

## REPRINT

# SIDRA for the Highway Capacity Manual

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### REFERENCE:

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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 Though some aspects of this paper may be outdated, this reprint is provided as a record of important aspects of the SIDRA INTERSECTION software, and in order to promote software assessment and further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.

## SIDRA for the Highway Capacity Manual

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### INTRODUCTION

**SIDRA (Signalized Intersection Design and Research Aid)** is a software package developed by the Australian Road Research Board as an aid for *capacity, timing and performance* analysis of signalized intersections. First released in 1984, SIDRA was in use for *practice, research and teaching* in 140 organisations/sites in 23 countries as of April 1990.

With input and output facilities at individual turn, lane, lane group, approach road, movement grouping and intersection levels, SIDRA provides a flexible structure which allows multilevel analysis of very simple to very complex intersection conditions. The ability of the user to *calibrate* SIDRA models for local conditions is an important feature of SIDRA.

The capacity and timing analysis methods used in SIDRA have evolved from the ARRB Research Report ARR No. 123 (1), and are now substantially more advanced. Extensive documentation is available on SIDRA (2-14). General reviews of Australian research on traffic signals are also available (15,16).

The 1985 Highway Capacity Manual (HCM) (17) introduced various improvements to the existing signalized intersection analysis methods, and brought the Australian and U.S. methodologies closer together. Many suggestions have been made to further improve the methodology for signalized intersection analysis described in the HCM and implemented in the Highway Capacity Software (HCS) package (18), and work is in progress towards this end (19-37).

This paper presents information about the HCM option in SIDRA and discusses various aspects of the HCM/HCS methodology as well as the proposals to modify it. An application of SIDRA to an example from the HCM is presented. For more detailed information on the HCM option in SIDRA, the reader is referred to SIDRA document DN 1709 (14).

### THE HCM VERSION OF SIDRA

A Highway Capacity Manual option has been implemented fully in SIDRA version 3.2 (11-14) in order to facilitate the comparison of the SIDRA and HCM methodologies, and to incorporate some useful features of the HCM into SIDRA for the benefit of its users. In turn, this has resulted in identifying various areas for potential improvement in the HCM methodology which should benefit the users and developers of the HCM and HCS.

Although the HCM version of SIDRA was basically developed for research purposes, it is fully developed for use by practitioners who may wish to take advantage of the more detailed analysis method offered by SIDRA (analysis in US or metric units is allowed). SIDRA will be distributed in the USA and internationally by the McTRANS transportation software distribution centre.

The HCM version of SIDRA answers many suggestions put forward by US researchers and practitioners for the improvement of the HCM methodology (19-37). The HCM option in SIDRA uses the capacity (basic saturation flow adjustment factors) and delay model parameters of the HCM in order to calibrate the general SIDRA models. This is done through a Default Values File which is accessible to the user (11). Detailed user guides and technical notes are available for the users of the HCM version of SIDRA (11,14).

Progression factors by arrival type for the effect of platooned arrivals on delay, the use of peak hour factor, and models for conflicting pedestrian volumes, parking and bus effects on saturation flows are the main features of the HCM that have been incorporated into SIDRA and made available to all SIDRA users. An output table which presents capacity, degree of saturation (*v/c ratio*), delay and level-of-service information in the HCM/HCS style is available.

Various features of SIDRA which are considered to be enhancements to the HCM/HCS methodology are described in this section.

#### Lane-by-Lane Analysis

Lane-by-lane level of detail used for capacity and performance (delay, queue length, etc.) modelling is a fundamental feature of SIDRA. The lane-by-lane method, which is also used in the Canadian and Swedish methods (38,39), offers many advantages over the *lane group* method which is used in the HCM/HCS as well as the UK OSCADY method (40). Eliminating the need to combine various approach lanes as lane groups provides freedom in movement description, and ensures more accurate and, in principle, simpler modelling.

#### Lane Flows and De Facto Lanes

SIDRA carries out lane flow calculations as an integral part of the capacity estimation process. Effective (*de facto*) exclusive lanes are established explicitly as part of this process. Lane underutilisation factors, parking and bus parameters, etc. can be specified by the user for individual lanes. Explicit modelling of lane flows helps the traffic engineer to design efficient lane arrangements.

Various problems of the HCM/HCS methodology in determining *de facto* exclusive lanes have been discussed in an unpublished note by the author (41). A limitation of the HCM method is to assume a right turn adjustment factor of 1.0 in lane flow calculations, neglecting the effect of conflicting pedestrian flows.

Some incorrect solutions have been obtained from the HCS package in heavy right turn volume cases. For example, consider the case where cycle time = 90 s, green time = 45 s, three lanes with basic saturation flow of 1800 tcu/h, through (T) volume of 400 veh/h, right-turn (R) volume of 600 veh/h, and ideal conditions except for a conflicting pedestrian volume of 400 ped/h.

The results summarised in Table 1 show the contrast between the HCS and SIDRA results. This example demonstrates an important problem with capacity analysis

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methods based on lane groups which give no information to the user about the individual lane flows and effective lane disciplines.

