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Lane-by-lane modelling of unequal lane use and flares at roundabouts and signalised intersections: the SIDRA solution

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1. INTRODUCTION

This paper has been prepared in response to two recent articles published in *Traffic Engineering and Control*, "ARCADY Health Warning: Account for unequal lane usage or risk damaging the Public Purse!" by Chard [1], and "Modelling flares at traffic signal-controlled junctions" by Simmonite and Moore [2]. These articles address prediction problems associated with the "approach" method of traffic modelling which lumps traffic in individual lanes of an intersection approach together.

Chard demonstrates by means of case studies that "*(the ARCADY model) can take no account of either unused or unequally used lanes or flared sections on roundabout entry approaches. ARCADY is, in fact, completely 'blind' to such occurrences, and as a consequence may produce hopelessly optimistic predictions.*" Chard describes a methodology to correct for this problem, but recommends that "*a new 'by lane entry' model rather than the current, and possibly now outdated, 'by approach entry' model (should be developed in the longer term)*". Indeed, the corrective method appears to be very inefficient as it would require repeated calculations for each possible demand pattern and lane discipline design.

Simmonite and Moore state that "*the art of modelling (flared approaches) is difficult and, as such, often overlooked by practitioners*". They point out to shortcomings of various methods to model flared approach roads at signalised intersections, especially when unequal lane use is expected due to short lanes combined with exclusive left-turn and right-turn lanes. They also discuss the difficulty of modelling such situations due to the dependence of short lane saturation flows on signal timings. For a full intersection example, the authors present results from various methods, including a new simulation program LINSAT. They propose the use of LINSAT alongside programs such as LINSIG, TRANSYT and OSCADY that employ modelling by "approach" or "lane groups".

The authors of the two articles do not seem to be familiar with the SIDRA software package which uses "lane-by-lane" modelling for all types of intersection (signalised, roundabout, sign control) [3]. This contrasts with the method of modelling by "approach" or "lane groups". The decision to adopt a lane-by-lane analysis method was made during the development of SIDRA for signalised intersections in early 1980s [4], and the method has been applied to roundabout modelling in later versions of SIDRA [5-10]. Research Report ARR 123 published in 1981 discussed possible cases of lane under-utilisation at signalised intersections, and described a method for lane flow calculations [11]. Estimation of lane flows and modelling of shared lanes were discussed in later papers [12,13]. SIDRA uses a short lane model which is rather complex in the case of signalised intersections due to the complexities introduced by signal phasings, filter turns and pedestrians. The SIDRA short lane model has not been published.

The SIDRA software package allows the user to input a detailed description of intersection geometry including data for individual lanes (lane disciplines, short lane lengths, shared and exclusive lanes, slip lanes, continuous lanes, lane width, lane utilisation ratio, number of buses stopping, etc). SIDRA computations are heavily based on estimating lane flows, modelling traffic in shared lanes including any lane blockages, establishing any *de facto* (effective) exclusive lanes, determining reduced short lane capacities and any excess flows from short lanes into adjacent lanes.

This paper discusses important aspects of the two articles from the perspective of the lane-by-lane method used in SIDRA. After presenting a summary of the main features of the SIDRA method for roundabouts, SIDRA results for roundabout examples (Cases A and C) of the paper by Chard [1] are given. This is followed by a brief discussion of short lane modelling in SIDRA, and various results for the signalised intersection example with short lanes (flares) given in the article by Simmonite and Moore [2]. The importance of the effects of flow patterns and signal timings on short lane capacity prediction is demonstrated through SIDRA results for random and platooned arrivals, and signal timings under different control conditions (isolated and coordinated fixed-time, and vehicle-actuated). This also helps to highlight some important extensions of the traffic signal analysis methods introduced in the latest SIDRA version 5.

2. MAIN FEATURES OF THE SIDRA METHOD FOR ROUNDABOUT ANALYSIS

The roundabout capacity analysis method described in Special Report SR 45 [5] was incorporated into the SIDRA package with some variations and extensions [6], and later into the Australian roundabout design guide [7]. Significant enhancements were introduced in SIDRA version 4.1 based on new research, representing the latest method in use in the current SIDRA version 5 [8-10]. This method takes into account not only the approach lane utilisation, but also the circulation lane utilisation as an important factor in determining the roundabout performance.

The SIDRA method for roundabout capacity and performance analysis is an extension of the traditional gap acceptance and queuing theory techniques. While the capacity prediction method differs from the empirical methods used in the UK and elsewhere, there is much in common between the gap-acceptance and empirical models. The basic premises of the SIDRA method are outlined below. For further details, refer to the SIDRA User Guide (Output Guide, Appendix B), and other references [3,8-10].

Basic Parameters

Entry stream behaviour is based on a gap-acceptance process similar to those used for minor streams at sign-controlled intersection and opposed (filter) turns at traffic signals, but with major differences in parameter values as relevant to roundabout conditions.

- ***Entry stream behaviour***

In SIDRA, the *critical gap and follow-up headway* parameters describing the entry stream behaviour depend on the roundabout geometry as well as the circulating and entry flow rates. The relevant parameters (considered for each approach road or for each entry lane as applicable) are:

* inscribed diameter of the roundabout (calculated from central island diameter and circulating road width values specified by the user),
* number of circulating lanes,
* number of entry lanes,
* average entry lane width,
* circulating flow rate (subject to capacity constraint, and with option to include a proportion of exiting flow),
* ratio of entry lane flow rate to circulating flow rate
(for the effect of heavy entry flows against low circulating flows),
* ratios of flow rates for *dominant* and *subdominant* entry lanes.

Normally SIDRA calculates estimates of critical gap and follow-up headways for individual lanes as a function of the above parameters. However, the user can specify known critical gap and follow-up headways instead. Different values can be specified for different movements from each approach. This can be used for calibrating the SIDRA capacity model for local conditions.

- ***Circulating stream characteristics***

In SIDRA, a bunched exponential *headway distribution* model is used for modelling circulating stream characteristics. The impact of the directional characteristics (origin-destination pattern), approach queuing and lane use characteristics of entry streams that contribute to each circulating stream are taken into consideration (see Figure 1). The relevant parameters are:

* minimum (intra-bunch) headway,
* proportion bunched in the circulating stream,
* extra bunching (e.g. effect of nearby signals),
* circulating lane use (depending on the approach lane use of contributing streams),
* total circulating flow rate (subject to capacity constraint, and with option to include a proportion of exiting flow),
* the proportion of the total circulating flow that originated from the dominant approach,
* the proportion queued for that part of the circulating stream that originated from the dominant approach (the dominant approach is determined by SIDRA for each entry stream as the approach that contributes the highest proportion of queued traffic in the circulating flow).

This level of detail allows the prediction of different capacity and delay values for a given circulating flow rate. For example, lower capacity and higher delay values will be obtained if the same circulating stream travels in a single lane rather than several lanes (irrespective of the number of available lanes). Similarly, lower capacity and higher delay values will be predicted if the proportion queued in the circulating stream (as determined by approach characteristics of the contributing streams) is higher. This makes the performance of roundabout approaches highly inter-dependent and requires an iterative solution method.

- ***Approach lane use***

Lane discipline characteristics (determined by lane markings) define *exclusive and shared lanes*. SIDRA carries out a detailed lane flow analysis to determine any *de facto exclusive lanes*. User-specified *lane under-utilisation* is taken into account in this process. It applies the shared lane model only to lanes which act as shared lanes in effective terms.

An important aspect of the SIDRA method is the designation of entry lanes as *dominant* and *subdominant* lanes. The *dominant* lane is the lane with the *highest flow* considering all approach lanes together except any exclusive slip lanes or continuous lanes. All other lanes are *subdominant* lanes. Importantly, the capacity of a subdominant lane is less than the capacity of a dominant lane (except when the follow-up headways are found to be equal, especially in the case of low circulating flow rates and low ratios of entry lane flows). Since the lane capacities and lane flows are interdependent, an iterative method is used.

To determine the dominant lane, all lane groups (as determined by exclusive and shared lane arrangements) are considered together. If all lanes have equal flows, the lane with the highest left-turn or right-turn flow is nominated as the dominant lane. If the left-turn and right-turn flows are also equal, the *rightmost* lane for driving on the left side of the road (the *leftmost* lane for driving on the right side of the road) is nominated as the dominant lane. The user may influence the lane flow calculations, therefore the choice of the dominant lane, by specifying low lane utilisation ratios for selected lanes. A lane with a low lane utilisation ratio will have less flow allocated to it, and hence it is less likely to be a dominant lane.

- ***Heavy vehicles***

  * The effects of heavy vehicles in the entry stream and circulating stream are taken into account. For this purpose, heavy vehicle data can be specified for each origin-destination stream separately. The alternative method of specifying demands in passenger cars is acceptable, although specifying heavy vehicle data directly is preferred since this is relevant to short lane capacity predictions (also useful in calculating queue length in metres).

- ***Other roundabout design parameters***

  * ***Short lanes***: Lanes of limited length are described by the user as geometric data. SIDRA assigns any *excess flows* to adjacent lanes when the average back of queue exceeds the available storage space in the short lane. Short lane modelling is based on mathematical relationships between the back of queue and available queue storage space. Back of queue predictions depend on demand flow rate as well as gap-acceptance characteristics (block and unblock intervals). Short lane modelling is discussed in more detail in Section 4.

