Comparison of roundabout capacity and delay estimates from analytical and simulation models

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NOTE:

COMPARISON OF ROUNDABOUT CAPACITY AND DELAY ESTIMATES FROM ANALYTICAL AND SIMULATION MODELS

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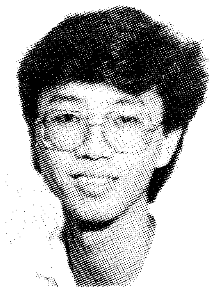
SUMMARY

The predictions of capacity and delay for a single lane entry stream at a single lane roundabout by two simulation models, ModelC and INSECT, and two analytical models, ARRB Special Report 45 (SR 45) and SIDRA, are compared. All these models are based on the use of gap acceptance method for predicting roundabout performance. Comparisons are made for low, medium and high circulating flow levels, and for undersaturated entry stream conditions (degrees of saturation in the range 0.10 to 0.95). The features of the models in relation to capacity and delay estimation are discussed in detail. The capacities and queueing delays predicted by ModelC simulation model and the two analytical models, SR 45 and SIDRA are found to be sufficiently close given the difficulty in making the analytical and simulation model assumptions compatible. Estimates of capacity and delay from INSECT are found to be over-sensitive to the origin-destination pattern of entry flows which contribute to a particular circulating flow. They are sufficiently close to estimates from other models when a balanced arrival flow pattern is used. Capacity and delay estimates from ModelC are less sensitive to changes in the origin-destination flow pattern.



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INTRODUCTION

1. The increasing number of roundabouts in the urban road system and the increasing flow levels in existing roundabouts necessitate effective design and evaluation of roundabouts as a traffic control device. A number of techniques have been developed to assist in this design and evaluation process. It is important to compare these techniques to determine their compatibility and achieve some degree of verification of them. This paper compares the predictions of the performance of a single lane roundabout by two simulation models, ModelC (Chung, Young and Akçelik 1992) and INSECT (Roads and Traffic Authority, NSW 1989; Tudge 1988), and two analytical models, SR 45 (Troutbeck 1989) and SIDRA (Akçelik 1991; Akçelik and Troutbeck 1991; Akçelik and Besley 1991). All these models are based on the use of the gap acceptance method for predicting roundabout capacity and performance (delay, queue length, etc.).

2. The SR 45 method as reported in the Australian Road Research Board Special Report No. 45 (Troutbeck 1989) allows for the effects of circulating flows, entry flows and roundabout geometry on gap acceptance parameters. This contrasts with the use of constant critical and follow-up headways as specified in the 1986 NAASRA Roundabout Guide. A new roundabout design guide which will be released as Part 6 of the AUSTROADS (1992) Guide to Traffic Engineering Practice, incorporates the SR 45 method .

3. The SIDRA package was originally developed for signalised intersection analysis. The latest version SIDRA 4 incorporates the SR 45 method for roundabout capacity prediction, but differs from SR 45 in introducing a time-dependent delay formula derived from the steady-state delay formula of SR 45 (Akçelik 1991, Akçelik and Troutbeck 1991).

4. ModelC is a microscopic (vehicle-by-vehicle) simulation model developed for the analysis of roundabouts. It is a time update simulation model, with vehicle movements governed by principles of car following. The conflict between entering and circulating vehicles are resolved by gap acceptance method. The results of ModelC validation using field data show that ModelC provides satisfactory prediction of roundabout performance (Chung, et al 1992). Better delay estimates were produced by ModelC using critical gap and follow-up headway values updated every minute during simulation using the SR 45 method, compared to the use of constant critical and follow up headways of 4 and 2 seconds (NAASRA 1986).

5. INSECT is a microscopic simulation model used mainly for modelling roundabouts and other unsignalised intersections (Roads and Traffic Authority, NSW 1989; Tudge 1988). The model is based on a vehicle-by-vehicle simulation technique with vehicle movements governed by car following rules. Conflict resolution is based on a gap acceptance method. Calibration and validation of the INSECT model was reported by Tudge (1988). Version 3.5 of INSECT was used for the analysis reported in this paper.