In Case (a), the HCS solution implies that right-turns can depart from 3 lanes (which may not be possible physically), and this is in spite of the user specification of right turns from Lane 3 only. In case (b), the HCS solution identifies Lane 2 as a de facto exclusive through lane, whereas the SIDRA solution indicates that Lane 2 should be a de facto exclusive right-turn lane.

In both cases, the two solutions are drastically different in terms of delays and degrees of saturation. The HCS solutions are incorrect in both cases. In Case (a), the SIDRA solution indicates that no through vehicle would benefit from going into Lane 3 (higher x, higher delay). The HCS solution indicates a satisfactory design, but it does not relate to the lane arrangement specified by the user. In fact, the specified lane arrangement would cause serious problems in practice if adopted for design. In Case (b), no through vehicle would benefit from going into Lane 2, but the lane flows are fairly well balanced, yielding a low degree of saturation. On the other hand, the HCS solution suggests that the specified lane arrangement will give an unacceptable solution. Contrary to the HCS solution, right-turns should be allowed to go into Lane 2 as specified by the user.

**Table 1**  
**Comparison of SIDRA and HCS results for a simple example for de facto lane identification with heavy right turn volumes**

Specified Lane Dis.	SIDRA Solution			HCS Solution		
	Effective Lane Dis.	Deg. of Sat., x	Delay d (sec)	Implied Lane Dis.	Deg. of Sat., x	Delay d (sec)
<b>Case (a)</b>						
T	T	0.222	9.8	T R	0.465	11.3
T	T	0.222	9.8	R		
T R	R	1.011	48.5	R		
			33.0			
<b>Case (b)</b>						
T	T	0.444	11.4	T	1.011	48.4
T R	R	0.505	122	T		
R	R	0.505	122	R		
			11.9	32.9		

**Two Green Periods**

The use of two green periods with different saturation flows is essential for accurate modelling of protected-permitted turns (1,21) as well as slip lanes and turns on red. Much development effort has gone into modelling capacity and performance, determining critical movements (periods) and computing signal timings with two green periods per cycle, and the results have been incorporated into SIDRA.

The alternative method of combining the two green periods with an average saturation flow as in the UK OSCADY program (40) is not considered to be satisfactory for modelling capacity and performance. The HCM method for protected-permitted turns has various limitations (5,6,9,21,23,33), and the HCS method of providing the user with options to split arrival volumes

between the two green periods does not seem to give a satisfactory result although it is an improvement over the HCM method.

**Permitted (Opposed) Turns**

A unique feature of SIDRA is to model opposed (permitted) turns by the *lost time method* which treats blocked intervals as effectively red (1,9,11). This method usually results in a shorter effective green time for a lane with opposed turns compared with adjacent through traffic lanes. This method cannot be used for shared lanes unless a lane-by-lane analysis method is adopted. It gives more accurate capacity and performance prediction compared with the *adjustment factor method* which is associated with the method of analysing by lane groups (8,9).

Using the lost time method, explicit modelling of protected-permitted turns, slip lanes, turns on red, etc. is achieved in a general way for exclusive and shared lanes without need for the use of complicated adjustment factor equations.

The opposed turn model used in SIDRA takes into account the number of lanes and the individual lane characteristics of opposing movements (there can be several of them) in estimating the blocked interval lengths and filter turn saturation flow rates. The parameters of the gap acceptance model used for this purpose can be specified for individual movements. The user can also specify different priority rules for opposed and opposing turns. For opposed turns from shared lanes, a variable number of vehicles turning at the end of green time is allowed as in the HCM, but the user can specify the maximum number of vehicles that can depart. A detailed discussion of the subject can be found in references (8-11).

**Lane Blockage in Shared Lanes**

In shared lanes, *lane blockage* is modelled explicitly and in a very general way that allows for any type of interaction between movements in the lane. The model predicts capacities due to departures before being blocked using *free queues* and lane flows as variables, and treats the intervals of no departure (i.e. when the lane is blocked) as *lost time* (or effective red). This model is useful for all cases of opposed turns in shared lanes including the complicated cases of protected-permitted turns, slip lanes and turns on red.

**Right Turn on Red**

The HCM/HCS method for estimating the effects of right turns on red (RTOR) is to subtract the RTOR volume from the total right-turn volume. This method is inadequate since the RTOR volume should vary depending on intersection geometry, volumes and signal timings. At the same time, the volume subtraction method is never a satisfactory method for performance estimation (full flow rates are needed for predicting lane blockage effects, short lane capacities, queue lengths, delays, etc.).

SIDRA offers a comprehensive method of modelling RTOR, which makes use of the general opposed turn (protected-permitted) and shared lane modelling features employed in SIDRA (14). The method is similar to the gap acceptance based method described in a recent paper (37), but it is a fully developed capacity and performance prediction method. The same method is also applicable to traffic in *slip lanes*.

**Short Lanes**

Capacities of *short lanes* (turn bays, or lanes with parking upstream) are modelled in a detailed way. *Excess flows* from short lanes are added to adjacent lane flows when the queue storage capacities are exceeded. This is an important aspect of signalized intersection operation which has been neglected in the HCM/HCS and the OSCADY program, while the Canadian and the Swedish methods allow for short lanes (38,39).

