Paper presented at the ITE 2009 Annual Meeting, San Antonio, Texas, USA, August 2009

Evaluating Roundabout Capacity, Level of Service and Performance

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ABSTRACT

Results of research on roundabouts in the United States are presented in the NCHRP Report 572. The findings and recommendations of this report are important as they will be the basis of the 2010 Highway Capacity Manual methodology for operational analysis of roundabouts. This paper discusses various findings and recommendations of the NCHRP Report 572 on roundabout capacity and level of service. Discussions include issues related to the finding of lower capacity of roundabouts in the USA compared with Australian and UK roundabouts, and the choice of Level of Service (LOS) thresholds for roundabouts compared with those used for signalized and sign-controlled intersections. Capacity and the resulting degree of saturation (v/c ratio) estimates obtained using the NCHRP Report 572 and standard SIDRA INTERSECTION methods are compared by presenting single-lane and multi-lane roundabout examples. Importance of the basic findings of research on US roundabouts as presented in the NCHRP Report 572 is discussed. Various model extensions related to the use of the NCHRP 572 model in SIDRA INTERSECTION are discussed. An example is also given for modeling Roundabout Metering signals. Finally, the paper presents a discussion of the issue of possible increases in roundabout capacities in the USA over time due to changes in driver behavior.

INTRODUCTION

Based on a comprehensive evaluation of roundabouts in the United States, the NCHRP Report 572 *(1)* presented methods of estimating the operational and safety impacts of roundabouts. This paper focuses on the operational performance aspects of the report.

The NCHRP Report 572 stated "*Perceived differences in driver behavior raise questions about how appropriate some international research and practices are for the United States. … Under NCHRP Project 3-65, (the researchers) reviewed existing safety and operational models. After compiling a comprehensive inventory of roundabouts in the United States, they traveled to several representative ones to gather geometric, operational and safety data. … They then evaluated the different analytical models to determine how well they replicate U.S. experience.*"

On operational performance, the report concluded that "*Currently, drivers in the United States appear to use roundabouts less efficiently than models suggest is the case in other countries around the world. In addition, geometry in the aggregate sense (number of lanes) has a clear effect on the capacity of a roundabout entry; however, the fine details of geometric design (lane width, for example) appear to be secondary and less significant than variations in driver behavior at a given site and between sites.*".

The report proposed exponential models of capacity for single-lane and two-lane roundabouts, and recommended that level of service (LOS) criteria are the same as those currently used for unsignalized intersections.

The report also recommended that "*Because driver behavior appears to be the largest variable affecting roundabout performance, calibration of the models to account for local driver behavior and changes in driver experience over time is highly recommended to produce accurate capacity estimates.*" and stated that "*These models have been incorporated into an initial draft procedure for the Highway Capacity Manual (2010),which the TRB Committee on Highway Capacity and Quality of Service will continue to revise until its eventual adoption.*".

This paper discusses findings and recommendations of the NCHRP Report 572 on roundabout capacity and level of service. Discussions include issues related to the finding of lower capacity of roundabouts in the USA compared with Australian and UK roundabouts, and the choice of Level of Service (LOS) thresholds for roundabouts compared with those used for signalized and sign-controlled intersections.

The NCHRP Report 572 recognized the SIDRA INTERSECTION software (previously named aaSIDRA) developed in Australia by the author of this paper as one of the "*two major software implementations in use in the United States*" and included evaluation of the capacity model used in the software *(2)*.

The original roundabout capacity model in SIDRA INTERSECTION is based on research on Australian roundabouts *(3-16)* thus reflecting Australian driver characteristics. When the early results of the NCHRP 3-65 research were published *(17-19)*, indicating that capacities of roundabouts in the USA were significantly lower compared with the Australian and UK roundabouts, the SIDRA INTERSECTION capacity model was calibrated for US applications to provide capacity estimates closer to those observed in the USA. For this purpose, the Environment Factor parameter of the model was set to 1.2 as the default for US versions of SIDRA INTERSECTION while the value of this parameter for the original capacity model is 1.0. For the purpose of this paper, the US version of the SIDRA INTERSECTION roundabout capacity model with the Environment Factor value of 1.2 will be referred to as the "**SIDRA Standard**" model.

In SIDRA INTERSECTION Version 4 released recently, the roundabout capacity models proposed in the NCHRP Report 572 report have been implemented directly as an alternative to using the SIDRA Standard model. This model will be referred to as the "**NCHRP 572**" model.

This paper presents comparison of capacity and the resulting degree of saturation (v/c ratio) estimates obtained using the NCHRP 572 and SIDRA Standard models by presenting single-lane and multi-lane roundabout examples. Various model extensions related to the use of the NCHRP 572 model in SIDRA INTERSECTION are discussed. An example is also given for modeling Roundabout Metering signals *(20-22)*.

Importance of the basic findings of research on US roundabouts as presented in the NCHRP Report 572 is discussed. Finally, the paper presents a discussion of the issue of possible increases in roundabout capacities in the USA over time due to changes in driver behavior.

EXAMPLES

Two examples shown in *Figures 1 and 2* are used to compare estimates of capacity and degree of saturation (v/c ratio) from the SIDRA Standard and the NCHRP 572 capacity models.

For the SIDRA Standard capacity model, Environment Factor of 1.2 is used. For the NCHRP 572 capacity model, Origin-Destination factors or adjustment factors for Entry /Circulating Flow Ratio are not used, and the Capacity Constraint method applies in one case (see the discussion in the following sections).

For the NCHRP 572 model, the capacity equation for "single-lane roundabouts" is applied to all single-lane circulating road cases, including multilane approaches. For multi-lane approach lanes with multi-lane circulating roads, different equations apply.

For both capacity models, lane flows are determined according to the SIDRA INTERSECTION principle of equal degrees of saturation which assigns lower flow rates to lanes with lower capacity.

Analyses are carried out for 15-min peak period. The hourly flow rates calculated from 15-min peak volumes are shown in *Figures 1 and 2*. Peak Flow Factors are 1.0 due to the use of known peak flow rates.

Geometric parameters other than number of lanes and lane disciplines are not used in the NCHRP 572 model. Geometric parameters are applicable to the SIDRA Standard model only. Although geometric parameters have been shown in both metric and US customary units, the latter system is used in the analysis reported in this paper. The parameter values in metric and US customary units are not necessarily precise converted values.

Example 1: Single-Lane Four-Way Roundabout

This one-lane roundabout case (*Figure 1*) is based on the example described in Highway Capacity Manual 2000, Chapter 17, Part C *(23)*. The entry flows represent a fairly balanced origin-destination flow pattern.

The results from the SIDRA Standard and NCHRP 572 capacity models for this example are shown in *Table 1*. The capacities and degrees of saturation estimated by the two models are seen to be very close. This indicates that the use of the Environment Factor value of 1.2 in the SIDRA Standard model approximates the NCHRP 572 model closely, with slightly (about 3-4 %) lower capacities estimated by the SIDRA Standard model.

When the Environment Factor value of 1.0 is used, capacities are about 30 per cent higher for this example, corresponding to the Australian driving characteristics as represented by the original SIDRA model.