6. This paper focuses on the comparison of capacity and delay estimates by the SR 45, SIDRA, ModelC and INSECT models for a single entry stream at a roundabout for several levels of circulating flows at a typical single lane roundabout. The specification of the roundabout geometry and flow conditions is given in *para.* 7 followed by detailed discussions of the features

of the models in relation to capacity and delay estimation in *para. 8–27.* The results from different models are discussed in *para. 28–33.*

ROUNDABOUT SPECIFICATION

7. To assess the techniques for estimating roundabout capacity and delay at a fundamental level, this study concentrated on predicting the performance of a a single entry stream at a roundabout (South approach in *Figure 1*). A typical single lane roundabout with a central island diameter of D_c = 14 m, circulating road width of w_c = 8 m (hence inscribed diameter of D_i = 30 m) and average entry lane width of w_L = 5 m was chosen as shown in *Figure 1.* A simple origin-destination flow pattern was used with through flows on the East and South approaches, and no arrival flows on the West and North approaches (*Figure 1*). This means that the arrival flow from the East approach becomes the circulating stream which controls the entry flow from the South approach. Three circulating flow rates of 450, 900 and 1350 veh/h were chosen for this study to represent low, medium and high flows, respectively. For each circulating flow, the entry flow from the South approach was varied to yield degrees of saturation in the range 0.10 to 0.95. The effect of the origin-destination flow pattern was also investigated subsequently.

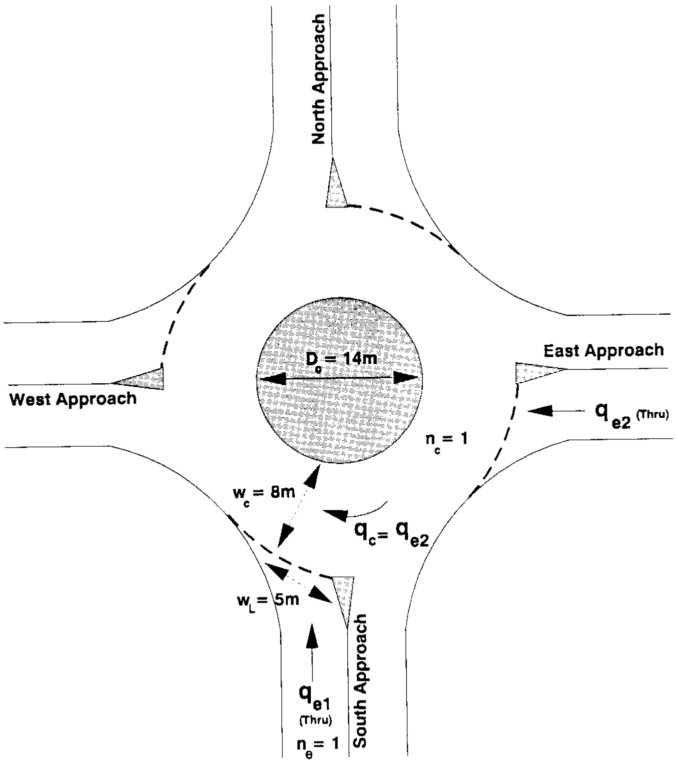

Fig. 1 – The single lane roundabout specification for this study

FEATURES OF MODELS

8. The methods relevant to estimation of capacity and delay at roundabouts by the analytical and simulation models considered in this paper are described in this section.

SR 45 AND SIDRA MODELS

Capacity Estimation

9. The following formula is used for estimating ***capacity*** of a roundabout entry stream in SR 45 and SIDRA:

$$Q_e = \frac{3600\,\varphi\, q_c\, e^{-\lambda(\alpha-\Delta)}}{1-e^{-\lambda\beta}} \quad (1)$$

where

$$\lambda = \frac{\varphi\, q_c}{1-\Delta q_c} \quad (2)$$

Q_e = capacity of the roundabout entry (veh/h),
q_c = total flow rate for the circulating stream (*veh / sec*),
β = follow-up headway calculated from *Equation 3,*
α = mean critical gap calculated from *Equation 4*,
φ = proportion of free vehicles calculated from *Equation 5*, and
Δ = intra-bunch headway from *Equation 6.*

10. The SR 45 formulae for estimating the ***follow-up headway*** (β in seconds) and the ***mean critical gap*** (α in seconds) for the single lane roundabout specified in *para. 7* can be written as:

$$\beta = 2.819 - 3.94\text{x}10^{-4}\, q_c \quad (3)$$

$$\alpha = (1.641 - 3.137\text{x}10^{-4}\, q_c)\,\beta \quad (4)$$

where q_c is the circulating flow rate (veh/h). For example, for q_c = 900 veh/h, β = 2.464 s and α = 3.348 s.