### Saturation Flow Adjustment Factors

SIDRA accounts for the effect of *turn radius* on saturation flow explicitly. In addition to the HCM method of adjusting saturation flows, the effect of conflicting pedestrian streams on turning traffic can be accounted for by using the lost time (effective red time) method. In modelling this type of effect on saturation flows, including opposed turn modelling, there is no limitation in terms of left or right turns, i.e. the models are generally applicable to all types of turns.

Variable passenger car equivalents are used for turning heavy vehicles as a function of the turn radius and conflicting pedestrian volume. The concept of excess headway equivalent has been introduced for this purpose (11).

### Volume Adjustment

In modelling unequal lane utilisation, protected-permitted turns, slip lanes, turns on red, etc., SIDRA does not adjust or manipulate arrival flow rates. Arrival flows are always used in vehicle units, and are only adjusted for peak hour factors and flow scales (growth factors). Arrival flows are never reduced in lieu of capacity effects (e.g. for RTOR effects in the HCS). All capacity effects are modelled by adjusting saturation flows and effective green times. This achieves a consistent method in capacity and performance prediction as discussed in ARR No. 123 (1).

Thus, the SIDRA method is in agreement with a suggestion by Strong (33) to modify the HCM volume adjustment method for lane underutilisation. However, Strong's suggestion that peak hour factors should also be applied as saturation flow adjustments rather than demand volume adjustments is not agreed with. This issue needs to be discussed in relation to variable demand modelling.

### Heavy Vehicle Data

Heavy vehicle volumes can be specified as percentage or actual vehicle values. Different heavy vehicle percentages can be specified for individual movements (lane groups). Different values of queue space per vehicle are used for light and heavy vehicles in order to determine queue lengths. These values also affect short lane capacities which depend on the number of available queue spaces. SIDRA calculates queue lengths for individual lanes according to the traffic mix in the lane.

### Performance Measures

The performance measures predicted by SIDRA include not only delay and queue length but also such characteristics as the number of stops, fuel consumption, pollutant emissions and operating costs. Fuel consumption is estimated using a four-mode elemental model which is based on ARRB work that won an ITE award in 1986 (42,43). The parameters of this model can be specified for local vehicle and driving characteristics (11).

In SIDRA, delay can be defined as *stopped or overall* delay. Levels of service are determined accordingly (11,14). The HCM progression factors for delay calculations are applied on a lane by lane basis. Since individual lanes in a lane group can have different degrees of saturation, and a shared lane can have turns with different arrival types, SIDRA calculates flow weighted average progression factors for movements (lane groups) which may differ from the corresponding HCS results. SIDRA allows the user to specify signal and arrival types for individual movements (lane groups), and uses an *uncoordinated turn* type. These features help to overcome various limitations of the HCM method as discussed by Strong (33).

SIDRA provides a generalised delay formula which can be calibrated through the Default Values File (7,11). Comments on an article by Burrow (44) about the generalised delay model are given in the Appendix.

An important issue in the calibration and application of delay equations is the use of the delay formula for individual lanes (as in SIDRA and the Canadian and Swedish models) rather than lane groups (as in the HCM/HCS and the OSCADY program). In multi-lane cases, smaller delays are obtained with the application of the delay formula on a lane group basis as discussed previously (2).

For example, consider arrival and saturation flow rates of 800 and 1600 veh/h per lane for one, two and four lane cases with identical conditions for individual lanes ( $\gamma = 0.5$ ). For cycle time = 100 s, effective green time = 50 s (hence,  $x = 1.0$ ) and progression factor = 1.0, SIDRA HCM version predicts an average delay of 43.7 s. On the other hand the HCS package will predict decreasing delays with increasing number of lanes in the lane group (43.5, 36.3 and 31.2 s, respectively). This may lead to misleading results in evaluating signal design options since higher delays may be predicted when lane arrangements are changed from shared lanes to exclusive lanes, e.g. from (L,T,T), which is a lane group with two lanes, to (L,T) which is two lane groups with one lane each (L = Left, T = Through).

The lane-by-lane application of the delay formula will also give better results in the case of unequal lane utilisation. These comments apply to all performance parameters (delay, queue length, stop rate, etc.).

### Level-of-Service Options

SIDRA offers the following Level-of-Service definitions as options (11,14):

- Delay only (stopped delay as defined by the HCM, or overall delay including stop-start delays);
- Both *delay* and the *degree of saturation* ( $v/c$  ratio) as specified by Berry (20);
- The *degree of saturation* only when delay calculations are not carried out (a SIDRA option); this could be useful for planning analysis purposes, e.g. see Cassidy and May (27);
- The *density* for uninterrupted movements (as specified in Chapters 3 and 7 of the HCM, but using passenger car space equivalents).

### Movement Data

In SIDRA, different ideal saturation flows, free queues (for lane blockage), speeds, queue spaces per vehicle, progression factors (signal and arrival types), etc. can be specified for individual movements. These different movement parameters are taken into account in shared lane capacity and performance predictions. The facility for *mixed flows* (a more advanced form of the TRANSYT shared stop-line facility) enhances this process.

