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Comparing lane based and lane-group based models of signalised intersection networks

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Abstract
This paper compares two analytical approaches for modelling signalised intersection networks in relation to the assessment of signal coordination quality as a fundamental element of network performance analysis. These are (i) the traditional model based on using "lane groups" or "links" through aggregation of individual lane conditions, and (ii) a new "lane-based" model of upstream departure and downstream arrival patterns as well as midblock lane changes between upstream and downstream intersections, and the resulting proportions of traffic arriving during the green period at an individual lane level. The latter is part of a lane-based network model that involves blockage of upstream intersection lanes by downstream queues (queue spillback) and capacity constraint applied to oversaturated upstream intersections. The differences between the two models are expected to be particularly important in evaluating closely-spaced intersections with high demand flows where vehicles have limited opportunities for lane changes between intersections. The lane-based model can make use of "special movement classes" for assigning specific movements to separate lanes and separate signal phases, and tracking of their second-by-second platoon patterns through the network separately. The paper presents a staggered T network example to demonstrate important aspects of modelling signal platoon patterns by approach lane use and movement class, and to compare the resulting traffic performance measures (delay, back of queue, level of service) with those estimated using the traditional method based on lane groups or links.

Keywords: traffic signals, intersection, network, lanes, lane groups, signal coordination, platoon, movement class, congestion, queue spillback, delay, queue, stops, level of service

1 Introduction

This paper presents a comparison of two different approaches to analytical modelling of signalised intersection networks. A new lane-based analytical model developed for the SIDRA INTERSECTION software (Akçelik 2015b; Akcelik and Associates 2015) and traditional lane-group (link) based models, for example as used in the US Highway Capacity Manual (TRB 2010) and the TRANSYT software (Robertson 1968, US DOT 1988) are considered for this purpose. Various discussions of the lane-based

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network model, including the discussion of lane blockage (queue spillback) and capacity constraint, have been presented in previous papers (Akçelik 2014a,b, 2015a,b; Nicoli, et al 2015; Yumlu, et al 2015). The two analytical modelling approaches compared in this paper differ from microsimulation modelling fundamentally. It would be useful to extend the lane use and performance comparisons to microsimulation modelling.

This paper discusses the implications of using a lane-based method for the modelling of vehicle platoon patterns in coordinated signal systems as distinct from the traditional lane-group (link) based models. For the lane-based model, the paper discusses the use of Special Movement Classes to assign selected movements to separate lanes as well as the use of unequal lane use specifications to minimize lane changes between closely-spaced intersections with the purpose of increasing the quality of signal coordination model. A staggered T-intersection example is presented to demonstrate important aspects of modelling signal platoon patterns by approach lane use and movement class.

2 Lane-Based Network Model

Unlike traditional network models that use aggregate models of *lane groups* or *links*, the *lane-based* network model can provide information about upstream departure and downstream arrival patterns, queue lengths, lane blockage probabilities, backward spread of queues, proportion of traffic arriving during green, and so on at an individual lane level. These are important in modelling vehicle platoon patterns for estimating performance measures (delay, back of queue, stop rate), and particularly important in evaluating closely-spaced signalised intersections with high demand flows where vehicles have limited opportunities for lane changing between intersections.

The new lane-based network model derives second-by-second downstream arrival patterns in accordance with the above requirements. Modelling of departure patterns at upstream lanes takes into account (i) probabilities of blockage by downstream queues (*queue spillback*) and the resulting capacity reductions at blocked upstream lanes, (ii) capacity constraint at oversaturated upstream lanes resulting in reduced downstream arrival flows, and (iii) lane choices of movements from approach lanes to exit lanes at the upstream intersection (lane movement flow proportions). The modelling of arrival patterns at downstream approach lanes takes into account implied midblock lane changes.

While estimation of individual lane capacities, lane flows and lane queues is important in assessing performance of a single intersection (Akçelik 1980, 1981, 1984, 1989, 1997), this becomes even more important in network modelling. The backward spread of congestion and upstream capacity constraint makes downstream and upstream lane departure and arrival patterns, lane capacities, lane flows and lane queues highly interdependent especially in the case of closely-spaced intersections.

Traditional network models have been concerned more about modelling forward movement of vehicle platoons than backward spread of queues between intersections (queue spillback) and capacity constraint related to oversaturated intersection conditions (Taylor and Abdel-Rahim 1998). Although all these elements are important, the lack of modelling of the capacity-reducing effect of blockage of departures by downstream queues and capacity constraint for oversaturated conditions on a lane-by-lane basis cannot provide a satisfactory network model for the high traffic demand conditions experienced in more recent times.