11. In *Equation 1*, the intra-bunch headway (Δ) is the minimum headway value within each bunch in the circulating stream (equal for all bunches), and the proportion of free vehicles (φ) represents the unbunched vehicles with randomly distributed headways. The ***proportion of free vehicles*** in the circulating stream is estimated from the following expression which has been obtained by a slight adjustment to Equations (7) to (10) of SR 45:

$$\varphi = 0.75\,(1-\Delta\, q_c) \quad (5)$$

where q_c is the circulating flow rate (veh/sec). The ***intra-bunch headway*** for single-lane circulating stream is constant and:

$$\Delta = 2 \text{ sec} \tag{6}$$

Thus, for example, for $q_c = 900$ veh/h, $\varphi = 0.75\,(1 - 2 \times 0.250) = 0.375$ s.

12. The gap acceptance parameters α, β, and φ, and the corresponding entry stream capacities (Q_e) calculated from *Equations 1 to 6* for circulating flow rates of 450, 900 and 1350 veh/h are given in *Tables I and II*. The relationship between the entry stream capacity and the circulating flow rate is shown in *Figure 2*.

13. The calculations in accordance with the SR 45 method were carried out by means of a spreadsheet. For SIDRA computations, the variable flow scale facility was used in order to obtain capacity and delay estimates in a single run.

TABLE I

Gap Acceptance Parameters for Comparison of Analytical Models (SR 45/SIDRA) and Simulation (ModelC)

Circulating flow q_c (veh/h)	Critical gap α (sec)	Follow-up headway β (sec)	Prop. of free vehs φ
450	3.96	2.64	0.563
900	3.35	2.46	0.375
1350	2.78	2.29	0.188

Inscribed diameter = 30, circulating road width = 8 m, single-lane entry, single-lane circulating stream (intra-bunch headway, $\Delta = 2$ s)

TABLE II

Comparison of Capacity Estimates from Analytical Models (SR 45/SIDRA) and Simulation (ModelC)

Circulating flow q_c (veh/h)	Entry capacity, Q_e (veh/h) SR 45 / SIDRA	Model C
450	960	899
900	708	682
1350	428	394

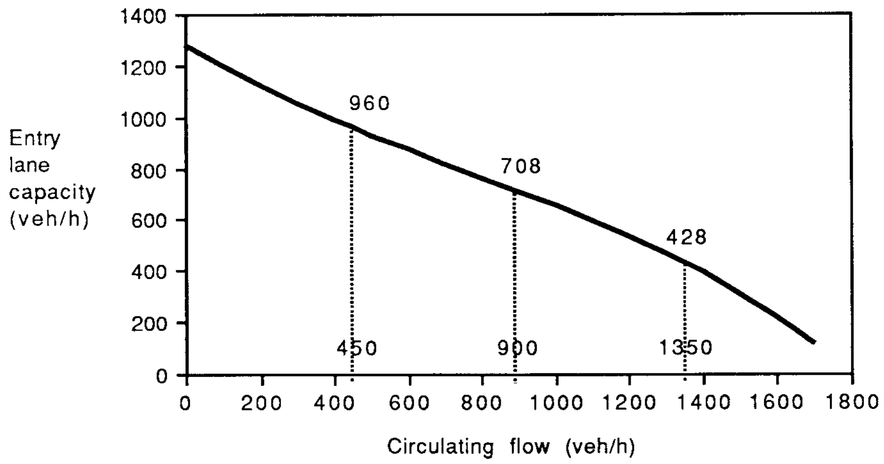

Fig. 2 – Entry lane capacity as a function of the circulating flow for the single lane roundabout considered in this study

Delay Estimation

14. The SR 45 (Troutbeck 1989) formula for estimating the ***average delay*** at a roundabout entry (d_{st} in seconds) is a steady-state delay model which can be expressed as follows :

$$d_{st} = d_m + \frac{3600\,k\,x}{Q_e\,(1-x)} \qquad (7)$$

where

k = delay parameter given by

$$k = d_m\,Q_e\,/\,3600 \qquad (8)$$

x = degree of saturation of the entry lane, i.e. the ratio of arrival (demand) flow rate to capacity ($x = q_e/Q_e$),

Q_e = entry lane capacity (veh/h),

d_m = minimum delay (in seconds) experienced by an entering vehicle in absence of queueing on the approach road:

$$d_m = \frac{e^{\lambda(\alpha-\Delta)}}{\varphi\,q_c} - \alpha - \frac{1}{\lambda} + \frac{\lambda\Delta^2 - 2\Delta + 2\Delta\varphi}{2\,(\lambda\Delta + \varphi)} \qquad (9)$$

where the gap acceptance parameters α, β, Δ, φ and λ are are given by *Equations 2 to 6,* and the circulating flow, q_c is in veh/sec.