  * ***Approach flaring*** effects are predicted through the use of short lane modelling when the flared section allows an additional queue to form, therefore acting as an additional (short) lane. Otherwise, the increased entry lane width will result in increased capacity prediction through a decreased value of the critical gap. Thus, the capacity predicted by SIDRA is sensitive to the ***entry width*** (through the number of entry lanes and the average

entry lane width). The Florida Roundabout Guide (Figure C-16) is in error in relation to this [14].

* In SIDRA, ***entry angle*** and ***entry radius*** do not affect capacities in accordance with the results of Australian research [5]. This is somewhat consistent with the ARCADY model which predicts small effects of these parameters. Turn radius is taken into account in geometric delay predictions by SIDRA.

* ***Slip lanes and continuous lanes***: Slip lanes are modelled by treating the exiting flow as the opposing stream. Traffic using continuous (uninterrupted) lanes that bypass the roundabout are subject to geometric delay only.

Analysis Method

The key features that distinguish SIDRA capacity and performance models from other models are as follows.

- ***Lane-by-lane analysis:*** All capacity and performance analysis techniques used by SIDRA are carried out on a lane-by-lane basis. This contrasts with analysis by *approach* (e.g. ARCADY) or *lane group* (US Highway Capacity Manual) [15]. The SIDRA method applies the equations for predicting capacity and performance (delay, queue length, etc) to each lane individually rather than to all lanes of the approach or the lane group. This has important implications in terms of the results obtained. The SIDRA method prevents the averaging of delays, and especially queue lengths, of individual lanes in the prediction process, which can be very misleading [4].

- ***Roundabout NOT as a series of T-junctions:*** The most important enhancement to the capacity estimation method introduced in SIDRA is allowance for ***approach flow interactions*** through the effects of directional characteristics (origin-destination pattern) of entry flows, amount of queuing on approach roads, and approach lane use [9-11]. This contrasts with the traditional method of roundabout modelling that treats the roundabout *as a series of independent T-junctions* with no interactions among approach flows. The interactive method used in SIDRA improves the prediction of capacities under heavy flow conditions, especially at multi-lane roundabouts with unbalanced entry flows. A *capacity constraint* method is also used to limit the flows contributing to circulating flows to capacity values for oversaturated lanes. SIDRA carries out many iterations in order to find an equilibrium solution that allows for these factors.

- ***Capacity and performance models:*** SIDRA uses a unique signal-analogy and overflow queue method for capacity and performance estimation [16]. This method is consistent with the traditional gap-acceptance and queuing theory models. The estimates from the SIDRA capacity formula are very similar to those given by alternative gap-acceptance formulas given the same parameter values describing the entry and circulating stream characteristics.

The important contribution of the signal-analogy and overflow queue concepts for roundabouts and sign control cases has been in the extension of the queuing theory methods to the prediction of essential statistics such as *back of queue* (average, 90th, 95th and 98th percentile values), queue move-up rate, effective stop rate, proportion queued and queue clearance time, as well as different delay statistics (total delay, stopped delay, idling time and geometric delay).

Users should be aware of the different queue length definitions used by different methods (e.g. ARCADY uses the *cycle-average queue* whereas SIDRA uses the *back of queue* although it has the option to predict the cycle-average queues).

- ***Consistency with other intersection types***: The SIDRA method emphasises the consistency of capacity and performance analysis methods for roundabouts, sign-controlled and signalised intersections achieved through the use of an integrated modelling framework. This includes the estimation of *geometric delays* and related slow-down effects for all intersection types. This helps with the evaluation of alternative intersection treatments in a consistent manner.

- ***Level of service***: This is important in the context of the US Highway Capacity Manual (HCM) [15]. The HCM does not define levels of service (LOS) for roundabouts. SIDRA uses the same LOS criteria for roundabouts and traffic signals since the performance of roundabouts is expected to be closer to traffic signals for a wide range of flow conditions.

Roundabout model accuracy

SIDRA methods are based on extensive research carried out in Australia. These can be outlined as follows.

- ***Research on behavioural parameters***: Surveys of entry lane and circulating stream characteristics at a number of roundabouts were carried out [4]. The research also included investigation of related capacity estimation. This research differed from research in the UK that emphasised measurement of total approach capacity with a view to direct capacity estimation without quantifying entry and circulating stream characteristics in gap-acceptance terms.

- ***Further research on capacity***: The early method to predict capacities and delays observed at a significant number of real-life intersections with heavy flow conditions was not found satisfactory (highly over-optimistic results were found). Improved methods first introduced in SIDRA 4.1 were found to give satisfactory capacity and performance estimation for heavy and highly directional demand cases [8-10]. The methods were developed from an analytical perspective, and checked by means of a microscopic simulation model (MODELC) creating a large number of demand pattern scenarios. Earlier research during the development of MODELC involved validation work based on surveys of capacities and delays at real-life intersections [17-19].

- ***Local calibration***: No model is expected to give perfect estimates of capacity and performance at a particular intersection. It may therefore be necessary to calibrate the model for local conditions. In the case of the gap-acceptance method used in SIDRA, capacities and delays at roundabouts are very sensitive to the circulating stream characteristics as well as the critical gap and follow-up headways as in the case of sign control. In the case of the empirical capacity estimation method used in ARCADY, the capacities and delays are expected to be sensitive to the parameters of the linear capacity model. Calibration is a difficult task in normal day-to-day practice, and impossible if the intersection does not exist. However, ARCADY's capacity calibration method is a useful tool.

- ***Design confidence***: SIDRA allows the design engineer to set a target (practical) degree of saturation to determine the maximum amount of demand flows that a roundabout can handle (therefore the design life of the roundabout). Default target degree of saturation for roundabouts is 85 per cent (compared with 80 per cent for stop-sign control). This provides an error margin to ensure that near-saturated conditions (where delay and queue length predictions become less reliable) are not approached. This seems to agree with the ARCADY method.

3. SIDRA RESULTS FOR ROUNDABOUT EXAMPLES

The SIDRA results for Cases A and C of the paper by Chard [1] are presented in Figures 2a to 4c in order to demonstrate how a lane-by-lane method solves the lane utilisation prediction problems. The examples highlight various interesting aspects of the SIDRA method. The use of SIDRA for these cases is straightforward, but various aspects of input preparation and output statistics will be discussed. Figures 2a to 4c are copies of SIDRA graphic screens and text output.

In order to match the ARCADY data in all cases, the analyses were carried out for a peak flow period of 15-minutes with a Peak Flow Factor of 0.91 (about 10 per cent increase over the input demand flows specified for the peak hour period).

The SIDRA delay results given here do not include geometric delays for the purpose of comparison with ARCADY results. The term "degree of saturation" is the same as "demand/capacity ratio (RFC)" in ARCADY usage. The SIDRA degree of saturation for an approach road is the critical lane (highest) degree of saturation.

Case A-1

This is a two-lane roundabout (two entry lanes and two circulating lanes for all approach roads) with lane disciplines as shown in Fig. 5a of Chard [1] (Arm C has 600 through and 600 right-turning vehicles). Although a two-lane roundabout, all origin-destination streams operate as single lane movements due to the exclusive lane arrangements specified, which reduces the capacity of the roundabout. Entry lane width was specified as 3.75 m for all lanes.

Figure 2a shows the approach demand and circulating flows used in SIDRA calculations (increased flows for the 15-min peak period). Circulating flow of 640 pcu/h for Arm A is reduced due to oversaturation predicted for the right-turn lane on Arm C. Figure 2b shows the average delays (in seconds) predicted for individual movements and approach roads. Figure 2c shows the SIDRA results for individual lanes. SIDRA is seen to predict oversaturated conditions for several lanes (more pessimistic results than ARCADY).

Comparison of ARCADY and SIDRA results (aggregate values for each approach road) are summarised in Table I (delays in seconds calculated from ARCADY total delays in veh-min/15 min given in Table I of Chard [1]). In this case, the ARCADY and SIDRA predictions appear to compare well except for Arm C (SIDRA predicts lower capacity for the through traffic lane as a subdominant lane). Higher percentage differences for degree of saturation (compared with capacity predictions) are due to the lane-by-lane method in SIDRA with unequal capacities and degrees of saturation for individual lanes. Delay differences are even larger, which is partly due to the differences in capacity and degree of saturation predictions, partly due to the lane-by-lane application of the SIDRA delay formula, and partly due to the differences in the SIDRA and ARCADY delay model structures.

Case A-2

This roundabout is the same as in Case A-1 except for Arm C which is specified as a single-lane approach with 1200 through vehicles (differs from Fig. 5b of Chard [1] which shows two lanes with an empty right-turn lane).

Figure 3a shows the approach demand and circulating flows used in SIDRA calculations. Circulating flow of 10 pcu/h for Arm A is a minimum value forced by SIDRA to avoid zero-flow condition. Figure 3b shows the average delays (in seconds) predicted by SIDRA for individual movements and approach roads. Figure 3c shows the SIDRA results for individual lanes.

Comparison of ARCADY and SIDRA results are summarised in Table II (delays for ARCADY calculated from Table II of Chard [1]). In addition to the problem with Arm C identified by Chard, the differences in the ARCADY and SIDRA predictions are seen to increase for Arm A as well. SIDRA predicts zero queuing delay associated with a substantially increased capacity for Arm A which has zero circulating flow. SIDRA results also indicate an improvement to Arm B (compared with Case A-1), which is a result of the improved conditions for Arm A (proportion queued on Arm A decreased from 0.84 to 0.06).