### Critical Movement Analysis

SIDRA employs a very general *critical movement identification* method as a basis for computing *signal timings* (cycle time and green splits) for simple as well as complex phasing arrangements. The basic principles of the method have been described in ARR No. 123 (1), and the method has been improved in SIDRA to handle the case of two green periods per cycle.

Unlike the HCM critical movement analysis method, the SIDRA method takes right turns into account. Any combination of overlap movements and two separate green periods per cycle for any movement are allowed. Different minimum and maximum green time constraints and different practical (maximum acceptable) degrees of saturation can be specified for different movements. Selected movements and individual green periods can be specified as *Undetected* in order to eliminate them from the critical movement analysis.

The limitations of the HCM critical movement analysis method as specified for the planning analysis procedure (24,27,34,35) include:

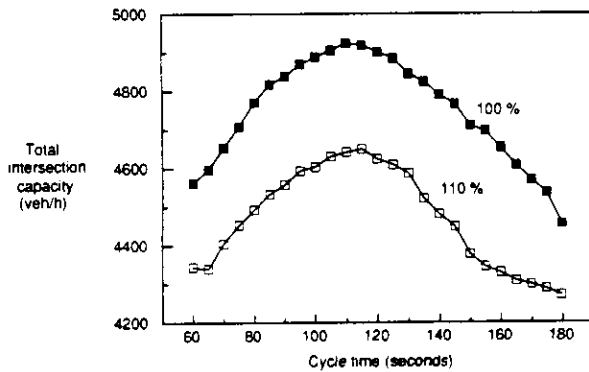
- (a) neglecting right turn movements, e.g. Eastbound right-turn lane should be critical in the HCM Example 4 (p.9-57) revised geometry case;
- (b) neglecting minimum (and any maximum) green times;
- (c) independence from cycle time (SIDRA uses *required times* in critical movement analysis which indicates that critical movements may change depending on the cycle time, especially because of minimum green time requirements);
- (d) *implying* a specific phasing arrangement (as a result, it is not generally applicable, e.g. it does not apply to a simple two-phase arrangement with permitted turns).

**Signal Timings**

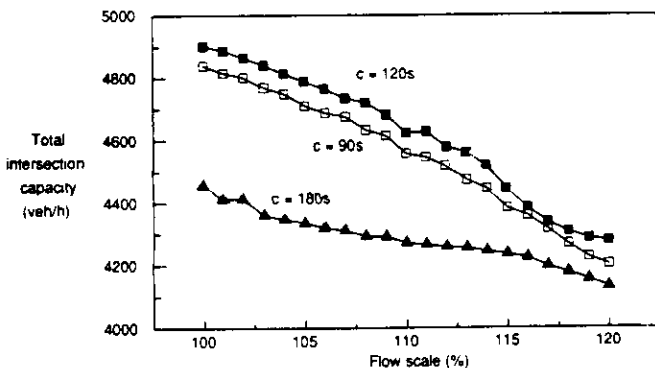
SIDRA can be used to determine both the cycle time and green splits, or only the green splits for a given cycle time. Alternatively, both cycle time and green splits can be given for capacity and performance estimation only. The user can specify *green split priorities* for selected movements, for example, for major road traffic (11,45). *Undetected movement and phase deletion* facilities are also available.

**Variable Cycle Time**

A *variable cycle time* facility allows the user to establish the relationship between the cycle time and capacity and other performance measures. An interesting feature of SIDRA is to indicate that the capacity can decrease as a result of increased cycle time. An example is given in *Figure 1* (see reference (12) for details).



**Fig. 1 - Example showing a decrease in total intersection capacity with increased cycle time (for flow scales of 100 and 110 per cent)**



**Fig. 2 - Example showing a decrease in total intersection capacity with increased demand flow level (for cycle times of 90, 120 and 180 s)**

**Variable Flow Scale**

Sensitivity analyses and intersection design life calculations can be carried out using the *variable flow scale* facility of SIDRA. This allows the user to change demand flow levels for all movements or for a selected group of movements. SIDRA results indicate that increased demand flow levels often result in decreased capacities. An example is given in *Figure 2* (see reference (12) for details).

**Iterative Method**

SIDRA employs an *iterative approximation* method of computation. *Main iterations* are carried out to allow for the interdependence of capacity and timing parameters, and *sub-iterations* are carried out to allow for the interdependence of capacities and lane flows of approach roads using the same signal phase (particularly with opposed turns in shared lanes).

**EXAMPLE**

A SIDRA Input Data Preparation Form for the HCM Example 3 (p. 9-50), and selected tables from SIDRA output (run with the timings calculated in the HCM) are given in *Figures 3 and 4*. Although SIDRA and HCS gave close results for the intersection degree of saturation, delay and level of service, substantial differences were found in left turn capacity and delay predictions. Problems of the HCM/HCS method with capacity and delay prediction for permitted left turns in this example were discussed previously (5,6); also see Bonneson and McCoy (21). Signal timing results from SIDRA were close to those calculated in the HCM (c = 120 s with up to 5 s difference in green times), the main difference being mainly due to the deletion of Phase B by SIDRA.

