed. Future research is needed for better modelling of heavy flow conditions. In such research, attention should be paid to details of how circulating streams are modelled, as well as to the determination of the critical gap and follow-up headways appropriate to different flow regimes. There are now many roundabouts with heavy flow conditions to enable this research.

Further research is also recommended on dominant flow effects at multi-lane roundabouts by means of simulation and real-life observations. This research could be extended to the modelling of the operation of roundabouts with part-time metering signals.•

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