Table III shows the comparison of the corrected ARCADY results (only Arm C results changed) with SIDRA results (identical to those in Table II). Capacity and degree of saturation predictions for Arm C are seen to get closer with corrected ARCADY results. Both the SIDRA and the corrected ARCADY delays are very high due to severe oversaturation predicted. The difference in the predictions is substantial, and is due to the differences in the delay models.

Case C

This is the roundabout shown in Fig. 7 of Chard [1]. For SIDRA, flaring on Arm A was converted to a short lane of 12 m (2 cars), and flaring on Arm B was converted to a short lane of 30 m (5 cars). Arm C was specified as a single-lane approach with no right turns. Arm D was specified with two full lanes. Entry lane widths were specified as 3.65 m for Arm A (two lanes), 4.50 m for Arm B (2 lanes), 4.55 m for Arm C (one lane), and 5.25 m for Arm D (two lanes).

Figure 4a shows the approach demand and circulating flows used in SIDRA calculations (flows for the 15-min peak period). Figure 4b shows the average delays (in seconds) for individual movements and approach roads. Figure 4c shows the SIDRA results for individual lanes. SIDRA forced the flow rates on Arm C up to the minimum value of 10 veh/h for each movement. This has negligible effect on results.

Comparison of ARCADY and SIDRA results for Case C are summarised in Table IV (delays in seconds calculated from ARCADY total delays given in Table IV of Chard [1]). It is seen that the capacity and delay predictions agree reasonably well (low delays predicted by both models).

Table V shows the comparison of the corrected ARCADY results (from Table V of Chard) with SIDRA results. It is seen that the differences between ARCADY and SIDRA predictions increase in spite of lack of prediction of individual lane performance by ARCADY.

The reason for high capacity and low delay values predicted by SIDRA for Arms A and D is the low circulating flow rates with very low proportion queued (see Table VI for additional SIDRA output statistics for Case C). The right-turn movement on Arm A and the left-turn movement on Arm D have high ratios of entry demand flow to circulating flow which produce higher capacities and lower delays.

The case of the heavy left-turn flow from Arm D presents an interesting SIDRA result which is worth explaining. For this movement, SIDRA predicts a low average delay (11.7 s) although it is at capacity (degree of saturation = 0.996). This movement has a high proportion queued (0.96) and a large back of queue (average: 14.0 veh, 95th percentile: 36.7 veh). These statistics can be explained by the fact that the high degree of saturation is a result of high demand rather than low entry lane capacity (capacity = 1684 veh/h, demand = 1677 veh/h). SIDRA performance models can distinguish between such a case of “high capacity, high demand, high degree of saturation” that results in “short delay and long queue” and the opposite case of “low capacity, low demand, high degree of saturation” which results in “long delay and short queue”. In terms of the gap acceptance process, the case of “short delay and long queue” corresponds to short block (red) time and long unblock (green) time, whereas the case of "long delay and short queue" corresponds to long block (red) time and short unblock (green) time. An example for the case of short delay and long queue is shown in Figure 5 where α = critical gap, β = follow-up headway, h = major stream headway, l = lost time, t_b, t_u = block and unblock times, r, g = equivalent red and green times [16].

4. MODELLING OF SHORT LANES (FLARES) AT SIGNALISED INTERSECTIONS

SIDRA determines the capacity of a short lane as a space-based capacity value that depends on the short lane length as well as the length of the red period and the amount of demand flow using the short lane. The short lane model in SIDRA is much more complex than the model described in ARR No. 123 [11] because of excess flow formulations and generalisations for the treatment of two green periods per cycle. The short lane model used in SIDRA has not been documented yet.

The short lane capacity in SIDRA is defined as the critical arrival flow rate which gives an *average* back of queue equal to the number of vehicles that can queue within the short lane (storage) length. As a result of this definition, a short lane degree of saturation, x = 1.0 means that the average back of queue equals the available short lane storage length, and possibly there is an excess flow in the adjacent lane. In SIDRA 5, the short lane capacity is affected by the arrival type (random or platooned arrivals) [20], and will differ between fixed-time and vehicle-actuated signals [21-23] with identical effective green and red times and identical flow characteristics.

The platooned arrivals model in SIDRA [20] is an extension of the US Highway Capacity Manual [15] progression factors method. The model recognises the fact that majority of signalised intersections in urban areas are not isolated sites but probably part of a coordinated signal system, and specific movements at an intersection may be well or poorly coordinated. A simple but effective method for modelling platooned arrivals is to use different arrival flow rates during the red and green periods. For this purpose, data can be specified either as an *arrival type* or as the *proportion of traffic arriving during the green period*.

If the average back of queue exceeds the short lane space available, a corresponding *excess flow* is calculated and assigned to the adjacent lane. The excess flow, which spills from the short lane into the adjacent lane, occurs at the point of entry to the short lane. In this case, the performance characteristics of the short lane movement and the adjacent movement are calculated with the modified flow compositions.

When the short lane flow is relatively low, it is possible to obtain a large degree of saturation (greater than 1.0) while the queue length is contained within the short lane, hence no excess flow is moved into an adjacent lane. This case could occur with opposed turns in the short lane where the opposed turn capacity is less than the short lane capacity. It is also possible for the average back of queue to be equal to the short lane length without any excess flow being moved (degree of saturation less than 1.0). This is a result of the second term of the queue length equation (overflow queue effect) being large. Irrespective of the occurrence of an excess flow, the short lane capacity may be reduced (i.e. the saturation flow may be less than the full saturation flow).

The signalised intersection example with short lanes given in the article by Simmonite and Moore [2] is used here to demonstrate the capabilities of SIDRA short lane modelling through results for random and platooned arrivals, and signal timings under different control conditions (isolated and coordinated fixed-time, and vehicle-actuated). Figures 6a and 6b show the SIDRA intersection geometry and phasing screens for this example. The geometry picture shows the short lane lengths in metres (assuming that the average vehicle spacing in queue is 6.0 m/pcu). The example given here includes some differences from the example by Simmonite and Moore. The exclusive right-turn lane on Arm C is specified as a short lane (90 m, or 15 pcu lengths). In all cases reported here, this lane acted as a full-length lane, i.e. there was no short lane effect. Left-turns from Arms A and B are overlap movements that run in two phases.

For all movements and phases, intergreen time = lost time = 5 s is used. Saturation flows for through movements are 1900 pcu/h whereas saturation flows for turning movements are 1810 pcu/h. The analysis period is one hour, and the Peak Flow Factor is 1.00 (thus, the demand volumes used are exactly as given in the original example). All SIDRA results for this example give average delays with geometric delays, and average back of queue values (rather than percentile queue lengths) to help with understanding the short lane results.

To demonstrate that short lane capacities and the resulting intersection performance depend not only on demand flow rates but also on the signal control method as well as the demand flow patterns (random vs platooned arrivals), SIDRA results are given for the following cases:

- Case 1: Isolated fixed-time signals with green splits using the EQUISAT (equal degree of saturation) method which is common to most signal analysis methods.

- Case 2: Coordinated fixed-time signals running under a network cycle time of c = 100 s, and green splits calculated with priority assigned to Arm A using a method which is unique to SIDRA (resulting in unequal degrees of saturation for critical movements). Platooned arrivals for Arms A and B were specified as follows:

  Arm A (good coordination): The proportion of traffic arriving during green, $P_G = 0.96$ for left-turns (large value due to longer green time) and $P_G = 0.77$ for through traffic.
  Arm B (poor coordination): $P_G = 0.29$ for left turns and $P_G = 0.14$ for right turns.
  Arm C: random arrivals (no coordination).

- Case 3-A: Vehicle-actuated signals using very short maximum green and gap settings to achieve a 50 s cycle time for comparison with the fixed-time case with the same cycle time:

  Maximum green settings: $G_{max} = 15$ s for through traffic and left turns, $G_{max} = 10$ s for right turns.
  Gap, or extension, settings as space time values [21-23]: $e_s = 2.5$ s for through traffic and left turns, $e_s = 2.0$ s for right turns.

- Case 3-B: Vehicle-actuated signals using longer maximum green and gap settings to achieve a 100 s cycle time for comparison with the fixed-time case with the same cycle time:

  Maximum green settings: $G_{max} = 35$ s for through traffic and left turns, $G_{max} = 25$ s for right turns.
  Gap settings: $e_s = 4.0$ s for through traffic and left turns, $e_s = 2.0$ s for right turns.

SIDRA results for these cases are presented in Figures 7a and 7b, and Tables VIIa to IXb. Notations used in the tables (based on SIDRA output tables S.7 and S.8) are:

L, T, R	=	Left-turn, Through and Right-turn movements (lanes numbered from left to right looking towards the exit direction),
r, g	=	effective red and green time,
q	=	lane demand flow (including any excess flow from adjacent short lane),

s = lane saturation flow (< indicates saturation flow reduced due to short lane effect),
Q = lane capacity,
x = lane degree of saturation,
d = average delay per vehicle,
N_b (veh) = average back of queue in vehicles,
N_b (m) = average back of queue in metres, and
SL (m) = short lane length in metres.

Figures 7a and 7b show the total intersection capacity and average intersection delay as a function of the cycle time as predicted by SIDRA for fixed-time signals (Case 1). These results are similar to those reported by Simmonite and Moore. The total intersection capacity (sum of lane capacities) is seen to decrease with increasing cycle times above 60 s, and the minimum intersection delay is obtained at c = 50 s. The SIDRA predictions of lane flows, saturation flows, delay, average back of queue, etc. for c = 50 s and c = 100 s are shown in Tables VIIa and VIIb, respectively.