15. SIDRA uses a time-dependent delay formula to estimate the ***average delay*** (d in seconds) at a roundabout entry (Akçelik 1991; Akçelik and Troutbeck 1991). This formula is derived from the steady-state delay formula of SR 45 (*Equation 7),* and is expressed as:

$$d = d_m + 900\,T\left[\,Z + \sqrt{Z^2 + \frac{8k\,x}{Q_e\,T}}\,\right] \qquad (10)$$

where

d_m = minimum delay in seconds (from *Equation 9),*

T = flow period in hours (duration of the time interval during which the demand flow rate persists),

x = degree of saturation in the specified flow period,

Z = x − 1,

k = delay parameter (from *Equation 8*), and

Q_e = entry stream capacity in veh/h (from *Equation 1*).

16. In both the steady-state and the time-dependent formulations (*Equations 7 and 10*), the second term accounts for the delays due to the presence of a queue in the entry lane. The two formulae give similar results for low degrees of saturation where the delays are not sensitive to the flow period. For high degrees of saturation, the time-dependent formula predicts smaller delay values because the arrival (demand) flow rate is assumed to last for a limited period of time (e.g. T = 0.5 h or 1 h) whereas the steady-state model assumes that the demand lasts for an infinite period of time (T = ∞). Thus, the time-dependent formula predicts finite delay values for demand flows at or above capacity whereas the steady-state model predicts infinite delays as demand flows approach capacity. These features of the two models can be seen from *Figure 3* which shows the delays predicted for a circulating flow rate of 900 veh/h at the roundabout specified in *para.7* (Q_e= 708 veh/h, d_m = 3.9 s and k = 3.9x708/3600 = 0.8).

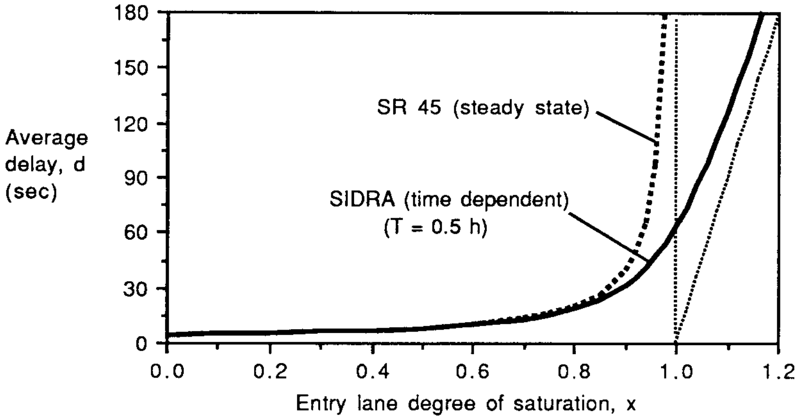

Fig. 3 – Relationship between the steady-state (SR 45) and time-dependent (SIDRA) delay models for the roundabout considered in this study (circulating flow, q_c = 900 veh/h, entry lane capacity, Q_e = 708 veh/h, k = 0.8)

MODELC

17. In this study, ModelC was used in a way to match the assumptions of the SR 45 method for capacity and delay estimation. Thus, the arrival flow distribution of the vehicles on the East approach, which will form the circulating flow against the traffic entering from the South approach (see *Figure 1*), is generated using the Cowan M3 Model (Cowan 1975). The proportion of free (unbunched) vehicles calculated from *Equation 5* was used for this model. The vehicles which accept gaps and enter the circulating stream follow each other in accordance with the car following rules of ModelC simulation. In this process, the acceleration and deceleration profiles of the lead car is important in determining the speed-time profiles of following vehicles. The acceleration and deceleration profile models described by Akçelik and Biggs (1987) have been adopted in ModelC. Due to the car following process, the proportion of free vehicles in the circulating stream at the conflict point in front of the South approach may differ from the proportion of free vehicles specified for arrivals on the East approach by a small amount. Arrivals for the entering stream (South approach) were generated from a shifted negative exponential distribution of headways with a 2-second minimum headway. In the subsequent analysis comparing INSECT and ModelC simulation models, the shifted negative exponential distribution of headways was used for all approaches of the roundabout for consistency between the two models (see *para. 32–33*).

18. Secondly, as assumed by the SR 45 method, the gap acceptance parameters (α, β, φ) estimated from *Equations 3 to 5* were used as constant values throughout simulation. Alternatively, ModelC can vary these parameters every minute according to the measured circulating flow rates in simulation.