**Table 2**

**Intersection delay and LOS results for the HCM Example 3: Effects of lane utilisation and right turn on red (RTOR) \***

Cycle Time c (sec)	Deg. of Satur. X	Aver. Delay d (sec)	Level of Service	Longest Queue (vehs)	Fuel Eff. (mi/ga)
<b>Without RTOR</b>					
Unequal lane utilisation (LUF = 1.05)					
120	0.958	259	D	34.0	19.4
Equal lane utilisation (LUF = 1.00)					
86	0.940	203	C	23.4	19.9
Difference between unequal and equal lane utilisation cases		2 %	22 %	31 %	3 %
<b>With RTOR</b>					
Unequal lane utilisation (LUF = 1.05)					
120	0.947	245	C	32.6	19.5
Equal lane utilisation (LUF = 1.00)					
87	0.930	190	C	22.9	20.1
Difference between unequal and equal lane utilisation cases		2 %	22 %	30 %	3 %
<b>RTOR Benefits</b>					
Unequal lane utilisation (LUF = 1.05)					
1 %	5 %	†	4 %	1 %	
Equal lane utilisation (LUF = 1.00)					
1 %	6 %	-	2 %	1 %	

\* Based on SIDRA timings (single run; 1-sec. cycle increment; maximum cycle time = 120 s).

† LOS changes from D to C, but the delay change is marginal.

A R R B - S I D R A 3.2

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 Australian Road Research Board  
 Rahmi Akcelik Registered User No. 1  
 Time and Date of Analysis 17:04:02 1990-04-30

HCM EXAMPLE 3 (P.9-50) RTs and LTs as SEPARATE Movs .... \* US3A \*  
 Short lanes neglected; Unequal lane util. --- TIMINGS GIVEN

SIDRA US Highway Capacity Manual (1985) Version

Cycle Time = 119

Table S.15 - CAPACITY AND LEVEL OF SERVICE (HCM METHOD)

Mov No.	Mov Typ	Green Time Ratio (g/C)		Total Flow (veh/h)	Total Cap. (veh/h)	Deg. of Satn (v/c)	Prog. Factor	Aver. Delay (sec)	LOS
		1st grn	2nd grn						
EASTBOUND APPROACH									
12	L	.025		71	76	.939	.85	88.2	F
11	T	.244		318	447	.712	.85	30.4	D
13	R	.244		106	165	.641	.85	29.4	D
Mov. Group:				495	688	.939		38.5	D
WESTBOUND APPROACH									
22	L	.092		118	119	.989*	.85	86.1	F
21	T	.244*		600	612	.981	.85	50.7	E
23	R	.244		23	26	.882	.85	42.9	E
Mov. Group:				741	757	.989		56.1	E
NORTHBOUND APPROACH									
32	L	.042	.462	134	350	.383	.85	6.0	B
31	T	.597*		1645	1707	.964	.85	23.8	C
33	R	.597		89	103	.867	.85	18.4	C
Mov. Group:				1868	2159	.964		22.2	C
SOUTHBOUND APPROACH									
42	L	.084*	.084	195	231	.844	.85	33.5	D
41	T	.639		934	1768	.528	.85	7.8	B
43	R	.639		78	164	.475	.85	7.5	B
Mov. Group:				1207	2163	.844		11.9	B
Intersection:				4311	5971	.989		27.0	D

Level of Service calculations are based on stopped delay.

\* Maximum v/c ratio, or critical green periods

Table S.6 - INTERSECTION PERFORMANCE

Total Flow (veh/h)	Total Delay (veh-h/h)	Aver. Delay (sec)	Total Stops (veh/h)	Stop Rate	Perf. Index	Aver. Speed (mi/h)	F U E L Eff. (mi/ga)	Total (ga/h)
4311	32.39	27.0	3757	.87	248.81	23.6	19.2	127.2

Progression Factors apply to delays only.

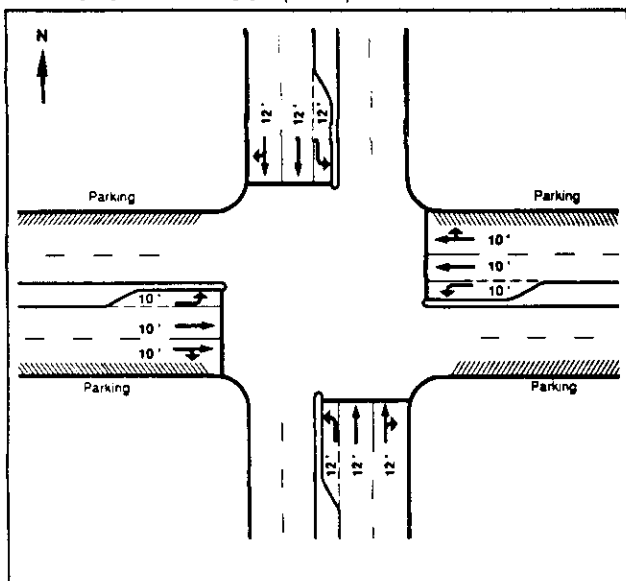
Queue length and stops are based on random arrivals (no platooning).