Table VIIa shows that, with the shorter cycle time of 50 s, only the left-turn lanes on Arms A and B have reduced saturation flows. The short through lane on Arm A acts as a full-length lane (s = 1900 veh/h), with equal lane flows in the two through lanes (350 veh/h). With the longer cycle time of 100 s (Table VIIb), the short through lane on Arm A has a reduced saturation flow (1123 veh/h) resulting in unequal lane flows in the two through lanes (260 and 440 veh/h). The saturation flows of left-turn lanes on Arms A and B are seen to be further reduced. No excess flows are predicted with c = 50 s or 100 s under this control method.

Case 2 results given in Table VIII show different short lane effects and intersection performance obtained under a different control method, i.e. green splits and good signal coordination that favour Arm A (compared with results given in Table VIIa for the isolated fixed-time case with the same cycle time, c = 100 s). It is seen that, for Arm A, the short lane saturation flows are much higher and the degrees of saturation, delays and back of queue values are much reduced. This is partly due to the reduced red time for the through movement, and partly due to favourable signal coordination for the left-turn and through movements. On the other hand, the performance of Arm B is worsened due to the decreased green time and unfavourable coordination. Arm C benefits from increased green time for the through movement on Arm A. No excess flows are predicted for Case 2.

Case 3-A results given in Table IXa for isolated vehicle-actuated control with c = 50 s show that, compared with the fixed-time isolated case with the same low cycle time (Table VIIa), similar short lane performance is achieved. However, green splits differ significantly. Generally, vehicle-actuated signals do not produce an equal degree of saturation solution. In this example, the performance of right-turn movement on Arm B is seen to be worse due to a shorter green time (degree of saturation = 0.95 against 0.79 in Case 1).

While the short lane performance for Case 3-A appears to be satisfactory, it is achieved with very short maximum green settings which are not likely to be used in vehicle-actuated control practice considering that such settings are used for all flow periods. Case 3-B results given in Table IXa for c = 100 s resulting from longer maximum green settings indicate worse short lane performance for the left-turn movement on Arm A (excess flow of 60 veh/h queuing in the adjacent lane). Compared with the results for the fixed-time case with c = 100 s (Table VIIb), queue lengths and delays on Arm A are seen to be longer, whereas Arm C indicates better performance.

5. CONCLUDING REMARKS

Lane-by-lane modelling is one of the reasons for increased popularity of the SIDRA software package which is currently in use by well over 700 organisations (sites) in more than 50 countries.

The inability of the "approach" method to take into account unused or unequally used lanes, an issue raised by Chard about the ARCADY software, is in fact a fundamental problem common to most software used today. It is recommended that all software products should be scrutinised with regard to this problem.

The approach method of analysis was appropriate as a simple method for manual calculations, but insistence on its use in sophisticated software is not justified. In fact, lane-by-lane modelling makes analytical formulation of complex traffic interactions easier as in the case of short lane modelling. However, changing an existing software from modelling by approach to lane-by lane modelling may not be a trivial task since capacity and performance models would need to be recalibrated, yet lane-by-lane data may not be available.

Modelling by approach is inadequate not only in relation to unequal lane use and flare (short lane) effects discussed in this paper, but also causes prediction problems in cases of shared lanes where the movements in the shared lanes have different departure characteristics causing temporary lane blockage (e.g. through traffic and filter turns, two movements that receive different green signals at different times in the signal cycle). Such cases combined with cases of unequal lane use and short lanes (flares) present even more complicated cases than the examples presented in this paper. The lane-by-lane method of SIDRA helps to model such complicated situations as well [13].

An important point in the comparison of fixed-time and actuated signal cases in analysing the signalised intersection example with short lanes is that an optimum fixed-time solution with a very short cycle time (Case 1) may not be relevant in practice. If the intersection is controlled by actuated signals with reasonably long maximum green settings, a longer cycle time, unequal degrees of saturation, and reduced short lane saturation flows would result in reality, as in Case 3-B. Thus, unless a short cycle time solution is translated into practice by operations engineers, analyses assuming fixed-time signals would result in misleading design solutions. This emphasises the importance of applying actuated signal analyses where relevant, which has been generally neglected to date. The actuated signal analysis method introduced in SIDRA 5 shows that methods based on the traditional assertion "vehicle-actuated signals operate as fixed-time signals during peak demand periods" do not produce a satisfactory solution for either peak or non-peak periods. Other existing signal analysis software packages need to address this issue as well.

Finally, it is emphasised that iterative methods using external tools such as LINSAT or the corrective method proposed by Chard for use with the ARCADY software are inefficient solutions for use by traffic engineers and planners in day-to-day practice. Although simulation tools such as LINSAT are useful on their own right, it is desirable to have the analysis of short lanes and other important intersection characteristics as an ***integral part*** of the overall timing, capacity and performance analysis process within the same software. This is because of the interdependence of signal control method, signal timings, demand flow rates and patterns, , and intersection geometry, as demonstrated through the SIDRA solutions presented in this paper. Lane-by-lane modelling makes such analytical solutions possible.

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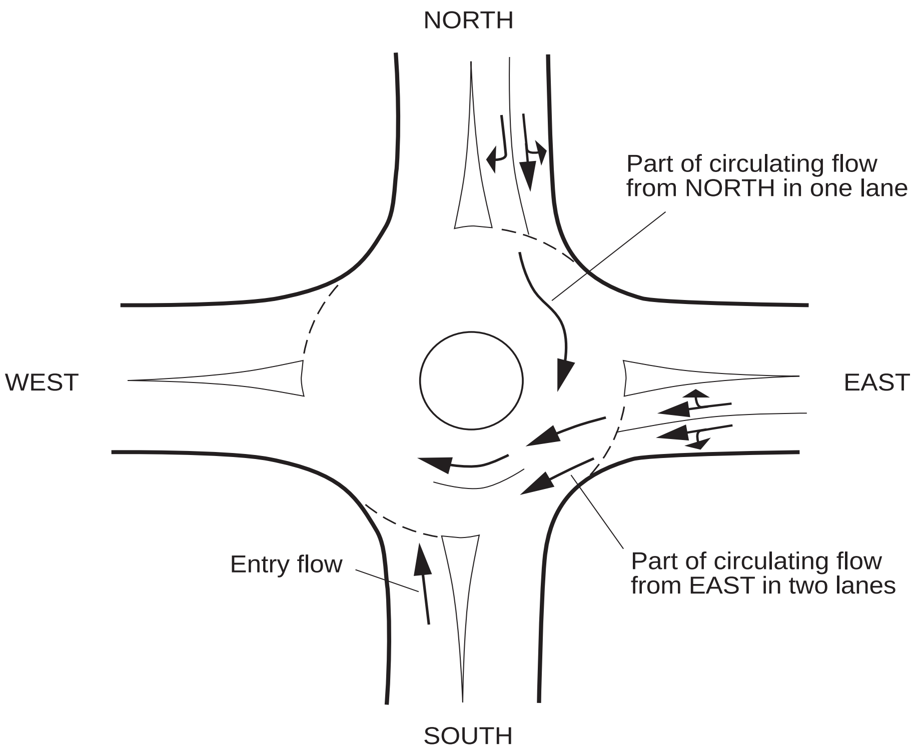

Figure 1 - Approach lane use effect on circulating stream characteristics at a multi-lane roundabout (an example)

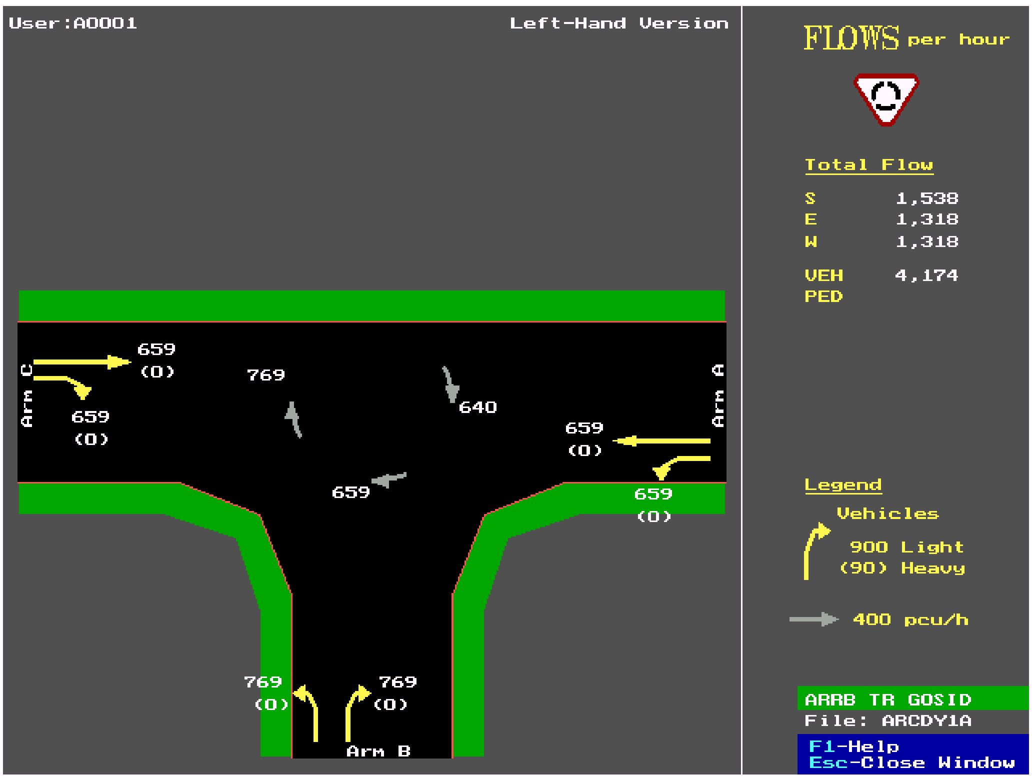

Figure 2a - Approach demand and circulating flow rates used in SIDRA calculations for the roundabout example (Case A-1)