Capacity Estimation Using ModelC

19. Vehicle-by-vehicle simulation models like ModelC and INSECT are not normally used for capacity estimation since, by definition, capacity (maximum possible entry flow rate) requires the existence of queues throughout the study period. To overcome this problem, special runs were carried out using ModelC with the entry stream loaded with a demand flow greater than capacity. The capacity was calculated using the *Equation 1,* and entry flows 5 per cent higher than the estimated capacity was specified. The capacity of the entering stream for the three circulating flow rates 450, 900 and 1350 veh/h were determined by running ModelC ten times with different sets of random numbers for each circulating flow. The average capacity values estimated from ModelC are tabulated in *Table II.*

Delay Estimation Using ModelC

20. For each circulating flow rate, ModelC was run with entry flow rates which yield degrees of saturation in the range 0.1 to 0.95. The capacities (Q_e) estimated from ModelC were used to calculate the arrival flow rates of the entry stream (q_e) at different degrees of saturation ($q_e = x\ Q_e$). Since the capacities predicted using ModelC are different from those predicted by the

SR 45 / SIDRA methods, the arrival flow rates used for ModelC at each degree of saturation are different from those used for the analytical models.

21. The analytical delay model of SR 45 is derived assuming arrivals and departures at the give-way line. To match the assumptions of this model, ModelC was used in a *vertical queueing* mode which generates the arrivals at the give-way line. This differs from the normal *car-following* method of ModelC where vehicles are generated at a distance upstream of the give-way line and move towards the roundabout according to car-following principles. Difference between the delay estimates from the two methods are small.

22. Since ModelC was used for simulating steady-state conditions as for the SR 45 delay equation, it was not applied to near-capacity and oversaturated entry flow conditions. On the other hand, the low degree of saturation of $x = 0.1$ was used to obtain an approximate minimum delay prediction from ModelC for comparison with the SR 45 formula (*Equation 9*).

23. Each ModelC simulation was run for 30 minutes after an initial *warm-up* period of 15 minute duration. The flow rates during the warm-up and the simulation period were the same. ModelC was used in this way to simulate delays for undersaturated conditions in a steady-state model fashion. Ten sets of random number were used to obtain delay estimates for each circulating and entry flow combination. The average of these ten runs was used as the result for the particular flow condition.

INSECT

24. Again, INSECT was used in a way to match the analytical model assumptions as much as possible, but this proved to be more difficult than ModelC due to the lack of access to the source code of INSECT. The critical gap and follow-up headway parameters calculated using the SR 45 method (*Equations 3 and 4*) and given in *Table I* were specified as input to INSECT. However, INSECT modifies the user-specified critical gap value as a function of the time each simulated vehicle spends in the queue (Tudge 1988). The values used by INSECT would be 1.5 times the user-specified critical gap value for a vehicle which arrives at the give-way line without any queue delay, and then would be decreased gradually subject to a minimum critical gap value of 2.2 s.

25. The definition of *queueing delay* given in the INSECT User Manual is "the total time that vehicles have spent stopped, either in a queue or waiting for conflicts to be resolved". We assume that, as a normal simulation method, the queueing delay given by INSECT is in fact *queueing time* including stopped time as well as queue move-up time, but excluding the initial deceleration time. This differs from the *queueing delay* predicted by the analytical model of SR 45 (see *para. 21* regarding the vertical queueing method used in ModelC simulation to overcome this problem). However, the difference between the queueing time and queueing delay is small in most cases.

26. To match the method used for ModelC, the warm-up time of INSECT was set to zero, but each simulation run was carried out for 45 minutes and only the results from the last 30 minutes were used. In other words, the first 15 minutes of INSECT simulation was treated as a warm-up period. This

method gives slightly different results compared to specifying a 15-minute warm up period for INSECT. The option of INSECT to perform five runs with different random seeds was used in this study and the average value from these five runs was taken as the result for the given flow.

27. INSECT capacity predictions were carried out using the method described in *para. 19* for ModelC. The length of the approach road section was specified as 300 m in order to contain long queues which develop in this type of simulation. INSECT capacity estimates were found to be much lower, and the delay estimates were found to be much higher, compared to those from SR 45, SIDRA and ModelC for the origin-destination flow pattern shown in *Figure 1*. As a result, comparison of capacities and delays for SR 45, SIDRA and ModelC only are given in *para. 28–31*. The findings from a separate comparison of INSECT and ModelC considering the effect of different origin-destination flow patterns are given in *para. 32–33*.