3 Vehicle Platoon Model for Signalised Intersection Networks

In the lane-based model, the modelling of *arrival patterns* of vehicle platoons at downstream intersection lanes takes into account lane changes due to *exit short lanes* at upstream locations and *approach short lanes* at downstream locations, as well as *midblock lane changes* based on matching of upstream and downstream lane flow rates. The second-by-second upstream departure flow patterns are moved forward towards the downstream lane stop lines at the approach cruise speed while applying any required lane changes. Any midblock inflow and outflow rates (differences in demand flow rates specified for upstream and downstream intersections) are also taken into account. The method is applied by Movement Class (Light vehicles, Heavy Vehicles, Buses, Large Trucks, etc.) since each class can have a different approach cruise speed and different lane use and can run in different signal phases.

The second-by-second platoon arrival patterns determined by the program are used for calculating *Percent Arriving During Green, Platoon Ratio,* and *Delay and Queue Progression Factors* for each approach lane for use in performance calculations. The method has its origin in the US Highway Capacity Manual (TRB 2010) for delay calculations (using the Delay Progression Factor), and its extension by the author (Akçelik 1995, 1996) for back of queue, queue clearance time, proportion queued, queue move-up rate and effective stop rate calculations (using the Queue Progression Factor).

The modelling of lane-based signal platoon patterns is further enhanced by using the Movement Class facility of the SIDRA INTERSECTION software. This is implemented by assigning two types of movements negotiating the network to Special Movement Classes: (i) through movements at external approaches which become turning movements at downstream internal approaches, and (ii) dogleg movements at staggered T intersections.

These movements can be assigned to separate lanes and separate signal phases, and their second-by-second platoon patterns can be tracked through the network separately. This improves the quality of signal platoon modelling and is expected to produce better results in assessing signal coordination quality and optimising signal offsets. The use of Special Movement Classes also helps to estimate unequal lane use cases at external approaches of a paired intersection system, a factor which also affects signal platoon patterns.

4 Analysis Using the Lane Based Network Model

A signalised staggered T intersection network is considered as an example to demonstrate important aspects of modelling signal platoon patterns and the resulting performance characteristics using a lane based model and comparing it with a lane-group based model.

The intersection geometry, signal phasing and related parameter values are shown in Figure 1.

Site Origin - Destination flows (intersection turning volumes) and Network Origin - Destination flows are shown in Figure 2.

The Site OD flows between the two intersections have been matched perfectly for the purpose of this example. If the Site OD flows at the two intersections result in upstream and downstream flows which do not match, midblock inflow and outflow values determined by the model are included in the analysis. This does not apply in this example. The Network OD flows that match the Site OD flows are also provided for analysing differences between analysis scenarios with and without the knowledge of Network OD flows.

For the lane-based network model, two analysis scenarios are considered to investigate the differences between the network model results including signal platooning and the resulting performance estimates with and without the use of Special Movement Classes and unequal lane use specifications to minimise midblock lane changes. The characteristics of the two analysis scenarios are described below.

Analysis Scenario (i) assumes that only the Site OD flows (intersection turning volumes) are known at each intersection, and the Network OD flows are not known. Under this scenario, equal lane use is assumed for the program to determine lane flow rates for multiple approach lanes, i.e. there are no user-specified lane utilisation ratios. The lane based model is able to use intersection turning volumes without knowing the Network OD flows but this is likely to imply significant midblock lane changes between the two intersections as shown by this example.