Fig. 4 - SIDRA output tables S.15 and S.6 (summary form) for the example in Fig. 3

## SIDRA INPUT DATA PREPARATION FORM (FOR RIGHT-HAND DRIVING)

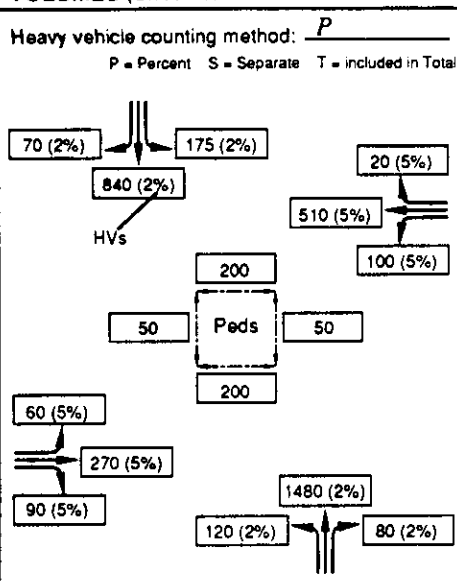
Prepared by : Rahmi Akcelik Computer File Name : US3A  
 Date : April 1990 Reference No. : \_\_\_\_\_  
 Intersection Title : HCM Example 3 (p. 9-50)  
 Run Description : Short lanes neglected; Unequal lane utilisation

### INTERSECTION LAYOUT (Description: \_\_\_\_\_)



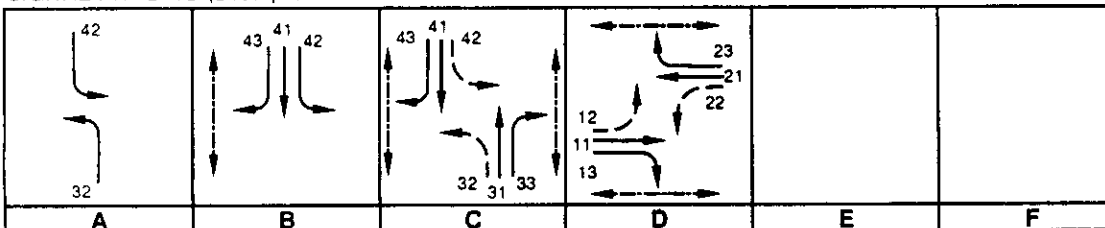
Include lane disciplines, short lane lengths, grades, etc.  
 Enter a description such as existing or proposed.

### VOLUMES (Unit time: 60 min)



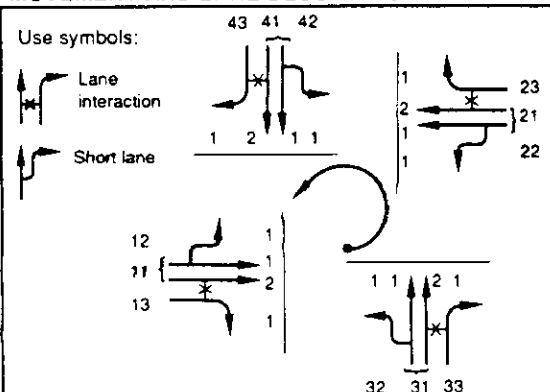
Show pedestrian volumes if necessary.

### SIGNAL PHASING (Description: \_\_\_\_\_)



→ Vehicle movement      ← Pedestrian movement      - - - Opposed turns

### MOVEMENT AND LANE DESCRIPTION



### OTHER FEATURES

- Area type: CBD (Env. code=2)
- Peak Hour Factors:  
 E-W: PHF=0.85, N-S: PHF=0.90
- Signal type: Actuated ( $x_p=0.95$ )
- Arrival type: 3 (PF=0.85) for all movs
- Lane underutil.: LUF=1.05 for (T+R) lanes
- Parking: E-W:  $N_p=5$ . All grades=0
- All movements:  $I=1=3$  s (unopposed)
- Mov. 42: start loss in Phase C=0
- Mov. 12: end departures  $n_{fm}=2.5$
- $G_{min}=22$  s (pedestrians)
- HCM timings:  $c=119$  s,  $F_i=0.8, 13, 87$

Specify movement types, turn types, timing data, etc.

Fig. 3 - SIDRA Input Data Preparation Form for the HCM Example 3 (p. 9-50)

To demonstrate the effects of RTOR and lane utilisation factors, the SIDRA results with and without RTOR, and with equal and unequal lane utilisation (LUF = 1.00 and 1.05) are given in Table 2. It is seen that the assumption about unequal lane utilisation implies substantial deterioration of intersection performance. The delay benefits from RTOR for this example (which has small right-turn volumes in shared lanes) are of the order of 5 per cent.

For detailed discussion of the application of SIDRA to Examples 1 to 5 of the signalized intersection chapter of the HCM, the reader is referred to SIDRA document DN 1709 (14).