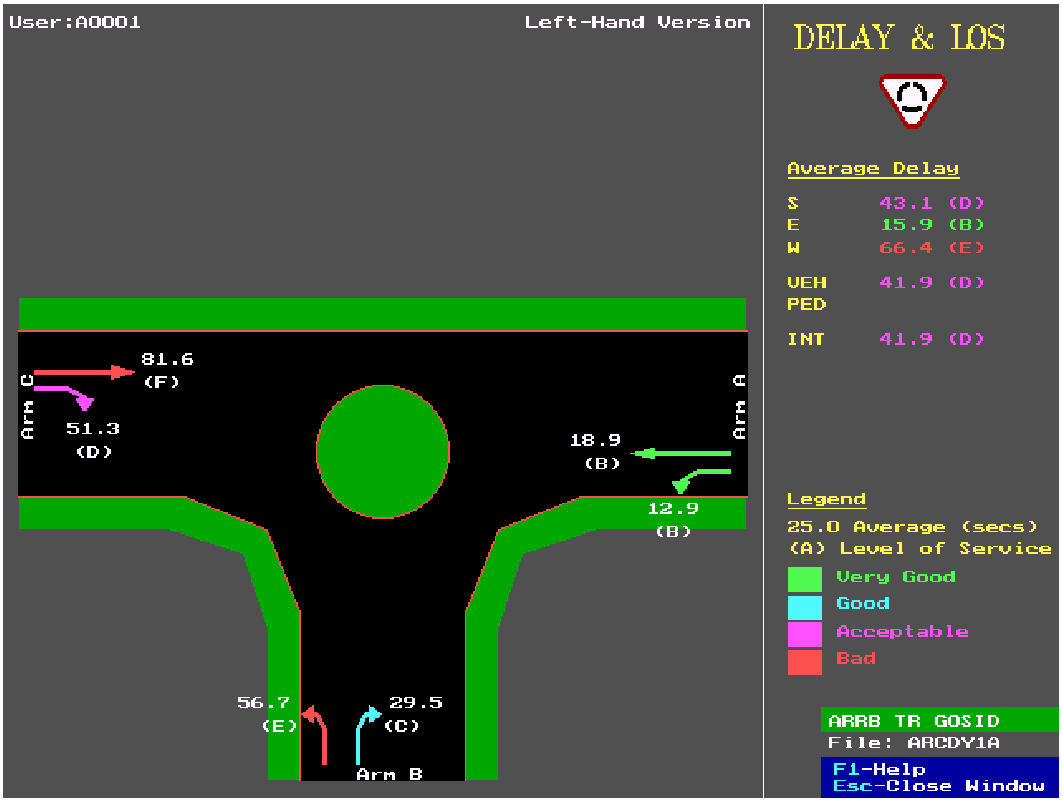

Figure 2b - SIDRA delay predictions for the roundabout example (Case A-1)

ARCADY Example: Article by B. Chard, Traf.Eng+Control, Mar 1997
Case A-1, Fig.5a: Arm C has 600 through + 600 right, PFF = 0.91
Intersection No.: ARC1A
Roundabout

Table S.7 - LANE PERFORMANCE

Lane No.	Mov No.	Arv Flow (veh /h)	Cap (veh /h)	Deg. Satn x	Aver. Delay (sec)	Eff. Stop Rate	Queue 95% Back (vehs)	Queue 95% Back (m)	Short Lane (m)
South:	Arm B								
1 L	1	769	723	1.063	56.7	2.15	41.7	250	
2 R	3	769	785	0.980	29.5	1.67	29.1	174	
East:	Arm A								
1 L	4	659	784	0.841	12.9	1.19	14.8	89	
2 T	5	659	725	0.909	18.9	1.38	19.5	117	
West:	Arm C								
1 T	11	659	590	1.117	81.6	2.49	44.5	267	
2 R	12	659	639	1.031	51.3	2.05	34.3	206	

Figure 2c - SIDRA lane performance predictions for the roundabout example (Case A-1)

Table I

Comparison of ARCADY and SIDRA results for Case A-1 (Fig. 5a and Table I of Chard [1])

	Capacity (veh/h)			Degree of saturation			Average delay (s/veh)		
	ARCADY	SIDRA	Difference	ARCADY	SIDRA	Difference	ARCADY	SIDRA	Difference
Arm A	1591	1509	-5%	0.828	0.909	10%	12.4	15.9	29%
Arm B	1590	1508	-5%	0.966	1.063	10%	36.1	43.1	19%
Arm C	1517	1229	-19%	0.867	1.117	29%	16.0	66.4	314%

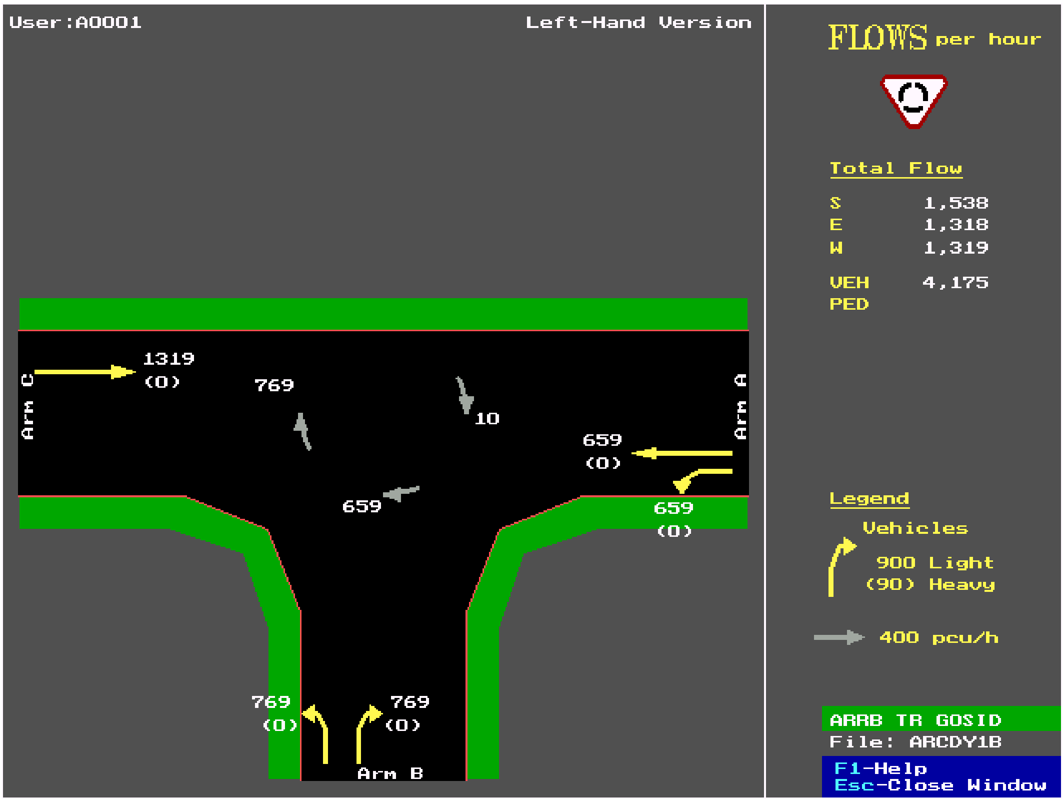

Figure 3a - Approach demand and circulating flow rates used in SIDRA calculations for the roundabout example (Case A-2)

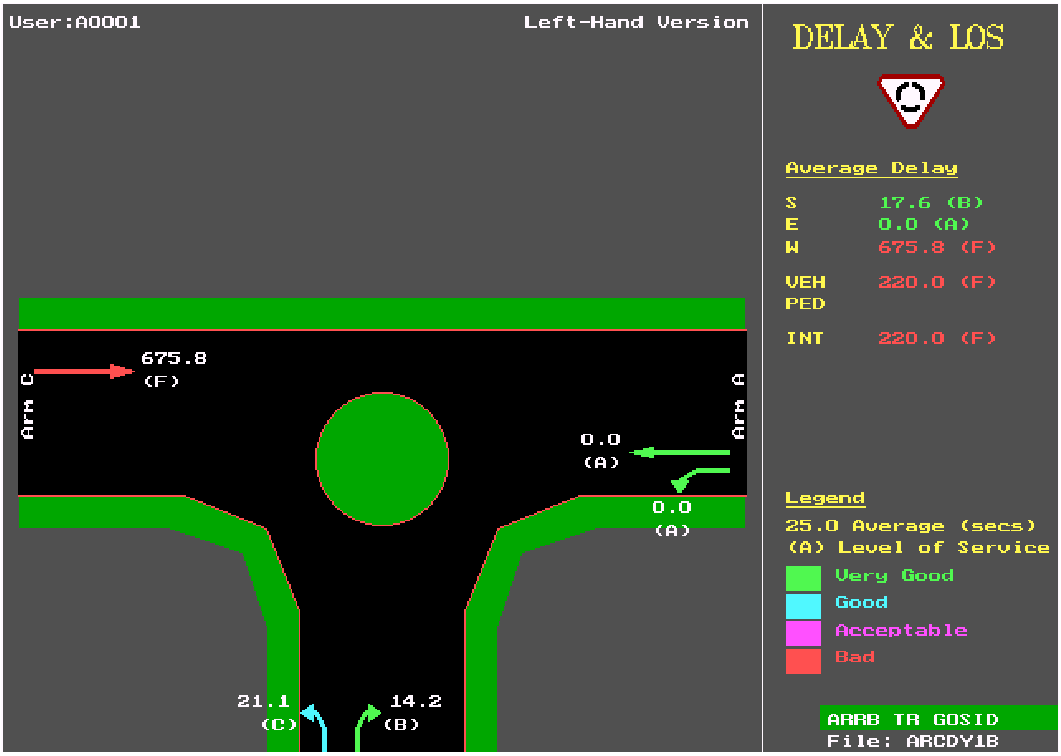

Figure 3b - SIDRA delay predictions for the roundabout example (Case A-2)