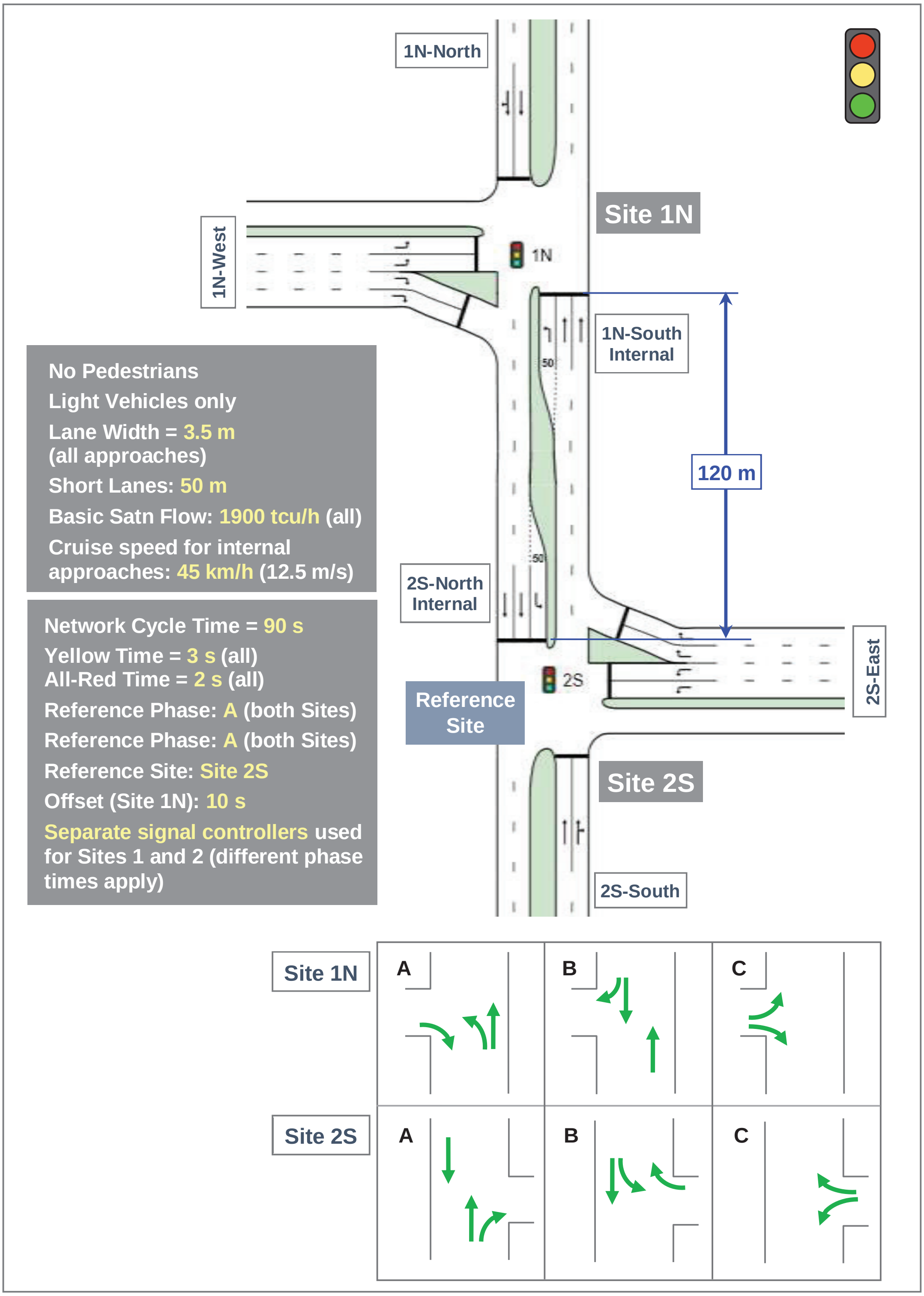

Figure 1 - Example: staggered-T intersection network (for both Scenarios (i) and (ii))