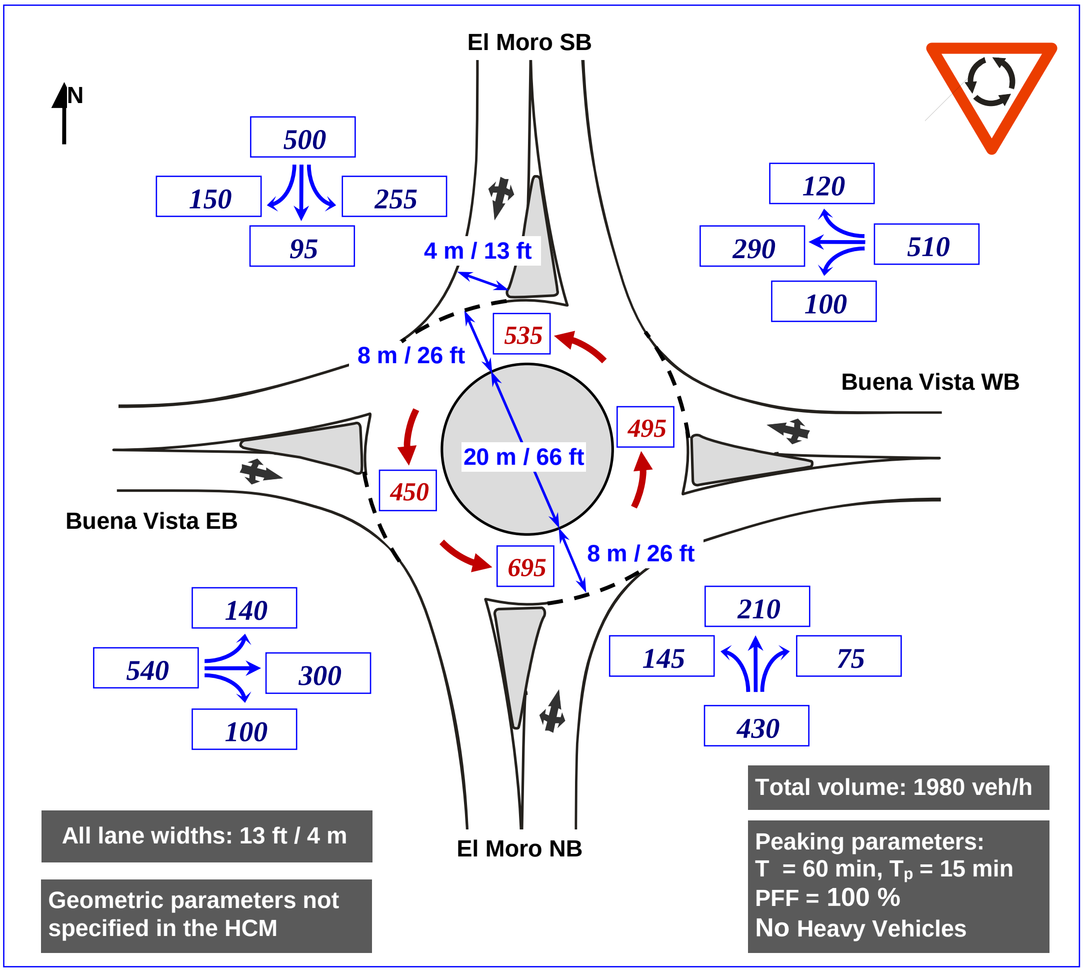

Figure 1 - Example 1: single-lane four-way roundabout given in HCM 2000, Chapter 17 *(23)*

Table 1 - Capacity results for Example 1 (single-lane four-way roundabout)

App. ID	Approach Name	Approach Flow (veh/h)	Circulating Flow (pcu/h)	Capacity (veh/h)	Degree of saturation (v/c ratio)
SIDRA Standard Capacity Model (Environment Factor = 1.2)					
S	El Moro NB	430	695	543	0.79
E	Buena Vista WB	510	495	671	0.76
N	El Moro SB	500	535	643	0.78
W	Buena Vista EB	540	450	703	0.77
NCHRP 572 Capacity Model					
S	El Moro NB	430	695	564	0.76
E	Buena Vista WB	510	495	689	0.74
N	El Moro SB	500	535	662	0.76
W	Buena Vista EB	540	450	721	0.75

Example 2: Two-Lane T-intersection Roundabout

This two-lane T-intersection roundabout example (*Figure 2*) is based on an example presented by Chard *(24,25)* who demonstrated the lack of sensitivity of the UK TRL linear regression model to different approach lane use arrangements. The case is presented for driving on the right-hand side of the road as applicable to US driving conditions. The volumes are modified in order to demonstrate the importance of approach and circulating road lane use issues as well as unbalanced flow conditions.

A variety of options are feasible for approach and circulating lane arrangements for this roundabout, using various combinations of approach roads with exclusive or shared lanes and single-lane or two-lane circulating roads. The following two cases are presented in *Figure 2* representing two different lane arrangements:

Case (i): The roundabout has two entry lanes and a single-lane circulating road for all approach roads. Approach lane disciplines are as shown in Figure 5a of Chard *(23)*. In this case, irrespective of specifying a single-lane or two-lane circulating road, all circulating streams would operate effectively as single-lane movements due to exclusive lane arrangements on approach roads (this reduces the capacity of the roundabout).

Case (ii): This is an alternative arrangement with two-lane approach roads with shared lanes and two circulating lanes for all approach roads. This arrangement increases capacities due to the better balance of flows in approach lanes to make use of available lane capacities as well as better opportunity to accept gaps in multi-lane circulating streams.

The geometry data for the two cases are summarized in *Table 2*. The inscribed diameter is the same (40 m / 132 ft) for both cases. Additional geometric parameters used in the UK TRL model are also given in *Table 2* for those who wish to analyse this example using the UK TRL capacity model *(13)*.

The circulating flow in front of each approach consists of traffic from one approach only at this roundabout. The entry and circulating flow rates indicate potential for unbalanced flow conditions.

Estimates of capacity and degree of saturation (v/c ratio) for the SIDRA Standard and NCHRP 572 models are given in *Table 3*. It is seen that the results are fairly close for Case (ii) but there are significant differences for Case (i) where capacity estimates from the NCHRP 572 method for the South and East approaches are lower resulting in higher degrees of saturation, especially for the East approach.

Nevertheless, both the SIDRA Standard and NCHRP 572 models identify the problem of unbalanced lane flows on the East approach, whereas the UK TRL model was shown to fail to indicate the problem for this approach *(13)* as originally demonstrated by Chard *(24,25)*. Both the SIDRA Standard and NCHRP 572 models give capacity estimates which differ significantly between Cases (i) and (ii) whereas the UK TRL model estimates for the two cases are the same.