RESULTS AND DISCUSSION

CAPACITY

28. *Table II* shows the capacities predicted from SR 45 (same from SIDRA) and ModelC for three circulating flow rates. The results show that the two sets of estimates are close (4 to 8 per cent difference) with all capacities predicted from ModelC being lower than the SR 45 estimates. This is quite satisfactory given the differences in the nature of analytical and simulation models in spite of the efforts made in matching the assumptions of simulation and analytical models.

DELAY

29. The results of the queueing delay estimates by the analytical models and ModelC are tabulated in *Table III* as a function of the degree of saturation. This facilitates a comparison of delay estimates as normalised values allowing for the differences between the capacity estimates from different models. The comparison of steady-state delay estimates from SR 45 and ModelC given in *Table III* are shown in *Figure 4*. The results show that the delay estimates from ModelC are close to the delay estimates from SR 45. The differences in queueing delays from the analytical models (SR 45, SIDRA) and ModelC at $x = 0.1$ are less than 0.5 sec. This indicates that the minimum delay estimates from these three models are very close. The differences in queueing delay estimates are seen to increase at high degrees of saturation (x approaching 0.95). The largest difference in queueing delay estimates from SR 45 and ModelC is at $x = 0.95$, at which point delay estimates are not very accurate as evidenced by large variation in simulation results.

30. The delays estimated by SIDRA and SR 45 methods are the same or very close for degrees of saturation less than 0.7 to 0.8. For higher degrees of saturation, the difference in delay between SIDRA and SR 45 increases. This is due to the time-dependent delay equation used in SIDRA as explained in *para. 16*. Since ModelC simulation was carried out in a steady-state fashion, the delays estimated by ModelC at high degrees of saturation are closer to the SR 45 estimates as expected.

TABLE III

Comparison of Delay Estimates from Analytical Models (SR 45/SIDRA) and Simulation (ModelC)

Circulating flow q_c (veh/h)	Degree of saturation x	Average queueing delay per vehicle (sec)		
		SR 45	Model C	SIDRA
450	0.10	1.7	1.3	1.7
	0.50	3.1	2.2	3.1
	0.70	5.2	3.7	5.1
	0.80	7.7	5.7	7.5
	0.85	10.3	6.6	9.8
	0.90	15.5	11.4	13.8
	0.925	20.7	15.2	17.1
	0.95	31.0	27.8	21.8
900	0.10	4.3	4.6	4.3
	0.50	7.8	7.0	7.7
	0.70	13.0	12.3	12.7
	0.80	19.4	18.1	18.2
	0.85	25.9	23.0	23.2
	0.90	38.9	39.9	30.7
	0.925	51.8	51.9	36.2
	0.95	77.7	64.1	43.3
1350	0.10	11.1	11.5	11.1
	0.50	20.0	19.4	19.8
	0.70	33.3	32.2	31.7
	0.80	49.9	44.6	43.5
	0.85	66.5	60.6	53.1
	0.90	99.8	98.4	65.5
	0.925	133.0	132.9	73.6
	0.95	199.5	186.6	83.1

SIDRA model with flow period = 0.5 h. ModelC simulation with warm-up period= 0.25 h and full simulation period = 0.5 h.

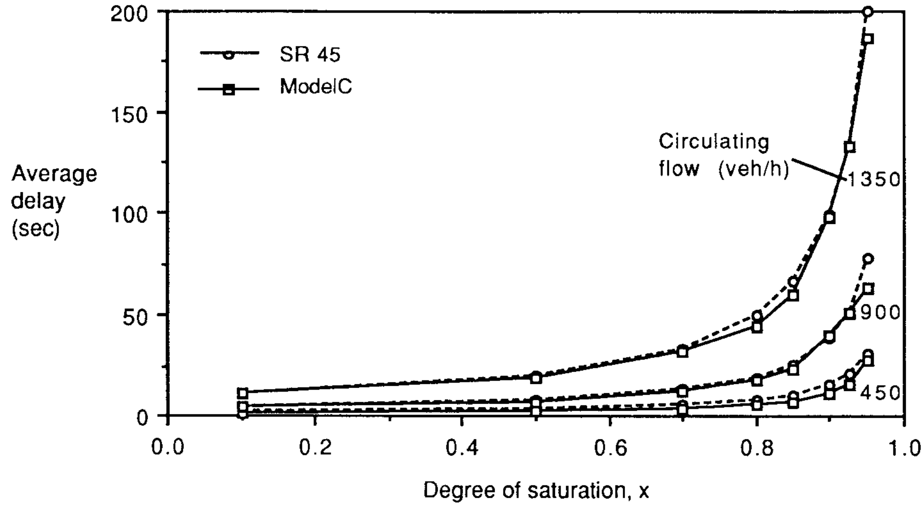

Fig. 4 – The comparison of steady-state delays from SR 45 and ModelC for low, medium and high circulating flows (as a function of the degree of saturation)

31. The steady-state delay estimates from SR 45 and ModelC as a function of the actual entry flow rates are shown in *Figure 5* (as opposed to the normalised results given in *Table III* and shown in *Figure 4*). Due to the random variations in simulation results coupled with differences in capacity estimates, *Figure 5* indicates more difference between delay estimates from SR 45 and ModelC compared with the results given in *Table III* and *Figure 4*.