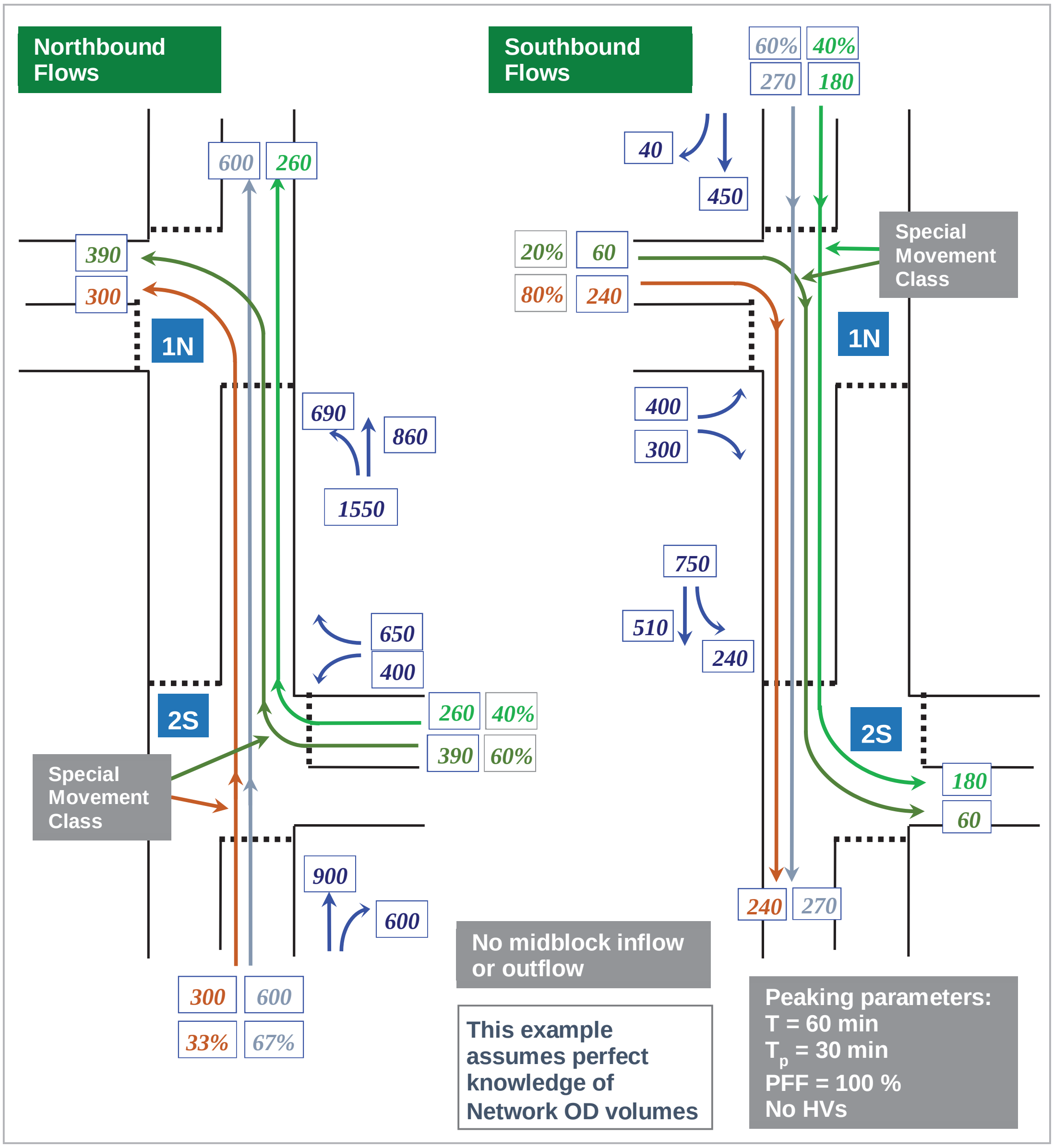

Figure 2 - Site and Network origin - destination (OD) flows for the example shown in Figure 1

Equal lane use for multiple approach lanes means that lane degrees of saturation are equal (Akçelik 1984, 1989, 1997). Where lanes have equal capacity values, equal lane use means equal lane flows. The assumption of equal lane use for all approaches of upstream and downstream intersections in the network results in implied midblock lane changes. These are identified by comparing the upstream lane flows (flows at entry to an internal approach) with downstream approach (stop line) lane flows.

Analysis Scenario (ii) assumes that the Network OD flows are known in addition to the Site OD flows as shown in Figure 2. It is a more detailed version of the use of the lane based network model. Special Movement Classes are assigned to upstream and downstream lanes according to destinations at the downstream intersection. This affects lane flow calculations generally, and in this example, the lane based model identifies unequal lane use for right-turning movement lanes on the East approach of Site 2 due to the high-volume dogleg movement (treated as a Special MC) assigned to Lane 3 only.

Under *Scenario (ii)*, lane utilisation ratios are specified for internal approach lanes at both intersections in order to minimise midblock lane changes. Lane utilisation ratio (LUR) is ratio of the subject lane degree of saturation to the degree of saturation of the critical lane in a lane group.

Both scenarios use default Lane Movement Flow Proportions based on 100% flow from each approach lane to the most direct exit lane.

Both scenarios are analysed using a Network Cycle Time of 90 s. For signal coordination purposes, Site 2 is the Reference Site (Offset = 0), and Phase A is the Reference Phase for both Sites. For all scenarios, Offset = 10 s was specified for Site 2. This means that the green time for the Site 2 Through phase starts at 0 seconds and the green time for the Site 1 Through phase starts at 10 seconds. This is around 80% of the travel time offset (13 s) for the Northbound Through movement, allowing for early arrival of the front of platoon due to platoon dispersion.

Phase Times were determined by the program by applying "green split priority" to coordinated (internal approach) movements as well as the external approach movements that start at the Reference Phase (Akçelik 1981, 1990). The Phase Times for the two scenarios differed (up to 4 seconds) due to different saturation flow rates resulting from changed lane use and different capacity losses due to lane blockage:

Scenario (i) Site 1N: Phase A = 56 s, Phase B = 18 s, Phase C = 16 s
Site 2S: Phase A = 58 s, Phase B = 18 s, Phase C = 14 s
Scenario (ii) Site 1N: Phase A = 56 s, Phase B = 18 s, Phase C = 16 s
Site 2S: Phase A = 54 s, Phase B = 20 s, Phase C = 16 s

5 Analysis Using the Lane-Group Based Network Model

The lane-group based network model of the example shown in Figures 1 and 2 is shown in Figure 3. It is seen that multiple lanes allocated exclusively to a movement are aggregated to a single lane group (link), or when there is a shared lane on the approach, all lanes used by the two movements sharing a lane are aggregated into a single lane group (link).

The lane saturation flow rates estimated by the lane based network model under *Scenario (i)* were aggregated to determine the lane group saturation flows. These are shown in Figure 3. These saturation flow rates include the effects of short lanes and upstream lane blockage (queue spillback) applicable in this example as estimated by the lane based network model. Since the lane-group based model does not have individual lane details, the model assumes equal lane use (even if this does not occur in reality).