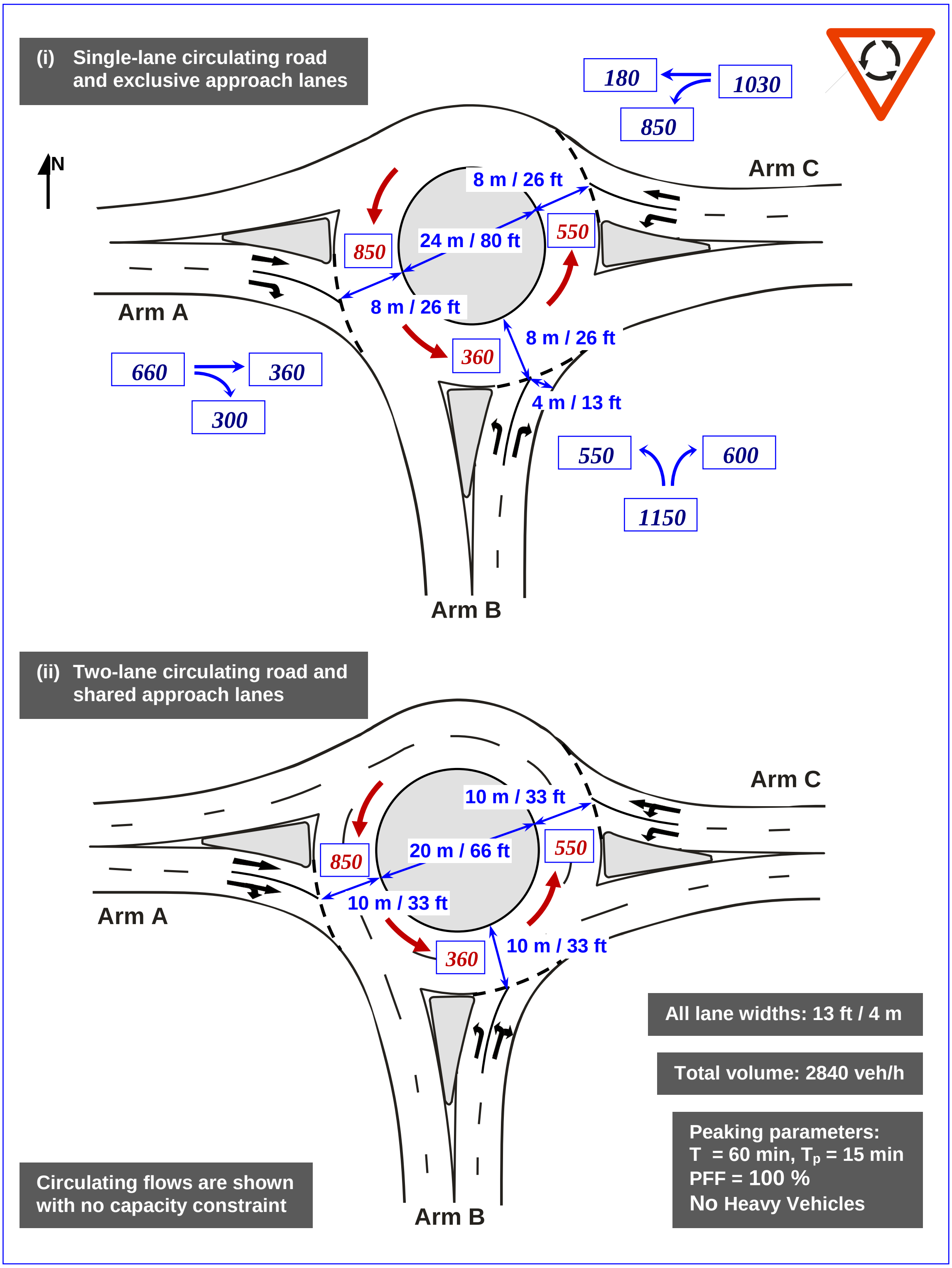

Figure 2 - Example 2: two cases of T-intersection roundabout lane arrangements based on an example given by Chard *(24, 25)*

Table 2 - Geometry data for the T-intersection roundabout

		Parameters common to cases (i) and (ii)							
Approach ID	Approach Name	Average entry lane width	Total entry width	Number of entry lanes	Inscribed diameter	Approach half width	Flare length	Entry radius	Entry angle
W	Arm A	13 ft (4 m)	26 ft (8 m)	2	132 ft (40 m)	23 ft (6 m)	33 ft (10 m)	66 ft (20 m)	40 ft (12 m)
S	Arm B	13 ft (4 m)	26 ft (8 m)	2	132 ft (40 m)	23 ft (6 m)	33 ft (10 m)	66 ft (20 m)	40 ft (12 m)
E	Arm C	13 ft (4 m)	26 ft (8 m)	2	132 ft (40 m)	23 ft (6 m)	33 ft (10 m)	66 ft (20 m)	40 ft (12 m)

		Case (i): Single-lane circulating road and exclusive approach lanes			Case (ii): Two-lane circulating road and shared approach lanes		
		Number of circulating lanes	Central island diameter	Circulating road width	Number of circulating lanes	Central island diameter	Circulating road width
W	Arm A	1	80 ft (24 m)	26 ft (8 m)	2	66 ft (20 m)	33 ft (10 m)
S	Arm B	1	80 ft (24 m)	26 ft (8 m)	2	66 ft (20 m)	33 ft (10 m)
E	Arm C	1	80 ft (24 m)	26 ft (8 m)	2	66 ft (20 m)	33 ft (10 m)

Both the SIDRA Standard and NCHRP 572 models estimate oversaturated conditions for the East approach (Arm C) in the case of single-lane circulating road with exclusive lanes, but estimate satisfactory operating conditions in the case of two-lane circulating road with shared lanes. These models estimate more favorable gap-acceptance conditions in the case of two-lane circulating flows, and the approach lane use is more balanced with shared lanes. The UK TRL model estimates satisfactory conditions for both cases *(13)*. Assumptions of the "approach" method used in the UK TRL model are close to the case of two-lane circulating road with shared approach lanes.

Using a lane-by-lane method, the SIDRA Standard and NCHRP 572 models identify critical lanes distinguishing between exclusive and shared lane cases and allowing for any unequal lane utilization, thus identifying oversaturation on the East approach in the case of single-lane circulating road with exclusive lanes. On the other hand, the TRL capacity model combines exclusive and shared lanes to obtain an average approach degree of saturation, and therefore cannot identify unequal lane utilization and cannot distinguish between different lane use arrangements.

SIDRA INTERSECTION estimates of delay, operating cost, fuel consumption and CO_2 emission comparing Cases (i) and (ii), i.e, the case of single-lane circulating road with exclusive lanes vs the case of two-lane circulating road with shared lanes shows that, considering annual values of one hour of traffic operation only, the difference between the two cases amount to approximately 5,600 person-hours of delay, US$57,000 in operating cost, 2,500 gal of fuel consumption and 24,000 kg of CO_2 emission per year (estimate based on the SIDRA Standard capacity model).