ARCADY Example: Article by B. Chard, Traf.Eng+Control, Mar 1997
Case A-2, Fig.5b: Arm C has 1200 through, PFF = 0.91
Intersection No.: ARC1B
Roundabout

Table S.7 - LANE PERFORMANCE

Lane No.	Mov No.	Arv Flow (veh /h)	Cap (veh /h)	Deg. Satn x	Aver. Delay (sec)	Eff. Stop Rate	Queue 95% Back (vehs)	Queue 95% Back (m)	Short Lane (m)
South: Arm B									
1 L	1	769	840	0.916	21.1	1.44	24.1	145	
2 R	3	769	911	0.844	14.2	1.24	18.1	109	
East: Arm A									
1 L	4	659	1981	0.333	0.0	0.61	2.1	13	
2 T	5	659	1622	0.406	0.0	0.64	2.9	17	
West: Arm C									
1 T	10	1319	535	2.464	675.8	6.49	267.6	1605	

Figure 3c - SIDRA lane performance predictions for the roundabout example (Case A-2)

Table II

Comparison of ARCADY and SIDRA results for Case A-2 (Fig. 5b and Table II of Chard [1])

	Capacity (veh/h)			Degree of saturation			Average delay (s/veh)		
	ARCADY	SIDRA	Difference	ARCADY	SIDRA	Difference	ARCADY	SIDRA	Difference
Arm A	2051	3603	76%	0.642	0.406	-37%	4.8	0	-100%
Arm B	1589	1751	10%	0.966	0.916	-5%	36.5	17.6	-52%
Arm C	1517	535	-65%	0.867	2.464	184%	16.0	675.8	4117%

Table III

Comparison of ARCADY (corrected) and SIDRA results for Case A-2 (Table III of Chard [1])

	Capacity (veh/h)			Degree of saturation			Average delay (s/veh)		
	ARCADY	SIDRA	Difference	ARCADY	SIDRA	Difference	ARCADY	SIDRA	Difference
Arm A	2051	3603	76%	0.642	0.406	-37%	4.8	0	-100%
Arm B	1589	1751	10%	0.966	0.916	-5%	36.5	17.6	-52%
Arm C	497	535	8%	2.646	2.464	-7%	1329.3	675.8	-49%

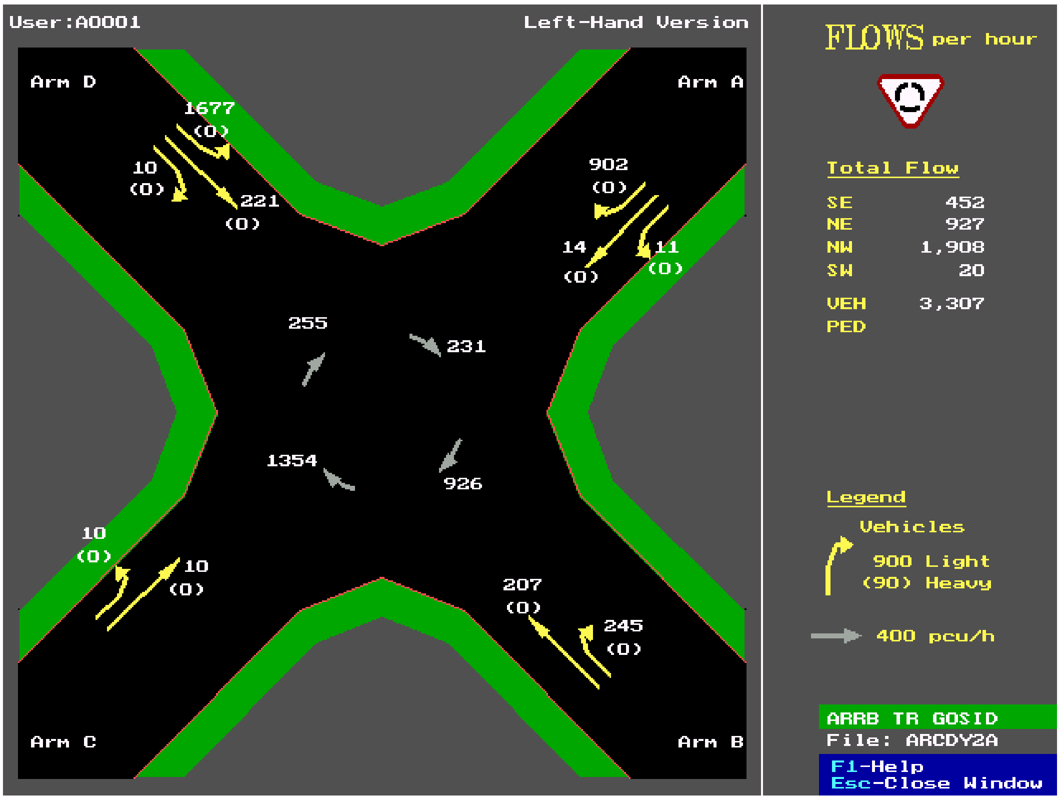

Figure 4a - Approach demand and circulating flow rates used in SIDRA calculations for the roundabout example (Case C)

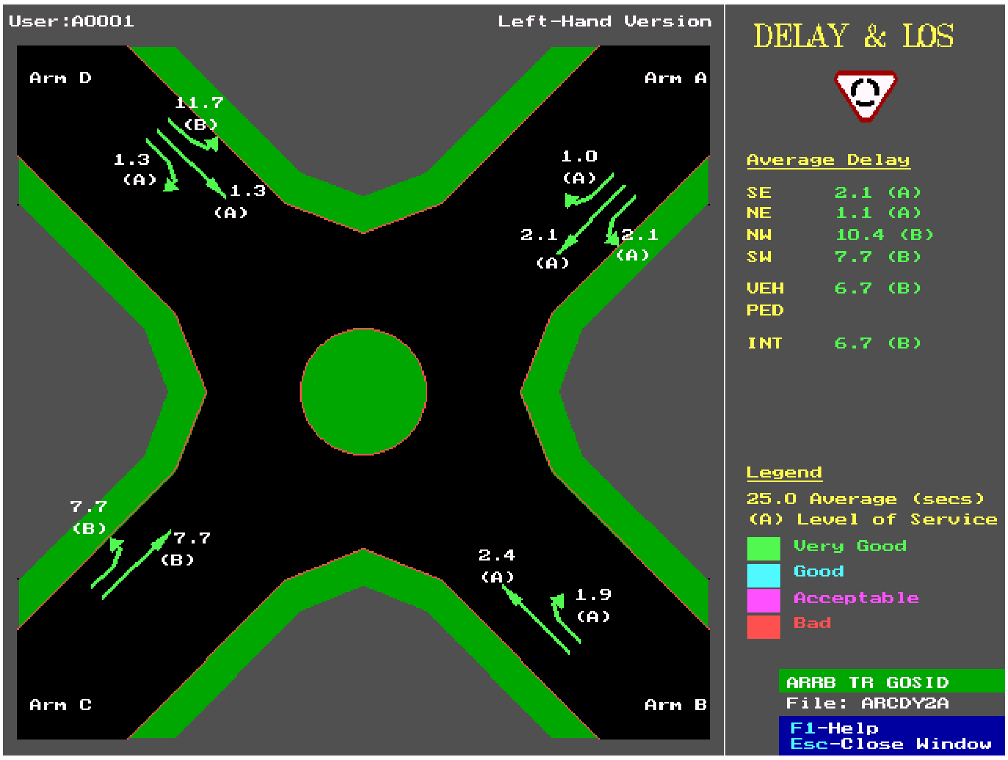

Figure 4b - SIDRA delay predictions for the roundabout example (Case C)

ARCADY Example: Article by B. Chard, Traf.Eng+Control, Mar 1997
Case C, Fig.7, PFF = 0.91
Intersection No.: ARC2A
Roundabout