When the lanes in a lane group have the same degree of saturation (equal lane use), the lane saturation flows can be added up to obtain the lane group saturation flow rate. When the lanes in a lane group have different degrees of saturation (unequal lane use), the lane saturation flow rates are weighted by lane utilisation ratios when obtaining the lane group saturation flow rate. This will ensure that the lane group degree of saturation equals the critical lane degree of saturation.

Signal timings obtained for *Scenario (i)* as given in Section 4 were specified for the lane-group based network model together with the saturation flow rates so as to limit the differences between the lane based and lane-group based models to modelling of signal platoons for the purpose of this paper. More extensive differences between the two models are expected to result if the signal timings are calculated by the lane-group model as well. In the lane-group based model, it is necessary to specify movement flow proportions for each upstream lane group according to the destination (downstream) lane group. Therefore, it is assumed that the network OD flows are known in the lane-group based network model for this example as in the lane based network model *Scenario (ii)* as shown in Figure 2.

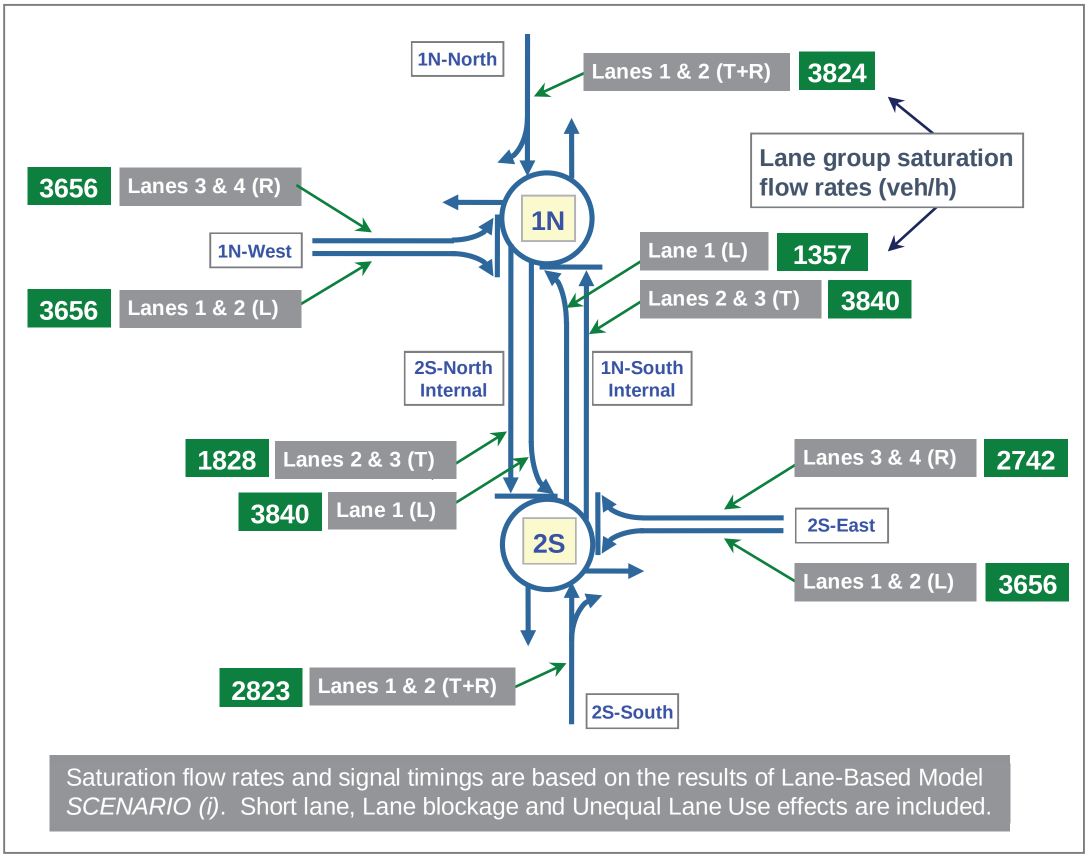

Figure 3 - Network specification and saturation flow rates for the Lane-Group Based Model for the example shown in Figures 1 and 2

For correct conversion of the queue length estimates in vehicles to queue distance values in metres for the lane-group based model, the default queue space values of 7 m for Light Vehicles and 13 m for Heavy Vehicles were halved for lane groups representing movements in two lanes.

6 Analysis Results

Both the lane based and lane-group based network models for the example shown in Figures 1 to 3 were processed in the SIDRA INTERSECTION software. This ensures that the differences between the two models are not due to inconsistent delay and queue equations (which might be the case when different software are employed). The lane-based approach is the main analysis method used in SIDRA INTERSECTION. The lane-group based approach was emulated by means of approximations using the software for this example only. For this purpose, each lane-group was treated effectively as a single lane with high saturation flow rate representing multiple lanes in the group where applicable.