Table 3 - Capacity results for Example 2 (two cases of T-intersection roundabout)

App. ID	Approach Name	Total Approach Flow (veh/h)	Circulating Flow (pcu/h) *[1]*	Critical Lane *[2]*	Critical Lane Flow (veh/h)	Total Approach Capacity (veh/h)	Critical Lane Capacity (veh/h)	Degree of saturation (v/c ratio)
Case (i): Single-lane circulating road and exclusive approach lanes **SIDRA Standard Capacity Model (Environment Factor = 1.2)**								
W	Arm A	660	**825**	1 (T)	360	1006	539	0.67
S	Arm B	1150	360	2 (R)	600	1905	988	0.61
E	Arm C	1030	550	1 (L)	**850**	**1286**	**825**	**1.03**
Case (i): Single-lane circulating road and exclusive approach lanes **NCHRP 572 Capacity Model**								
W	Arm A	660	**850**	1 (T)	360	1178	589	0.61
S	Arm B	1150	360	2 (R)	600	1576	788	0.76
E	Arm C	1030	550	1 (L)	**850**	**1304**	**652**	**1.30**
Case (ii): Two-lane circulating road and shared approach lanes **SIDRA Standard Capacity Model (Environment Factor = 1.2)**								
W	Arm A	660	**850**	2 (TR)	330	1210	605	0.55
S	Arm B	1150	360	2 (R) *[3]*	600	1768	887	0.68
E	Arm C	1030	550	2 (LT)	**515**	**1438**	**719**	**0.72**
Case (ii): Two-lane circulating road and shared approach lanes **NCHRP 572 Capacity Model**								
W	Arm A	660	**850**	2 (TR)	337	1220	623	0.54
S	Arm B	1150	360	2 (R) *[3]*	600	1741	878	0.68
E	Arm C	1030	550	2 (LT)	**552**	**1517**	**769**	**0.68**

[1] In case (i), the circulating flow rate for the West approach includes capacity constraint effect due to oversaturation on East approach (x > 1.0). Circulating flows for Case (ii) are without any capacity constraint since all approach lanes are estimated to be undersaturated (x < 1.0).

[2] Approach degrees of saturation represent the critical lane degrees of saturation (L: Left, T: Through, R: Right). Average degree of saturation (Total App. Flow / Total App. Capacity) should not be used to represent the approach conditions.

[3] De facto Exclusive right-turn lane identified by the program (Lane 1 underutilised)

BASIC FINDINGS OF NCHRP REPORT 572

Importance of the basic findings of research on US roundabouts as presented in the NCHRP Report 572 should be recognized. This research confirmed that, although important, roundabout geometry alone is not sufficient for modeling capacity of roundabouts (as in the UK TRL model), and the model must also include driver behavior parameters (as in the Australian method). The report found the driver behavior is "*the largest variable affecting roundabout performance*" although "*geometry in the aggregate sense (number of lanes) has a clear effect on the capacity of a roundabout entry*".

The NCHRP Report 572 recognized the importance of lane-by-lane modeling of roundabouts, as the key aspect of the impact of roundabout geometry on capacity, and found that "*the fine details of geometric design (lane width, for example) appear to be secondary and less significant than variations in driver behavior at a given site and between sites*". This confirms the basic premises of the Australian method, and is in sharp contrast with the UK TRL method. It should be noted that all these methods are "empirical", but differ on identifying key elements of real-life processes that should be included in modeling roundabout capacity.

The NCHRP 572 exponential regression model is in fact a gap-acceptance model which uses the form of ***Siegloch M1*** gap-acceptance model *(15)*. NCHRP 572 accepts that the exponential regression model has a gap-acceptance model form but it does not identify it as the Siegloch M1 model. Instead it states that this is a simplified form of HCM 2000 gap-acceptance capacity model, which is the ***Traditional M1*** model *(15)*.

The Traditional M1, Siegloch M1 and Akçelik M1 models (all assuming random arrival headways) give very close results *(15)*. This is shown in *Figure 3* for an example using the default gap-acceptance parameter values of t_f = 3.186 s (follow-up headway) and t_c = 5.193 s (critical gap) corresponding to the NCHRP 572 single-lane roundabout model. It is seen that Akçelik M1 model gives slightly lower values for high circulating (opposing) flow rate. This is a good feature as the NCHRP report 572 states that the exponential regression model (Siegloch M1) "*tends to overestimate capacities at higher circulating flows*". It would be interesting to assess the ***Akçelik M1*** model using the NCHRP capacity data.

Details of the capacity models and assumptions about arrival headways (random or bunched) referred to in this section can be found in a paper by the author *(15)*.

The NCHRP Report 572 also showed that the capacity model using exponential regression and using the model parameters derived from average field values of the gap-acceptance parameters t_f and t_c are very close. Thus modeling capacity by a gap-acceptance method (using t_f and t_c parameters determined in the field in a "theoretical" gap-acceptance equation) and modeling capacity by direct regression using field capacities give very close results. This confirms the validity of gap-acceptance methodology for roundabout capacity modeling.

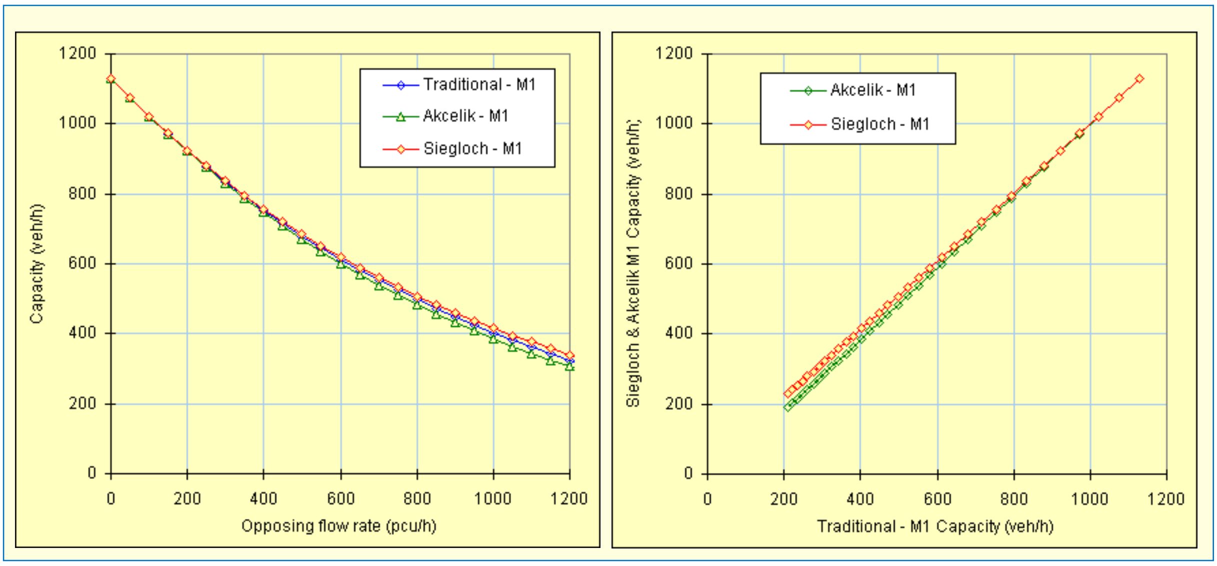

Figure 3 - Comparison of Traditional M1, Siegloch M1 and Akçelik M1 models
(example using t_f = 3.19 s, t_c =5.19 s)

MODEL EXTENSIONS

Direct implementation of the NCHRP 572 model in SIDRA INTERSECTION software (as an alternative tool for the implementation of Highway Capacity Manual procedures) has raised a number of issues which are listed below. These relate to possible extensions to the NCHRP 572 and HCM models.