INSECT-MODELC COMPARISON

32. As mentioned in *para. 27*, the analysis with the origin-destination flow pattern shown in *Figure 1* indicated that INSECT estimated much lower capacities and much higher delays compared with those from SR 45, SIDRA and ModelC. Considering that the simplistic flow pattern used in this analysis might have affected the results, the effect of different origin-destination flow patterns was investigated. The two simulation models INSECT and ModelC were compared for this purpose. The analysis was carried out for the medium circulating flow case of q_c = 900 veh/h only as it gave the closest results between ModelC and the analytical models as seen in *Table III*. The critical gap and follow-up headway values of 3.35 s and 2.46 s as predicted by the SR 45 / SIDRA method were used in these tests (*Table I*). It should be noted that INSECT manipulates the critical gap value specified by the user (*para. 24*). For ModelC, shifted negative exponential distribution of headways were used for all approaches of the roundabout for consistency with the INSECT model.

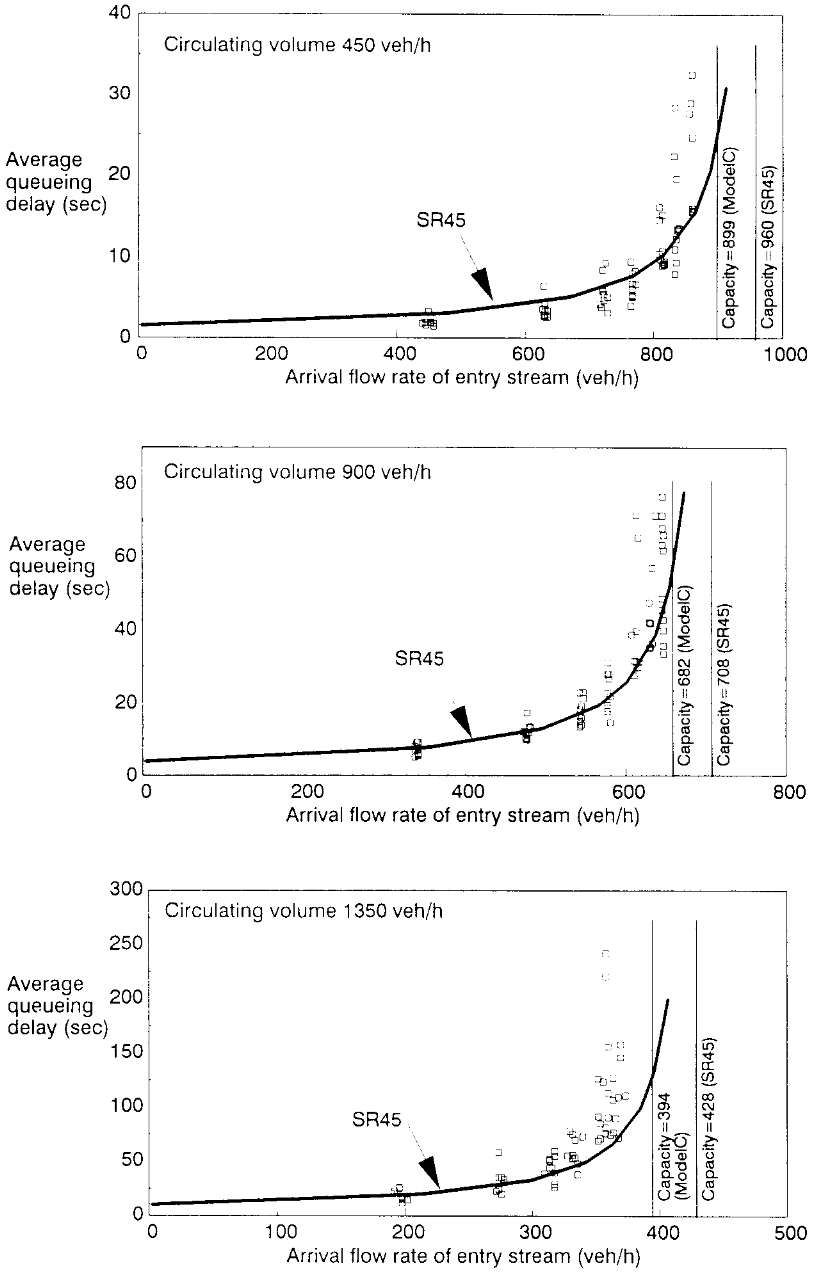

Fig. 5 – The comparison of steady-state delays from SR 45 and ModelC for low, medium and high circulating flows (as a function of the entry flow rate with capacity estimates shown)