Approach lane flows and midblock lane changes estimated by the lane based model are shown in Figure 4 for *Scenario (i)* and Figure 5 for *Scenario (ii)*. These detailed figures are provided for the purpose of visual representation of the method used to determine lane change values by comparing lane flow estimates for the upstream and downstream intersection lanes. Approach and exit lanes are numbered from left to right in the direction of movement. It is seen that equal lane use assumption implies significant midblock lane change values in *Scenario (i)* as seen in Figure 4. This is not expected in real-life operations when the distance between the two intersections is small.

With the use of special movement classes for lane assignment based on the knowledge of network OD flows, the implied midblock lane changes are reduced but still significant. Various assumptions are possible to minimise midblock lane changes when real-life observations of lane use are not available (Akçelik 2014a,b, 2015a). In this paper, unequal lane use is specified for internal approach Through movement lanes in *Scenario (ii)*. This minimises the midblock lane changes as seen in Figure 5. This is expected to be a more realistic representation of real-life operations in this case.

The results for *Scenarios (i) and (ii)* of the lane based model as well as the lane-group based model results are given in Table 1 for the South (internal) approach lanes of Site 1N and the East (external) approach lanes of Site 2S.

Significant differences in signal platoon characteristics (as indicated by the values of percent arriving during green and platoon ratio) and the delay and queue length values for the three cases are seen in Table 1. The analysis results for this example demonstrate significant effects of unequal lane use and lane blockage of upstream lanes (queue spillback) on the capacity and performance of the network.

Under both scenarios of the lane based model, short lane queue overflows from Lane 1 of the Site 1N South approach, and results in the adjacent lane queue blocking Lane 1 of the South approach and Lane 3 of the East approach at Site 2S, thus causing capacity reductions on these lanes. The amount of blockage is different under *Scenarios (i) and (ii)*.

The lane-group based model does not estimate performance of individual lanes. The differences in individual lane values can be significant especially for the back of queue estimates when the approach (midblock) distance between intersections is small, and therefore lane blockage effects are likely to come in, and when sensitivities are higher at high degrees of saturation. Average delay values per lane group can hide larger values of delay in individual lanes used by the movement when there is significant unequal lane use.

It is seen that both the lane group based model and *Scenario (i)* of the lane based model underestimated the delay and queue length on the East approach of Site 2S due to the assumption of equal lane use. On the other hand, in *Scenario (ii)* of the lane based model, the use of special movement classes identified the unequal lane use and the resulting high degree of saturation, delay and queue length values in Lane 3 of the East approach at Site 2S. Thus, the use of special movement classes helps with better estimation of the unequal lane use often observed at closely-spaced intersections due to the network origin - destination effects. Signal timings get affected by unequal lane use as well, and these in turn affect platoon characteristics, delay and queue length results.

7 Conclusions

Two lane use scenarios in the lane-based analytical network model and the lane-group based network model lane that does not consider lane use are analysed using the SIDRA INTERSECTION software and the resulting signal platoon characteristics and the delay and queue length estimates are compared using a staggered T intersection network example. It is shown that significant differences can results between these models.

The importance of the modelling of unequal lane use at closely-spaced intersections is emphasised. This method coupled with a lane-based model allowing for the backward spread of congestion and upstream capacity constraint, as well as features such as short lane overflow, is expected to produce better results in assessing signal coordination quality and optimising signal offsets.