In SIDRA INTERSECTION software, the NCHRP 572 model is applied to roundabouts with ***more than 2 lanes***. Lane-by-lane calculations to identify dominant and subdominant lanes as well as any de facto exclusive lane cases, and calculate lane flows and capacities accordingly, help with modeling of such roundabouts *(9, 13)*.

SIDRA INTERSECTION determines ***lane flows*** according to the *equal degree of saturation* principle subject to user-specified and program-determined lane underutilisation cases. This method allocates lower volumes to lanes with lower capacities. The methods that use the *equal lane volume* principle without considering lane capacities may end up allocating too much volume into low-capacity lanes, resulting in high degree of saturation and high delay, and therefore unreasonable lane flow distributions (i.e. implying that drivers choose lanes with higher delay). This may also manifest itself through inconsistent "critical lane" definition. The critical lane is the lane with highest degree of saturation, and a non-critical lane can have higher delay due to low degree of saturation and low capacity.

Modeling of ***short lane*** capacity is an important part of roundabout capacity modeling since such short lanes (flares) may be very effective in capacity terms at roundabouts. SIDRA

INTERSECTION uses a space-based capacity model for short lanes making use of gap-acceptance cycles (blocked and unblocked intervals) to determine excess flows overflowing from short lanes into adjacent lanes. Modeling of ***bypass lanes*** (slip lanes and continuous lanes) is also an important requirement.

Heavy Vehicle (HV) effects are usually taken into account by determining a ***HV factor*** to adjust opposing (circulating and exiting) flow rates, and follow-up headway and critical gap values, or to adjust capacity estimates directly. It is important that appropriate HV factors are calculated for ***each lane*** rather than the whole approach since different HV percentages for individual turning movements from an approach result in different HV percentages per lane according to lane flow allocations. Ability for the analyst to specify the ***heavy vehicle equivalent*** (default value of 2) as input per movement is useful for model calibration in specific situations where there are large commercial vehicles in particular turning movements.

The NCHRP Report 572 Appendix B describes a method for modeling ***pedestrian effects*** on roundabout entry lane capacity. Exit lane capacities as a function of pedestrian flows can also be determined for all roundabout legs using a gap-acceptance method. These methods have been included in SIDRA INTERSECTION, and are generally available for all versions of the software.

As recommended by the NCHRP Report 572, ***model calibration*** using the parameters of the exponential regression models is important for its applicability to different local conditions, and for accommodating changes in driver characteristics over time. This calibration is possible by specifying the exponential regression model parameters for individual approaches (with different parameters for single-lane and multi-lane cases), or specifying gap-acceptance parameters for individual movements, including right-turn bypass lane movements subject to yield condition (slip lane movements).

The ***Origin-Destination*** factor and adjustment factor for ***Entry /Circulating Flow Ratio*** for unbalanced flow conditions, which are important aspects of the SIDRA INTERSECTION roundabout model, can also be used in the NCHRP 572 capacity model in the software (optional). These are useful in dealing with specific conditions rather than relying on a regression method for general average conditions. For example, it is recognized that drivers can be more aggressive when the entry flow rate is very high. Iterative calculations are needed to apply the ***Origin-Destination*** factor since this factor depends on the demand flow pattern as well as the amount of queuing on approach lanes.

It is necessary to apply the ***capacity constraint*** method when one or more lanes are oversaturated (v/c ratio above 1). This method limits the amount of traffic that can enter the roundabout from each oversaturated lane to its capacity value. This affects the circulating and exiting flow rates of downstream approaches, thus requiring iterative calculations.

Extension of roundabout modeling to ***closely-spaced*** or ***multiple intersections***, including pedestrian crossings near intersections, is often required, for example, in the case of freeway interchange roundabouts. SIDRA INTERSECTION provides a *Capacity Adjustment* parameter which can be used to specify the amount of capacity reduction for upstream intersection lanes using the *probability of blockage* estimated for downstream intersection lanes where queue storage spaces are limited. This method can be employed with the NCHRP 572 model as well.

The *Extra Bunching* parameter can be used to model the effect of platooning caused by nearby ***upstream signals***. However, this is available with the bunched exponential model of headway distributions (M3D), therefore cannot be applied to the NCHRP 572 model based on the Siegloch M1 model which assumes random arrivals *(15)*.

All vehicles slow down to a safe negotiation speed at roundabouts, and therefore experience a ***geometric delay***. SIDRA INTERSECTION determines geometric delays as a function of approach and exit cruise speeds as well as the roundabout negotiation speeds, which depend on the geometric characteristics of the roundabout (negotiation radius and distance, and the associated speeds) as well the acceleration and deceleration characteristics of vehicles.. Geometric delays are added to queuing delays, and are considered to be part of the control delay. This is included when the NCHRP 572 capacity model is used as well. Determination of geometric delay is depicted for a left-turn movement in *Figure 4*.

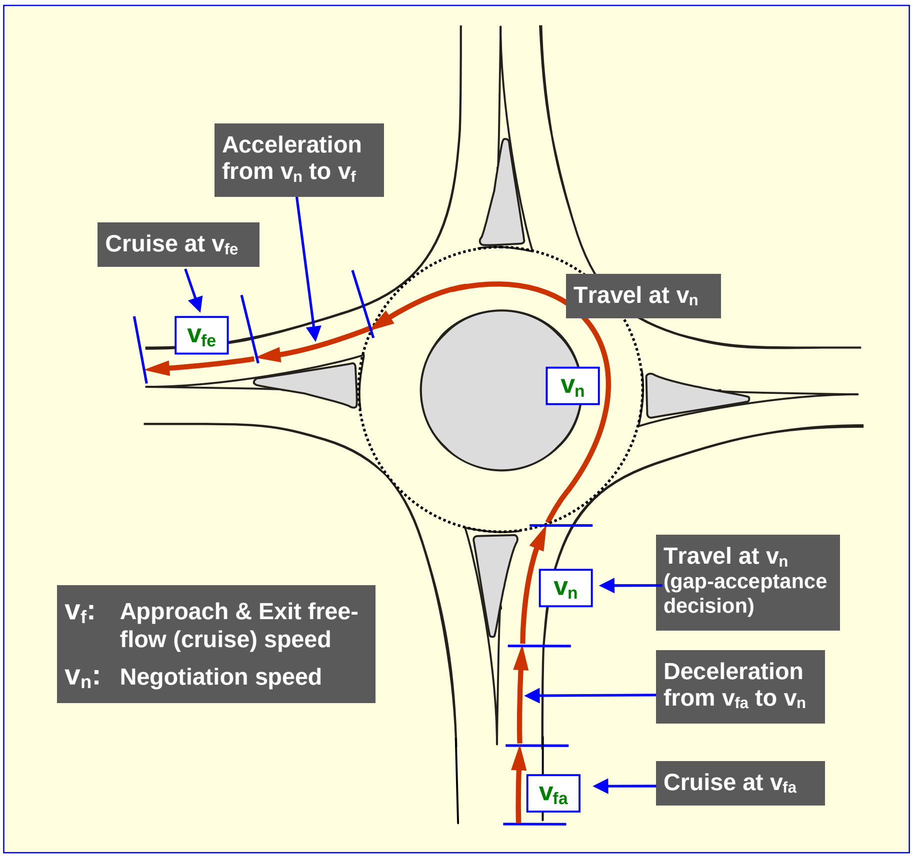

Figure 4 - Geometric delay parameters

Back of queue and ***stop rate*** estimates, as well as ***fuel consumption***, ***emission*** (including CO_2) and ***operating cost*** estimates consistent with the NCHRP 572 exponential regression models for capacity estimation are important model extensions offered by SIDRA INTERSECTION.