## CONCLUSION

While this paper has described many features of SIDRA which could be used to overcome various limitations of the current HCM/HCS methodology, it should be pointed out that SIDRA is by no means a perfect model. Since its first release, it has been under continuous revision either by developing new models and techniques through research at ARRB in response to user feedback, or by using the results of research carried out elsewhere (including some features of the HCM). It has various aspects which need further improvement (12).

Currently, SIDRA is being enhanced to incorporate models for roundabouts, other unsignalized intersections and paired/large intersections to make it a comprehensive intersection analysis tool that uses consistent methodology. Models for predicting delays, queue lengths and stop rates for platooned arrivals, geometric delay and stopped delay calculations as a function of the intersection geometry and traffic conditions, and a variable phasing facility are among the improvements planned.

A graphics-based input data editor allowing for approach-based data specification has been under development, and it is hoped that it will be released with the next major version of SIDRA.

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#### APPENDIX

##### A NOTE ON THE GENERALISED DELAY MODEL

This brief note is a response to an article by Ian Burrow (44). Burrow discussed the author's generalised delay formula (7) which brings together the Highway Capacity Manual (17), Australian (1), Canadian (38), and the TRANSYT (46,47) formulas. Burrow presented a formula which he claimed to provide "a more general form including all of the previous expressions". Burrow also discussed the effects of assumptions related to variable-demand conditions on delay estimates. In this note, it is shown that Burrow's claim that he presented a more general form of the delay formula for constant-demand conditions is misplaced. A full response to Burrow's article is to be published elsewhere.

It should be noted that the generality of the author's model is not only due to the parameters of the delay model, but also due to its formulation through the *overflow queue* concept which allows the estimation of the overflow terms of delay, queue length and number of stops in a simple and

consistent manner. As such, the Australian method is significantly different from the TRRL method discussed by Burrow. There are also differences in the definitions of delays and queue lengths in the TRRL and Australian methods. It is therefore important that efforts to bring different methods into a generalised modelling framework should be carried out in an overall capacity and performance prediction context with consistent definitions.

Furthermore, it is suggested that limiting the discussion of the issue of delay model generality to the overflow delay term only may be misleading. For example, the modelling of the uniform delay term allowing for two separate green periods per cycle may have more important implications in many real-life cases. It is also important that delay estimation should not be discussed in isolation from capacity estimation, especially in the case of modelling variable-demand conditions.

In this context, the application of delay models on a lane-by-lane basis (as in SIDRA) rather than a lane group basis (as in OSCADY), and the effect of platooned arrivals on the overflow queue/delay should be mentioned as important issues largely ignored in the literature to date.

### A General Overflow Delay Formula for Constant-Demand Conditions

Burrow proposes that his Equation 3 for constant-demand (and zero initial queue) conditions presents a more general overflow delay formula than the author's formula (7). To show that this claim is misplaced, the following *unsimplified* form of the overflow term of the delay equation can be considered:

$$d_0 = 900 T x^n [ (x - 1 - \alpha') + \sqrt{(x - 1 - \alpha')^2 + 4 \alpha' (x - x_0)} ] \quad (1)$$

for  $x > x_0$  (zero otherwise)

where

- $d_0$  = average overflow delay per vehicle in seconds,
- $T$  = flow period in hours,
- $x$  = degree of saturation,
- $x_0$  = the degree of saturation below which the overflow delay is zero, and
- $\alpha'$  = the positive value of the  $\alpha$  term introduced by Burrow:

$$\alpha' = -\alpha = 2\gamma/QT \quad (2)$$

where

- $\gamma$  = main parameter of the delay model, and
- $Q$  = capacity in vehicles per hour (=  $sg/c$  where  $s$  = saturation flow rate in vehicles per hour,  $g$  = effective green time,  $c$  = cycle time),

Equation 1 here differs from Equation 1 of the author's earlier article (7) only in replacing  $(x - 1)$  by  $(x - 1 - \alpha')$ . Equation 1 with the  $\alpha'$  term is the *unsimplified* formula found by applying the coordinate transformation technique, originally conceived by Whiting for use in the TRRL TRANSYT program and developed in detail for a variety of queueing situations by Kimber and Hollis (49), to the following formula for steady-state overflow delay,  $d_{OS}$ , developed by the author (48) as an approximation to Miller's overflow delay formula (50):

$$d_{OS} = \frac{\gamma (x - x_0)}{Q (1-x)} \quad (3)$$

for  $x > x_0$  (zero otherwise)

where  $x$ ,  $x_0$ ,  $Q$  and  $\gamma$  are as in Equation 1. Note that  $x^n$  in Equation 1 was introduced as a calibration factor after coordinate transformation.