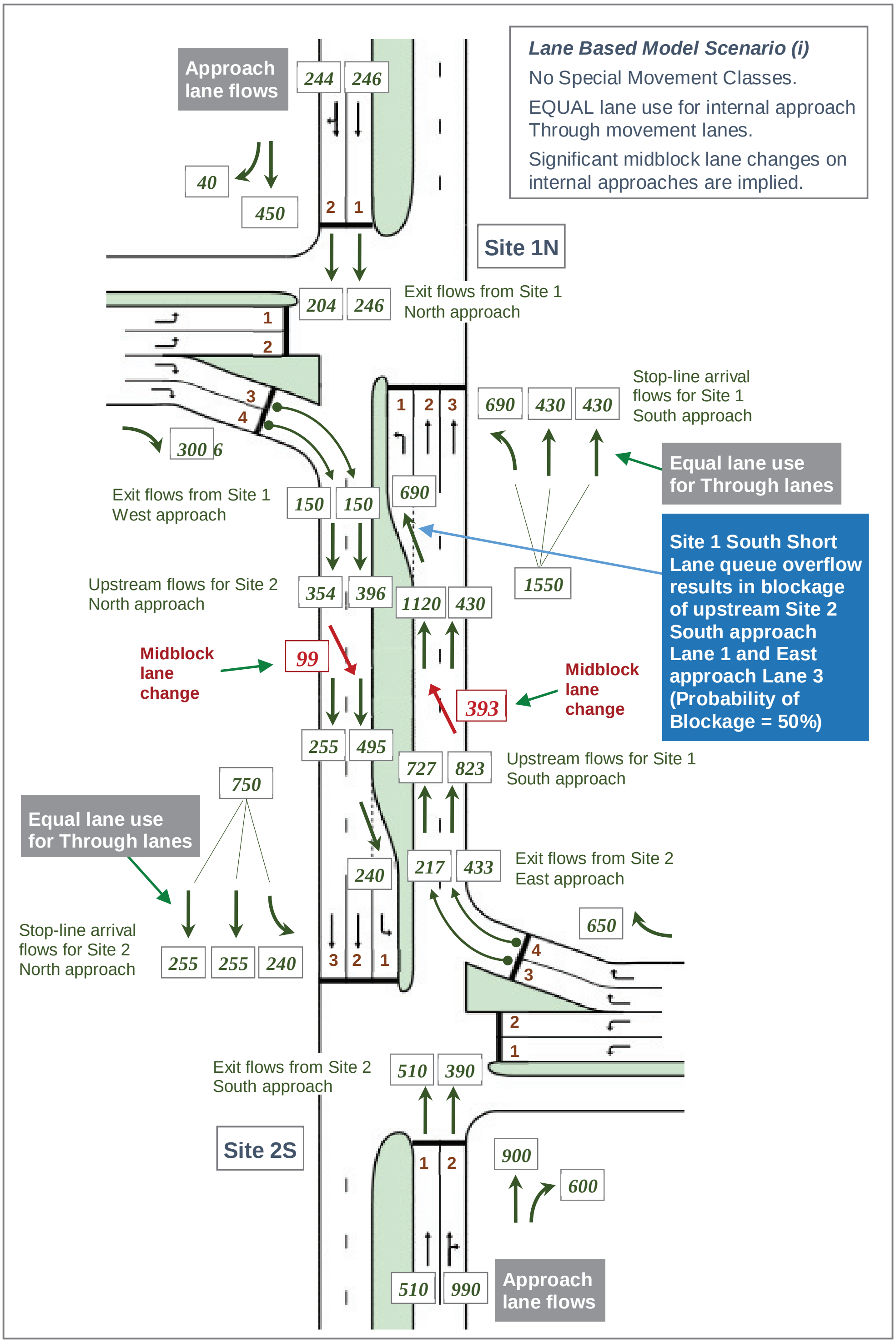

Figure 4 - *Scenario (i)*: No Special Movement Classes and EQUAL lane use for internal approach Through movement lanes for the example shown in Figures 1 and 2