33. Three origin-destination flow patterns were considered in terms of contribution to the circulating flow (q_c = 900 veh/h) for the South approach:

Pattern A: all circulating flow originates from the East approach as in *Figure 1* (900 veh/h through flow from East to West);

Pattern B: all circulating flow originates from the North approach (900 veh/h right turn flow from North to West); and

Pattern C: a balanced origin-destination pattern with 300 veh/h from North to West (right turn), 300 veh/h from North to South (through), 600 veh/h from East to West (through), as well as 450 veh/h from West to East (through).

For each origin-destination flow pattern, capacities were estimated using the method described in *para. 19*, and delays were estimated by varying the entry flow on the South approach from 100 to 600 veh/h. The results are given in *Table IV*. It is seen that the capacity and delay estimates from INSECT are over-sensitive to the origin-destination pattern of entry flows which contribute to a particular circulating flow. INSECT is found to be unstable in the cases of unbalanced arrival flow patterns (***Patterns A and B***) as evidenced by extremely high and low values of delay, respectively. In the case of the more balanced ***Pattern C***, the INSECT results are closer to those from ModelC (and therefore to those from the analytical models). Compared with INSECT, ModelC is seen to be less sensitive to changes in the origin-destination flow pattern. However, it indicates changes in capacity and delay estimates with changes in the origin-destination flow pattern. Note that ModelC results (***Pattern A***) in *Table IV* differ from the corresponding values in *Tables II and III* (for q_c = 900 veh/h) due to the difference in arrival headway distributions (see *para. 17 and 32*).

TABLE IV

Comparison of the Estimates of Average Delay (Seconds) and Capacity (veh/h) from ModelC and INSECT Simulation Models (Circulating Flow = 900 veh/h)

Entry flow rate q_e (veh/h)	MODELC			INSECT		
	Pattern A (All from East)	*Pattern B* (All from North)	*Pattern C* (From East+Nth)	*Pattern A* (All from East)	*Pattern B* (All from North)	*Pattern C* (From East+Nth)
100	4.1	2.9	3.6	15.6	0.0	7.2
200	3.9	3.6	4.5	19.6	0.0	9.7
300	5.6	4.6	5.7	28.8	0.1	11.7
400	9.1	6.4	7.7	60.0	0.1	16.3
500	20.7	11.9	13.3	–	0.1	21.6
600	–	47.2	39.6	–	0.3	28.5
Capacity	609	630	656	414	738	770

CONCLUSION

34. The capacities and queueing delays predicted by ModelC simulation model and the two analytical models, SR 45 and SIDRA are found to be sufficiently close given the difficulty in making the analytical and simulation model assumptions compatible. The differences in capacities predicted by SR 45 / SIDRA and ModelC are small (4 to 8 per cent difference). The steady-state delay estimates from SR 45 and ModelC also compare well. The minimum delay estimates by SR 45 / SIDRA and ModelC are very close. The differences in queueing delay estimates are seen to increase at high degrees of saturation ($x = 0.90–0.95$). Delay estimates at high degrees of saturation are not very accurate as evidenced by large variation in simulation results. When compared for a given degree of saturation, delays are closer because the effects of differences in capacities predicted by analytical and simulation models are reduced by this process. Earlier validation studies (Chung, et al 1992) showed that ModelC provides satisfactory prediction of roundabout performance. Comparisons of delay estimates from ModelC and various models available internationally also showed satisfactory agreement. These findings increase the confidence in the analytical models, and makes ModelC a useful tool for producing data for further development of analytical techniques.

35. ModelC indicates changes in capacity and delay estimates with changes in the origin-destination flow pattern of entry flows which contribute to a particular circulating flow. Compared to ModelC, INSECT capacity and delay estimates are found to be over-sensitive to the origin-destination flow pattern. When a balanced origin-destination flow pattern is used, INSECT capacity and delay estimates are sufficiently close to estimates from other models.

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