Table S.7 - LANE PERFORMANCE

Lane No.	Mov No.	Arv Flow (veh /h)	Cap (veh /h)	Deg. Satn x	Aver. Delay (sec)	Eff. Stop Rate	Queue 95% Back (vehs)	Queue 95% Back (m)	Short Lane (m)
SouthEast: Arm B									
1 T	22	201	874	0.230	2.4	0.72	1.0	6	30
2 TR	22, 23	251	1095	0.230	1.9	0.73	1.0	6	
NorthEast: Arm A									
1 LT	24, 25	25	430	0.058	2.1	0.60	0.2	1	12
2 R	26	902	1640	0.550	1.0	0.63	4.7	28	
NorthWest: Arm D									
1 L	27	1677	1684	0.996	11.7	0.99	36.7	220	
2 TR	28, 29	231	801	0.289	1.3	0.68	1.2	7	
SouthWest: Arm C									
1 LT	30, 31	20	526	0.038	7.7	0.77	0.2	1	

Figure 4c - SIDRA lane performance predictions for the roundabout example (Case C)

Table IV

Comparison of ARCADY and SIDRA results for Case C (Table IV of Chard [1])

	Capacity (veh/h)			Degree of saturation			Average delay (s/veh)		
	ARCADY	SIDRA	Difference	ARCADY	SIDRA	Difference	ARCADY	SIDRA	Difference
Arm A	1693	2070	22%	0.547	0.550	1%	4.7	1.1	-76%
Arm B	1687	1969	17%	0.267	0.230	-14%	2.9	2.1	-27%
Arm C	706	526	-25%	0.011	0.038	245%	6.2	7.7	25%
Arm D	2656	2485	-6%	0.714	0.996	39%	4.7	10.4	123%

Table V

Comparison of ARCADY (corrected) and SIDRA results for Case C (Table V of Chard [1])

	Capacity (veh/h)			Degree of saturation			Average delay (s/veh)		
	ARCADY	SIDRA	Difference	ARCADY	SIDRA	Difference	ARCADY	SIDRA	Difference
Arm A	1117	2070	85%	0.829	0.550	-34%	17.4	1.1	-94%
Arm B	1688	1969	17%	0.267	0.230	-14%	2.9	2.1	-27%
Arm C	706	526	-26%	0.011	0.038	245%	6.2	7.7	25%
Arm D	1510	2485	65%	1.255	0.966	-23%	314.2	10.4	-97%

Table VI

Additional SIDRA results for Case C

Approach	Lane	Dominant or Subdom. lane	Critical gap (s)	Follow-up headway (s)	Prop. queued	Average back of queue (veh)	Cycle-average queue (veh)	Delay without geometric delay (s/veh)	Delay including geometric delay (s/veh)
Arm A	LT	Subdom.	6.99	4.00	0.402	0.1	0.0	2.1	11.4
	R	Dominant	3.21	1.84	0.425	1.5	0.3	1.0	13.1
Arm B	T	Subdom.	2.85	2.30	0.502	0.3	0.1	2.4	11.8
	TR	Dominant	2.40	1.93	0.483	0.3	0.1	1.9	13.8
Arm C	LT	Dominant	2.46	2.16	0.739	0.1	0.0	7.7	16.9
Arm D	L	Dominant	2.21	1.84	0.957	14.0	5.4	11.7	20.7
	TR	Subdom.	4.31	3.59	0.319	0.4	0.1	1.3	10.8

L: Left, T: Through, R: Right

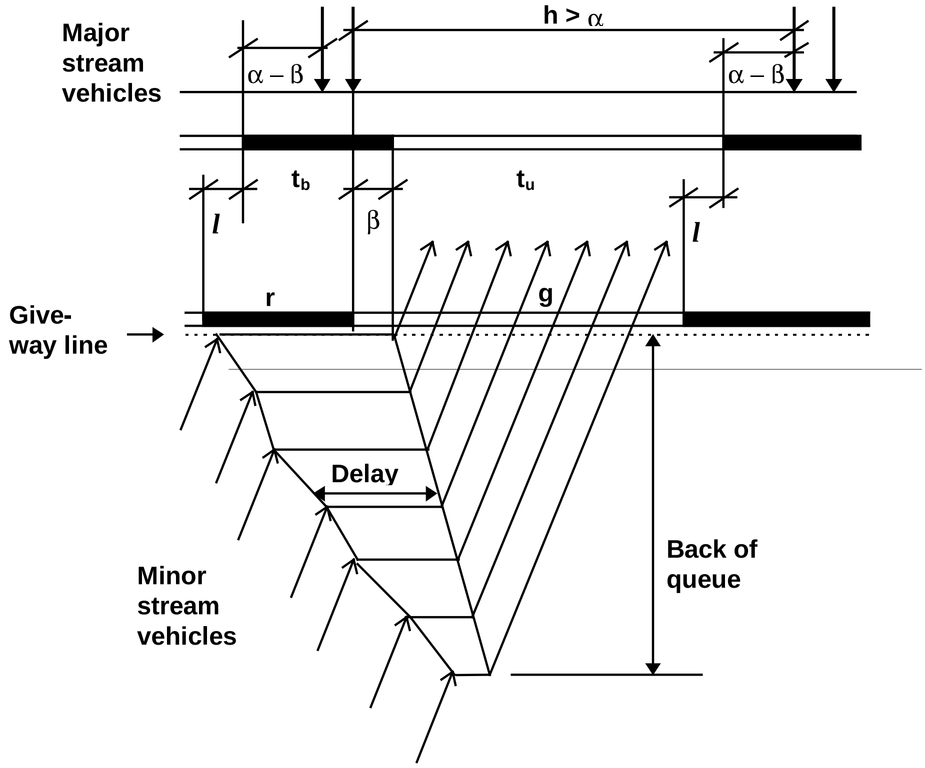

Figure 5 - The case of short delay and long queue (an example)

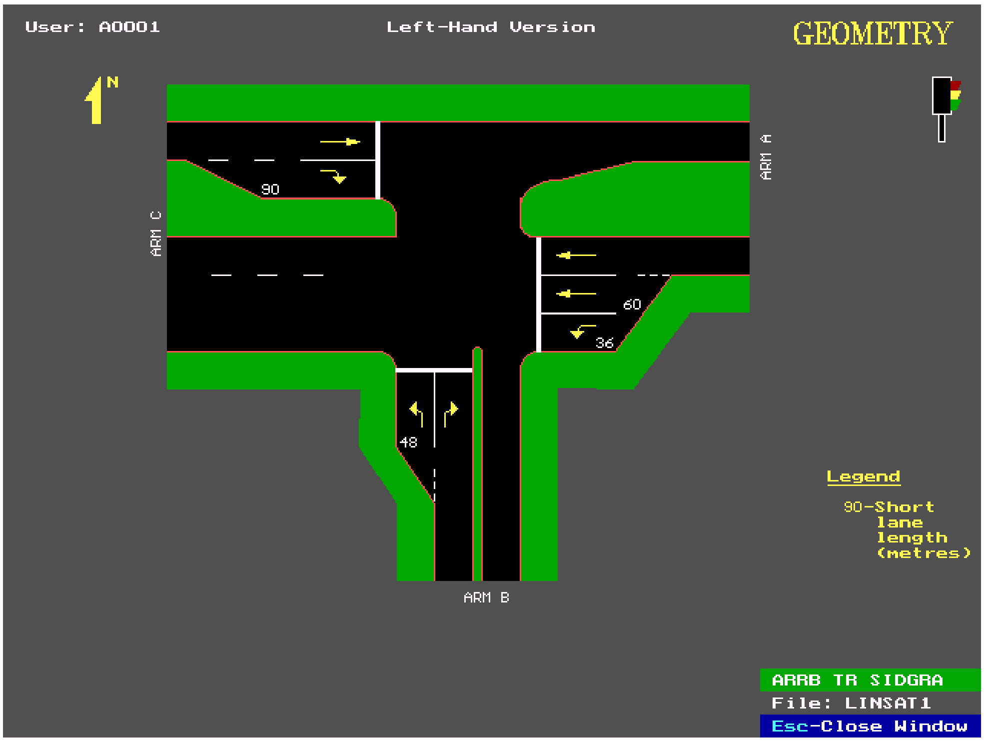

Figure 6a - SIDRA intersection geometry screen for the signalised intersection example with short lanes

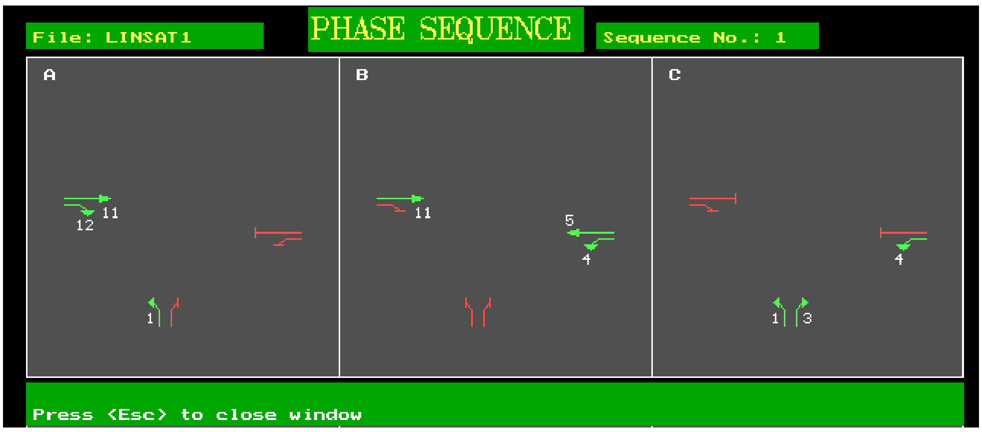

Figure 6b - SIDRA intersection phasing screen for the signalised intersection example with short lanes