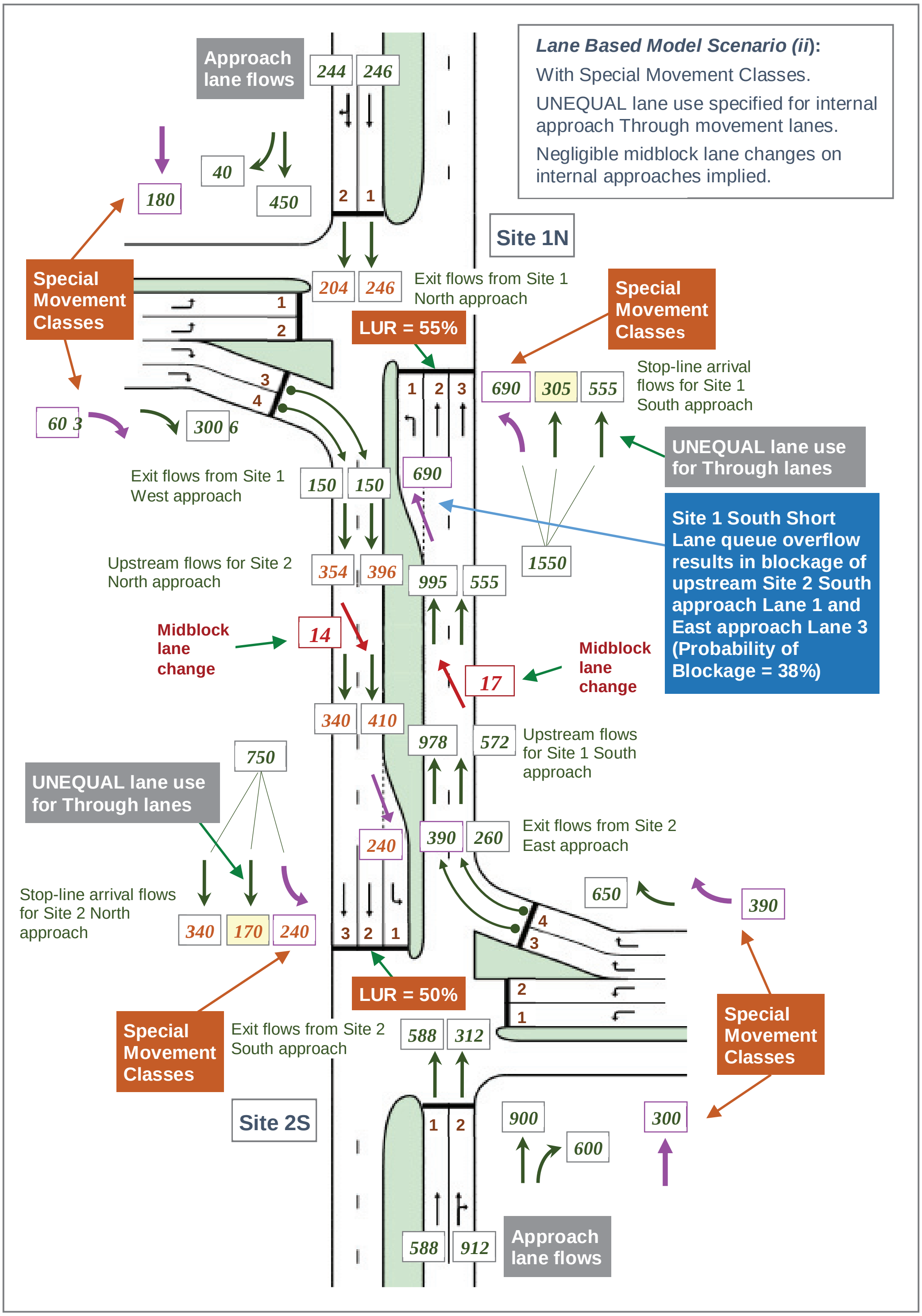

Figure 5 - *Scenario (ii)*: WITH Special Movement Classes and UNEQUAL lane use for internal approach Through movement lanes for the example shown in Figures 1 and 2

Table 1: Results for lane based model *Scenarios (i) and (ii)* and the lane-group based model for South (internal) approach lanes of Site 1N and East (external) approach lanes of Site 2

Lanes and Lane Groups	Arrival Flow (veh/h)	Saturation Flow (veh/h)	Degree of Saturation (v / c)	Per cent Arriving During Green (%)	Platoon Ratio	Average Delay (s)	95th %ile Back of Queue (m)
LANE BASED MODEL Analysis Scenario (i) Network OD Volumes NOT known. Special Movement Classes or Unequal Lane Use NOT specified.							
LANE BASED MODEL: Site 1N - South approach [Saturation Flows program-determined]							
Lane 1	690	1357 (1)	0.897	58.8%	1.038	34.9	196
Lane 2	430	1920	0.292	76.2%	0.994	3.3	39
Lane 3	430	1920	0.292	66.6%	0.869	4.4	54
LANE BASED MODEL: Site 2S - East approach [Saturation Flows program-determined]							
Lane 3	217	914 (2)	0.790	30.0%	1.000	45.1	72
Lane 4	433	1828	0.790	30.0%	1.000	40.5	133
LANE BASED MODEL Analysis Scenario (ii) Network OD Volumes known. Special Movement Classes and Unequal Lane Use specified.							
LANE BASED MODEL: Site 1N - South approach [Saturation Flows program-determined]							
Lane 1	690	1459 (1)	0.835	45.4%	0.801	23.8	171
Lane 2	305 (3)	1920	0.207 (3)	98.0%	1.278	0.3	2
Lane 3	555	1920	0.377	90.6%	1.181	1.7	24
LANE BASED MODEL: Site 2S - East approach [Saturation Flows program-determined]							
Lane 3	390	1143	0.991	34.4%	1.000	89.9	201
Lane 4	260 (4)	1828	0.413 (4)	34.4%	1.000	30.0	62
LANE-GROUP BASED MODEL Saturation flow rates and signal timings from LANE BASED model Scenario (i) used.							
LANE-GROUP BASED MODEL: Site 1N - South approach [Saturation Flows specified]							
Group 1 (Lane 1)	690	1357	0.897	41.0%	0.724	41.0	124
Group 2 (Lanes 2 & 3)	860	3840	0.292	82.2%	1.072	2.9	30
LANE-GROUP BASED MODEL: Site 2S - East approach [Saturation Flows specified]							
Group 2 (Lanes 2 & 3)	650	2742	0.790	30.0%	1.000	38.2	95

(1) Saturation Flow reduced due to Short Lane effect.

(2) Saturation Flow reduced due to downstream queue blockage.

(3) Unequal Lane Use specified to minimise midblock lane changes (Lane Utilisation Ratio = 55%). See Figure 5.

(4) Unequal Lane Use identified by the program due to Special movement Class (dogleg movement) assigned to Lane 3 (Utilisation Ratio = 42%). See Figure 5.

Further analyses of different lane use scenarios are recommended for their effects on signal platoon patterns and resulting performance estimates. Real-life surveys of lane use at closely-spaced intersections and analyses using micro-simulation to compare results with those from analytical models are recommended.

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