An acceptable simplification to Equation 1 is to neglect  $\alpha'$  in  $(x - 1 - \alpha')$  as adopted in the original TRANSYT (46) formula. This simplification causes only a slight overestimation of the overflow delay value around capacity, which is of the order of 1 to 2 per cent (negligible considering the uniform delay term also). Contrary to what Burrow's article suggests, this simplification does not make the model less general since parameter  $\alpha'$  is still in the formula. Replacing  $(x - 1 - \alpha')$  by  $(x - 1)$  and putting  $\alpha' = 2\gamma/QT$ , Equation 1 can be written as:

$$d_0 = 900 T x^n [ (x - 1) + \sqrt{(x - 1)^2 + 8\gamma (x - x_0)/QT} ] \quad (4)$$

for  $x > x_0$  (zero otherwise)

Thus, Equation 4 is equivalent to the overflow delay term in Equation 1 of the author's earlier article (7). This model is seen to have the same generality as the formula proposed by Burrow in including parameter  $\gamma$ , but is *more general* due to the  $x_0$  parameter which allows for *capacity per cycle* which is not included in TRRL models. The reader is referred to papers by Sosin (51,52) and Olszewski (53) as well as earlier papers (49,51) about the importance of the *capacity per cycle* parameter.

Parameter  $\gamma$  in Equations 3 and 4 corresponds to parameter  $k$  in Equation 7 of the author's earlier article (7). Parameter  $k$  is the same as parameter  $\gamma$  in Burrow's model, and  $\alpha'$  and  $\gamma$  in Equations 1 to 4 in this note are related to parameters  $m$  and  $k$  in Equation 1 of the author's earlier article (7) through

$$m = 4 \alpha' QT = 8\gamma = 8k \quad (5)$$

Thus, the following conclusions apply to Burrow's Equation 3 and Table 1 ("TRRL model"):

- (a) There is no need to introduce parameter  $\alpha'$  (or  $\alpha$ ) if the simplified equation which neglects  $\alpha'$  in  $(x - 1 - \alpha')$  is adopted as in Equation 4. Defining parameter  $\alpha$  as zero for models other than Burrow's Equation 3 is not correct (this does not make sense in terms of its definition unless  $\gamma = 0$ ).
- (b) Parameter  $m = 4\gamma$  for Burrow's Equation 3 is not correct since  $m = 8\gamma$  for all models generally. In other words, all models have a  $\gamma$  parameter defined as  $\gamma = m/8$ . Thus, the HCM, Canadian and original TRANSYT models have  $\gamma = 0.5$ , the Australian model has  $\gamma = 1.5$  and the alternative HCM model has  $\gamma = 1.0$  (the reason for high values of the  $\gamma$  parameter in the Australian and the alternative HCM models is the  $x_0$  parameter).
- (c) The introduction of parameter  $\beta$  is unnecessary. The unsimplified form of the model (Equation 1) shows that the use of parameter  $\alpha'$  (or  $\alpha$ ) is sufficient. However, note that the main parameter is  $k$  (or  $\gamma$ ), and the introduction of parameter  $\alpha'$  (or  $\alpha$ ) is useful only for the unsimplified form of the formula as it provides a convenient form of the model. Furthermore, the definition of  $\beta = -x_0$  for the Australian model is not correct;  $x_0$  is a different parameter which comes from the steady-state delay model (Equation 3). Parameter  $x_0$  is unique to the Australian model and it makes it a more general model than Burrow's proposed model which has no equivalent parameter. Also note that the use of parameters  $\alpha$  and  $\beta$  throughout the second last paragraph of the first column in page 30 of Burrow's article is the wrong way round (i.e.  $\alpha$  and  $\beta$  need to be transposed).

As stated by Burrow, the generality of *Equations 1 and 4* helps to provide a single delay model which is useful for a variety of situations. This has been useful towards the development of the SIDRA package as a comprehensive intersection analysis tool which can be applied to signalized, roundabout and other unsignalized intersections. Delay model parameters for these applications (as well as an uninterrupted travel model) can be set by the user in the SIDRA Default Values File. As in TRRL models,  $k = 1.0$  and  $x_0 = 0$  are used as standard default values for unsignalized intersections.

In conclusion, the  $x_0$  parameter in the Australian model offers an additional facility to calibrate the performance model. In expressing  $x_0$  as a function of *capacity per cycle* ( $sg$ ), the Australian method (49,51) offers a more general model than TRRL models. The  $\beta$  parameter in Burrow's proposed model is not a substitute for this characteristic

of the Australian model. Burrow seems to attribute the finding that "as with the Australian model, (his proposed expression) predicts slightly lower delays at higher capacities for the same value of  $x$ " to the  $\beta$  parameter in his model. However, this feature is shared by all time-dependent models considered in the author's earlier paper (7) as can be seen from *Equation 4* in this paper (if  $Q$  increases,  $d_0$  decreases). The Australian model predicts lower delays for higher  $sg$  values for the same degree of saturation and the same capacity. For example,  $s = 1800$  veh/h and  $g/c = 1/3$ , gives  $Q = 600$  veh/h which may correspond to  $sg = 15$  veh/cycle ( $g = 30$  s,  $c = 90$  s) or  $sg = 20$  veh/cycle ( $g = 40$  s,  $c = 120$  s). In this case, the longer green time appears to give lower overflow delay compensating for the increased value of uniform delay due to the longer cycle time. Burrow's proposed model would give the same value of delay for both values of  $sg$  in this example.