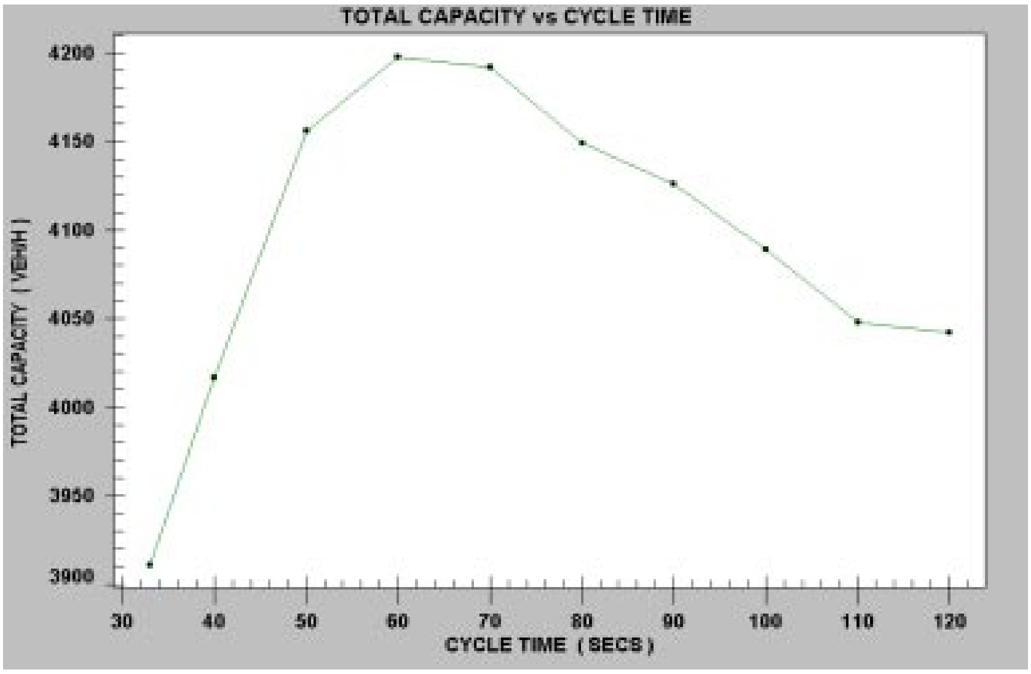

Figure 7a - Total intersection capacity as a function of the cycle time as predicted by SIDRA for fixed-time signals (Case 1)

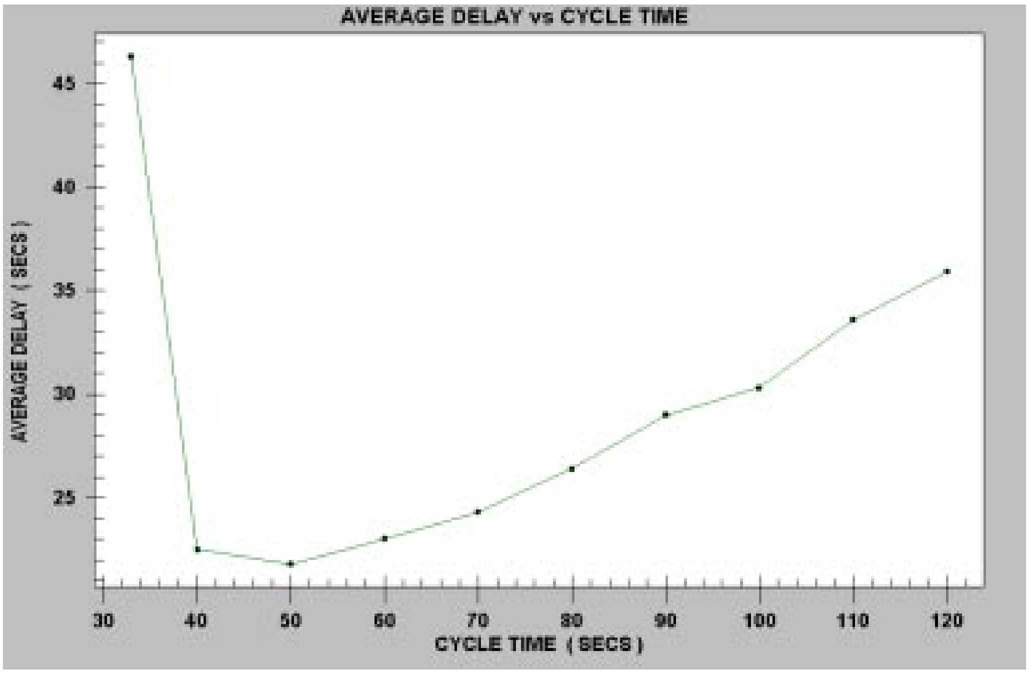

Figure 7b - Average intersection delay as a function of the cycle time as predicted by SIDRA for fixed-time signals (Case 1)

Table VIIa

SIDRA predictions for fixed-time, isolated signals (Case 1, c = 50 s)

	Lane & Mov.	r (s)	g (s)	q (veh/h)	s (veh/h)		Q (veh/h)	x (= q/Q)	d (s/veh)	N_b (vehs)	N_b (m)	SL (m)
Arm A	1 L	21	29	500	1068	<	619	0.807	24.0	6.0	36	36
	2 T	38	12	350	1900		456	0.768	22.7	5.6	33	60
	3 T	38	12	350	1900		456	0.768	22.7	5.6	33	
Arm B	1 L	22	28	228	1291	<	723	0.315	15.6	1.7	10	48
	2 R	38	12	342	1810		434	0.787	32.9	5.6	34	
Arm C	1 T	22	28	500	1900		1064	0.470	7.2	4.5	27	
	2 R	39	11	300	1810		398	0.754	32.4	4.8	29	90

< means reduced short lane saturation flow

Table VIIb

SIDRA predictions for fixed-time, isolated signals (Case 1, c = 100 s)

	Lane & Mov.	r (s)	g (s)	q (veh/h)	s (veh/h)		Q (veh/h)	x (= q/Q)	d (s/veh)	N_b (vehs)	N_b (m)	SL (m)
Arm A	1 L	28	72	500	722	<	520	0.962	24.5	6.0	36	36
	2 T	63	37	260	1123	<	416	0.626	24.7	5.7	34	60
	3 T	63	37	440	1900		703	0.626	27.8	10.8	65	
Arm B	1 L	47	53	228	825	<	437	0.522	23.0	3.6	22	48
	2 R	70	30	342	1810		543	0.630	42.2	8.9	53	
Arm C	1 T	40	60	500	1900		1140	0.439	11.5	8.0	48	
	2 R	82	18	300	1810		326	0.921	71.8	11.3	68	90

Table VIII

SIDRA predictions for fixed-time coordinated signals with platooned arrivals (Case 2, c = 100 s)

	Lane & Mov.	r (s)	g (s)	q (veh/h)	s (veh/h)		Q (veh/h)	x (= q/Q)	d (s/veh)	N_b (vehs)	N_b (m)	SL (m)
Arm A	1 L	28	72	500	1787	<	1287	0.389	11.7	0.9	6	36
	2 T	54	46	324	1636	<	753	0.430	8.1	3.1	19	60
	3 T	54	46	376	1900		874	0.430	8.4	3.9	23	
Arm B	1 L	56	44	228	744	<	327	0.697	33.8	5.4	33	48
	2 R	79	21	342	1810		380	0.900	62.9	11.9	71	
Arm C	1 T	31	69	500	1900		1311	0.381	6.9	6.2	37	
	2 R	82	18	300	1810		326	0.921	71.8	11.3	68	90

Table IXa

SIDRA predictions for isolated vehicle-actuated signals (Case 3-A, c = 50 s)

	Lane & Mov.	r (s)	g (s)	q (veh/h)	s (veh/h)		Q (veh/h)	x (= q/Q)	d (s/veh)	N_b (vehs)	N_b (m)	SL (m)
Arm A	1 L	20	30	500	1067	<	640	0.781	19.9	5.1	31	36
	2 T	35	15	350	1900		570	0.614	17.5	4.7	28	60
	3 T	35	15	350	1900		570	0.614	17.5	4.7	28	
Arm B	1 L	25	25	228	1333	<	667	0.342	17.6	2.0	12	48
	2 R	40	10	342	1810		362	0.945	44.7	7.2	43	
Arm C	1 T	20	30	500	1900		1140	0.439	6.2	4.1	25	
	2 R	40	10	300	1810		362	0.829	34.6	5.0	30	90

Table IXb

SIDRA predictions for isolated vehicle-actuated signals (Case 3-B, c = 100 s)

	Lane & Mov.	r (s)	g (s)	q (veh/h)	s (veh/h)		Q (veh/h)	x (= q/Q)	d (s/veh)	N_b (vehs)	N_b (m)	SL (m)
Arm A	1 L	35	65	440	677	<	440	1.000	27.7	6.0	36	36
	2 T	65	35	287*	1153	<	404	0.711	27.9	6.6	40	60
	3 T	65	35	473	1900		665	0.711	31.6	12.3	74	
Arm B	1 L	45	55	228	822	<	452	0.504	22.3	3.5	21	48
	2 R	75	25	342	1810		452	0.756	49.3	9.7	58	
Arm C	1 T	35	65	500	1900		1235	0.405	9.2	7.0	42	
	2 R	75	25	300	1810		452	0.663	47.7	8.2	49	90

*** Includes excess left-turn flow of 60 veh/h from Lane 1**