For unsignalised intersections, HCM 2000 gives a ***cycle-average queue*** rather than a back of queue. The average queue length that incorporates all queue states including zero queues is called the cycle-average queue length, and is determined as the product of the average queuing delay per vehicle and the flow rate. This includes the instances with zero queues. On the other hand, HCM 2000 Chapter 16 (Signalized Intersections) uses the back of queue concept. For consistency, SIDRA INTERSECTION gives back of queue estimates in all output reports for unsignalised intersections as well. Cycle-average queues are also given in the queue length tables for information only.

The NCHRP Report 572 recommended that ***Level of Service*** (LOS) criteria for roundabouts are the same as those currently used for unsignalized (sign-controlled) intersections. The use of sign-controlled intersection LOS thresholds for roundabouts would favor signalized intersections against roundabouts by allocating a better LOS grade for a given delay, therefore introducing a bias against roundabouts in assessment of alternative intersection treatments. This is of particular concern due to low capacity estimates from the NCHRP 572 model compared with capacities observed in Australia and UK. Higher capacities from the models derived in Australia and UK might indicate potential increases in capacities of US roundabouts which could be achieved over time (this is discussed in a later section in this paper).

Use of LOS for critical lane of each approach would create further bias against roundabouts when compared with other intersections since the estimation of LOS using average delay per approach is common for other intersection types, and use of average delay for intersection LOS is available for signalized intersections. All of these LOS estimates are available in SIDRA INTERSECTION.

SIDRA INTERSECTION offers options for choice of ***alternative LOS criteria for roundabouts*** including a ***SIDRA Roundabout LOS*** option with thresholds between those for signal and stop-sign control. The thresholds used when this option is selected are presented in columns titled Roundabouts in *Table 4* (LOS based on delay only), *Table 5* (LOS based delay and degree of saturation) and *Table 6* (LOS based on degree of saturation only). In *Tables 4 and 5*, the delay thresholds for the *SIDRA Roundabout LOS* option are the same as LOS thresholds for signals for LOS A, B and C. In *Table 6*, the practical (target) degrees of saturation for different intersection types are used as the LOS C/D limit.

The default LOS thresholds for the NCHRP 572 method in SIDRA INTERSECTION are the ***same as signalized intersections*** as in the SIDRA Standard method. Furthermore, a ***LOS Target*** parameter can be used to specify the acceptable LOS level for particular intersection types, e.g. for design life analysis.

For all intersection types, SIDRA INTERSECTION output reports include "Worst Movement Delay", "Worst Lane Delay", "Worst Movement LOS" and "Worst Lane LOS" values which could be used together with approach and intersection values in performance assessment. Worst Lane LOS is available as design life target.

Table 4 - Level of Service definitions for VEHICLES based on DELAY only

Level of Service	Control delay per vehicle in seconds (d)		
	Signals	Roundabouts	Stop and Give-Way / Yield Signs
A	d ≤ 10	d ≤ 10	d ≤ 10
B	10 < d ≤ 20	10 < d ≤ 20	10 < d ≤ 15
C	20 < d ≤ 35	20 < d ≤ 35	15 < d ≤ 25
D	35 < d ≤ **55**	35 < d ≤ **50**	25 < d ≤ **35**
E	**55** < d ≤ 80	**50** < d ≤ 70	**35** < d ≤ 50
F	80 < d	70 < d	50 < d

Table 5 - Level-of-service definitions for VEHICLES based on both DELAY and DEGREE OF SATURATION

Level of Service	Control delay per vehicle in seconds (d)			Degree of saturation (v/c ratio) (x)
	Signals	Roundabouts	Stop and Give-Way / Yield Signs	
A	d ≤ 10	d ≤ 10	d ≤ 10	0 < x ≤ 0.85
B	10 < d ≤ 20	10 < d ≤ 20	10 < d ≤ 15	0 < x ≤ 0.85
C	20 < d ≤ 35	20 < d ≤ 35	15 < d ≤ 25	0 < x ≤ 0.85
D	35 < d ≤ 55	30 < d ≤ 50	25 < d ≤ 35	0 < x ≤ 0.85
	0 < d ≤ 55	0 < d ≤ 50	0 < d ≤ 35	0.85 < x ≤ 0.95
E	55 < d ≤ 80	50 < d ≤ 70	35 < d ≤ 50	0 < x ≤ 0.95
	0 < d ≤ 80	0 < d ≤ 70	0 < d ≤ 50	0.95 < x ≤ 1.00
F	80 < d	70 < d	50 < d	1.00 < x

Table 6 - Level-of-service definitions for VEHICLES based on DEGREE OF SATURATION only

Level of Service	Degree of saturation (x) ***SIDRA Method***			Degree of saturation (x) ***ICU Method***
	Signals	Roundabouts	Stop and Give-Way / Yield Signs	All intersection types
A	x ≤ 0.60	x ≤ 0.60	x ≤ 0.60	x ≤ 0.60
B	0.60 < x ≤ 0.70	0.60 < x ≤ 0.70	0.60 < x ≤ 0.70	0.60 < x ≤ 0.70
C	0.70 < x ≤ **0.90**	0.70 < x ≤ **0.85**	0.70 < x ≤ **0.80**	0.70 < x ≤ 0.80
D	**0.90** < x ≤ 0.95	**0.85** < x ≤ 0.95	**0.80** < x ≤ 0.90	0.80 < x ≤ 0.90
E	0.95 < x ≤ 1.00	0.95 < x ≤ 1.00	0.90 < x ≤ 1.00	0.90 < x ≤ 1.00
F	1.00 < x	1.00 < x	1.00 < x	1.00 < x

Roundabout metering signals can be used to create gaps in the circulating stream in order to solve the problem of excessive queuing and delays at approaches affected by highly directional flows *(20-22)*. The use of metering signals is a cost-effective measure to avoid the need for a fully-signalized intersection treatment. The Roundabout metering analysis method in SIDRA INTERSECTION can be used with capacities estimated using the NCHRP 572 method as well. This subject is further discussed in a separate section below.

Potential Differences from the NCHRP 572 Capacity Model Estimates

Given the above model extensions, the following is a summary of ***potential differences*** from the original NCHRP 572 capacity model estimates:

- SIDRA INTERSECTION solution is based on the *equal lane utilisation* (equal lane degree of saturation) principle unless exclusive lanes are specified by the user or defacto exclusive lane cases are identified by the program. This means that lane flows will differ for cases of multi-lane entry and circulating flows since dominant and sub-dominant lane capacities are different.
- When one or more lanes are oversaturated (v/c ratio above 1), *capacity constraint* will apply, and the capacity estimates of downstream entry and slip lanes will be affected due to reduced circulating and exiting flow rates.
- The *Origin-Destination* factor is not used by default. If used, this will affect the capacity estimates significantly, resulting in lower capacity estimates depending on balance of O-D demand patterns.
- Default setting for *Entry /Circulating Flow Ratio adjustment* is *Medium*, and this may affect the capacity estimates, resulting in slightly higher values than the original NCHRP 572 estimates. This effect can be removed by setting the parameter to *None*.
- If the *HV Method for Gap Acceptance* is selected as *Include HV Effect if Above 5 per cent*, then the HV effect on capacities will be less, therefore capacity estimates will be larger, generally.
- Delay formula used will be the standard SIDRA INTERSECTION model, including geometric delays determined according to the approach and exit cruise speeds and roundabout negotiation speeds.

ROUNDABOUT METERING SIGNALS

The use of roundabout metering signals is a cost-effective measure to avoid the need for a fully-signalized intersection treatment. Roundabout metering signals are installed on selected roundabout approaches and used on a part-time basis since they are required only when heavy demand conditions occur during peak periods. The Roundabout metering analysis method in SIDRA INTERSECTION can be used with capacities estimated using the NCHRP 572 method as well *(20-22)*.

A typical arrangement for roundabout metering signals and an example from Melbourne, Australia *(21)* are shown in *Figure 5* (picture modified to show driving on the right-hand side of the road). The term *Metered Approach* is used for the approach stopped by red signals (approach causing problems for a downstream approach), and the term *Controlling Approach* is used for the approach with the queue detector, which is the approach helped by metering signals.

When the queue on the Controlling Approach extends back to the queue detector, the signals on the Metered Approach display red (subject to signal timing constraints) so as to create a gap in the circulating flow. This helps the Controlling Approach traffic to enter the roundabout. When the red display is terminated on the Metered Approach, the roundabout reverts to normal operation.

The introduction and duration of the red signal on the Metered Approach is determined by the Controlling Approach traffic. The duration of the blank signal is determined according to a minimum blank time requirement, or extended by the metered approach traffic if detectors are used on that approach.

Two-aspect yellow and red signals are used for metering signals. The sequence of aspect display is Off to Yellow to Red to Off. When metering is not required neither aspect is displayed. Various site-specific methods may also be used to meter traffic, e.g. using an existing upstream midblock signalized crossing on the metered approach.

The Australian Traffic Signal Guide *(26)* recommends the use of a minimum of two signal faces, one primary (signal face mounted on a post at or near the left of the stop line on the approach) and one tertiary (signal face mounted on a post on the downstream side to the left of that approach) for driving on the left-hand side of the road. A regulatory sign STOP HERE ON RED SIGNAL is fixed to any signal post erected adjacent to the stop line on the Metered Approach, as drivers do not expect to stop at the advance stop line location. Stop lines are located not less than 3 m / 10 ft in advance of the give-way (yield) line but are preferably positioned approximately 20 m / 70 ft from the give-way (yield) line. Queue detector setback distance on the controlling approach is usually in the range 50-120 m / 150-400 ft.

In some cases, it may be necessary to supplement the traffic signals with explanatory fixed or variable message signposting. Where sight restrictions exist, advance warning signals are considered.

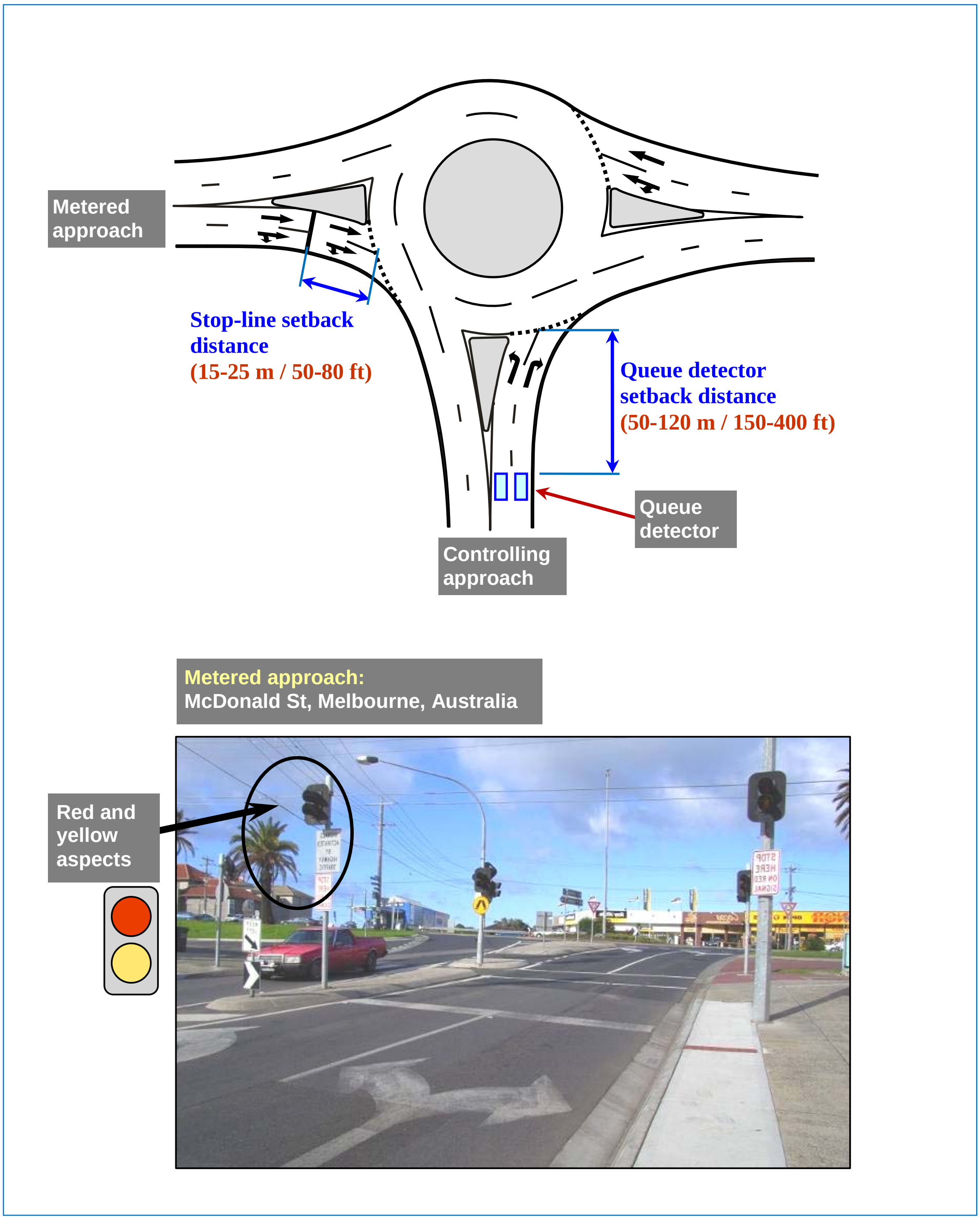

Figure 5 - Roundabout metering signals

Table 7 - Example 2, Case (i) with and without roundabout metering signals (results using the SIDRA Standard Capacity Model with Environment Factor = 1.2)

App. ID	Approach Name	Total Approach Flow (veh/h)	Circul. Flow (pcu/h) *[1]*	Critical Lane *[2]*	Critical Lane Flow (veh/h)	Total Approach Capacity (veh/h)	Critical Lane Capacity (veh/h)	Degree of saturation (v/c ratio)
Without roundabout metering signals								
W	Arm A	660	**850**	1 (T)	360	1006	539	0.67
S	Arm B	1150	360	2 (R)	600	1905	988	0.61
E	Arm C	1030	550	1 (L)	**850**	**1286**	**825**	**1.03**
With roundabout metering signals								
W	Arm A	660	**850**	1 (T)	360	1383	742	0.49
S	Arm B	1150	360	2 (R)	600	1294	671	0.89
E	Arm C	1030	550	1 (L)	**850**	**1604**	**971**	**0.88**

An example for modeling roundabout metering signals is given here for Example 2, case (i) presented above. In this example, the Arm B (South) is the Metered Approach and Arm C is the Controlling Approach. As seen in *Table 7* which presents results when the SIDRA Standard capacity model is used, the metering signals are seen to balance the degrees of saturation on these approaches. The timings producing the results in *Table 7* are: Cycle Time = 100 s, Blank Time = 67 s, Red Time = 33 s

FUTURE CAPACITY INCREASES

The NCHRP Report 572 found lower capacities at US roundabouts compared with those in Australia and UK. The question arises about whether capacity of US roundabouts will increase over time due to " *changes in driver experience over time*". Higher capacities from the models derived in Australia and UK might indicate potential increases in capacities of roundabouts which could be achieved in the USA with increased driver familiarity and increased driver aggressiveness due to higher demand and congestion levels at roundabouts in the future.

Rodegerdts *(18)* suggested that possible reasons for lower capacities at US roundabouts include driver unfamiliarity with roundabouts as a relatively new control device, larger vehicles, prevalence of stop control, especially use of all-way stop control and lack of use of two-way yield control, and lack of use of turn signals on exits causing driver hesitation during the yield process.

The factors for and against possible increase in roundabout capacities in the USA over time could be as follows.

For:

- In addition to the expected increase in efficiency in driver behaviour due to increased familiarity, one could consider that increased congestion levels due to increased demand levels will also result in more aggressive driver behaviour.

- The capacity is also affected by vehicle length (or queue space including gaps between vehicles in queue) and acceleration capability. If we consider that vehicle length will be reduced (effect of fuel cost and push for more efficient vehicles) and acceleration capabilities will improve in the future, then we would expect capacity increases associated with this as well.

Against:

- In terms of the all-way stop control and two-way yield control at minor intersections, the practice in Australia is opposite to the US practice, i.e. all-way stop control is almost non-existent, and two-way yield signs are used commonly. If this difference is a significant factor affecting driver characteristics at roundabouts (more hesitant drivers who come to a complete stop before accepting gaps, resulting in lower capacities), it would be hard to speculate if this aspect of US driving culture and traffic control environment would not continue to affect roundabout capacities in the future. Note that lower gap-acceptance parameters are used in Australia for sign-controlled intersections as well, compared with those specified in HCM 2000 based on US research on sign-controlled intersections.

- Recent roundabout research in Australia as part of our roundabout metering research *(18)* indicated that, on average, the follow-up headway and critical gap values in Australia did not change much since 1980s in spite of significant increases in demand and congestion levels at roundabouts.

- Preference for larger vehicles may not change over time, or changing vehicle population may mean somewhat reduced acceleration capabilities.

A method described by the author *(27)* for analyzing the relationship between capacity and driver behavior can be used to explore the question. The method uses the queue discharge headway (follow-up headway at roundabouts and sign-controlled intersections) as a key parameter that determines capacity, and expresses the queue discharge headway as a function of the driver response time during queue discharge, spacing between vehicles in the queue (jam spacing) and saturation (queue discharge) speed:

$$h_s = t_r + L_{hj} / v_s \qquad (1)$$

where h_s = the saturation (queue discharge) headway (seconds), t_r = driver response time during queue discharge (seconds), L_{hj} = queue space per vehicle (jam spacing) including the vehicle length and the gap distance between vehicles in the queue (metres or feet), and v_s = saturation speed (m/s or ft/s).

Equation (1) shows the importance of vehicle length and driver alertness which affect not only the driver response time but also the queue discharge speed and the gap distance left between vehicles in the entry lane queue (e.g. less gap under pressure of high traffic demand levels, more gap during bad weather conditions or uphill grade, and so on).

Application of *Equation (1)* to roundabouts was discussed previously *(27)*. This considered the Environment Factor value of 1.2 used in SIDRA INTERSECTION to calibrate the model to achieve lower capacities observed in the USA. Consider *Example 1* given in this paper (one-lane roundabout with a central island diameter of 20 m / 66 ft and circulating road width of 8 m / 26 ft, and with no heavy vehicles).

For the South approach, the software estimates a negotiation speed of v_{en} = 24.8 km/h (15.4 mph), hence v_s = 6.89 m/s (22.6 ft/s) and a follow-up headway of t_f = 2.91 s (= h_s) with the SIDRA Standard capacity model. Using a jam spacing of L_{hj} = 7.62 m (25 ft), which is the default value in the US version of SIDRA INTERSECTION, a driver response time of t_r = 2.91 - 7.62 / 6.89 = 1.8 s is determined.

Using an Environment Factor of 1.0 as in the original model, the SIDRA Standard capacity model estimates a follow-up headway of t_f = 2.40 s, which implies a driver response time of t_r = 1.3 s. This means that, all other factors being the same (including a jam spacing of L_{hj} = 7.62 m / 25 ft) and roughly speaking, a decrease of 0.5 s in the US driver's response time could achieve roundabout capacity values observed in Australia (30 per cent higher capacity in *Example 1*). Using a jam spacing of L_{hj} = 7.0 m (23 ft) to account for smaller vehicles, which is the default value in the non-US versions of SIDRA INTERSECTION, a driver response time of t_r = 2.40 - 7.0 / 6.89 = 1.4 s is determined. In this case, about 0.4 s of the 0.5 s decrease in the follow-up headway is attributed to the driver response time and about 0.1 s is attributed to the reduced vehicle length.

This analysis indicates that small reductions in driver response times due to the reasons considered above could result in significant capacity increases at US roundabouts over time. The parameters of the NCHRP 572 model can be calibrated accordingly and further analysis of possible capacity increases over time could be carried out.

CONCLUDING REMARKS

It is recommended that issues raised in this paper are further investigated. This should be done not only in relation to alternative analytical models, but also in investigating the assumptions regarding driver characteristics used in microsimulation modeling.

ACKNOWLEDGEMENTS

The author is the developer of the SIDRA INTERSECTION model, and comments presented in this paper regarding other models should be read with this in mind.

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