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Dipartimento di Ingegneria Civile, Edile ed Ambientale

Tesi di laurea:

Analysis of bus lanes at signalized intersections: field observations vs. modeling with "Sidra Intersection 5.1" and "LinSig 3.1".

Analisi di corsie preferenziali per i bus nelle intersezioni semaforizzate: osservazioni sperimentali e modellazione con "Sidra Intersection 5.1" e "LinSig 3.1".

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INTRODUCTION

This thesis, that has been developed in Norway thanks to an Erasmus scholarship, has been drafted in part in Norway under the supervision of Arvid Aakre (professor at NTNU, Norwegian University of Science and Technology) and in part in Italy under the supervision of Claudio Meneguzzer (professor at the University of Padova).

The main goals of the thesis are to model an intersection with and without a bus priority lane using the software Sidra Intersection 5.1, and to analyze the outputs, comparing them to results achieved during the field observations (carried out in Trondheim, Norway).

Before describing the modeling of the real intersection in Trondheim, Sidra capabilities will be listed and illustrated through a short summary of the user manual and through some examples presented during a workshop in Oslo. It should be highlighted that this "training" has been very useful in order to reach an adequate knowledge of the traffic modeling tool.

After the software description, the field observation details will be given and the data processing will be defined. All the information collected during the field survey will be used as input parameters (for example, traffic volumes, geometric characteristics and so on) in the modeling, while the data processing results will be compared to Sidra Outputs.

Moreover, in order to make the thesis project more exhaustive, another traffic engineering software will be used and once again the outputs will be utilized for the comparison. This software is LinSig, version 3.1 (JCT Consultancy).

The thesis will end with a presentation of the main conclusions about the software modeling, highlighting some limitations of the study and indicating some possible directions for future research.

ACKNOWLEDGEMENTS (RINGRAZIAMENTI)

Quando ho iniziato questo lungo e impegnativo percorso di studi, oramai la bellezza di sette anni fa, mai avrei pensato che la mia carriera universitaria si sarebbe conclusa con una tesi in inglese frutto di sei splendidi mesi nella fredda e calorosa Norvegia. Eppure sono qui, davanti a 125 pagine di fatica e soddisfazione, pronto ad iniziare un nuovo capitolo della mia vita, tanto incerto quanto stimolante.

E allora non posso che ringraziare tutte le persone che in questi anni mi hanno sostenuto e aiutato nei più svariati modi a raggiungere l'obiettivo finale.

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Un grazie speciale a tutta la mia incredibile famiglia. Sembrerà banale, ma le parole non sono sufficienti per spiegare tutto quello che sono stati in grado di fare per me in questi anni, quindi mi limiterò a ricordarlo dentro di me, credo sia più che sufficiente. Mamma Daniela, Luigi, Giada, Nonna Lucia, Zia Stefania, Simone e Zio Costantino, persone speciali per una famiglia speciale.

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Come non ringraziare i miei colleghi di studio Marco, Giovanni, Martino e Marco, con i quali le "centinaia" di ore davanti ai libri si sono rivelate più leggere e divertenti del previsto.

And last but not least, my international “Never give up crew”, with whom I spent six of my best months ever. Actually they didn’t help me with the thesis (this is clear), but they gave me something unforgettable. Thank you Andres, Eira, Silvia, Ines, Beppe, Mirko, Ju Ju, Artitz, Carmen, Vittoria, Stefano, Francesco, Alberto, Fabio, Giusy and Iolanda.

Orgogliosamente dedico la mia tesi e la mia laurea ad una persona che mi ha lasciato troppo presto ma che allo stesso tempo mi ha fatto diventare quello che sono. A te Papà.

CHAPTER I

INTRODUCTION TO SIDRA INTERSECTION

In this chapter, the main characteristics of Sidra Intersection will be described. The purpose is to understand what Sidra is and what Sidra can do.

Thus, all the input dialogs will be listed and described.

In addition some important model parameters will be identified for calibrating Sidra Intersection, in order to obtain valid outputs.

Then the main output parameters taken into consideration during the comparison of alternative intersection designs will be listed, but the explanation of each parameter will be given in the next chapters when they will be used.

I. 1. What is Sidra Intersection?

The Sidra Intersection software is “an advanced micro-analytical tool for evaluation of alternative intersection designs in terms of capacity, level of service and a wide range of performance measures including delay, queue length and stops for vehicles and pedestrians, as well as fuel consumption, pollutant emissions and operating cost.”¹

The first release of the software was in 1984 with the name Sidra 2.0 (**S**ignalized, and unsignalized, **I**ntersection **D**esign and **R**esearch **A**id). In this thesis, the last version of Sidra Intersection, Version 5.1 released in March 2011, following the release of Highway Capacity Manual 2010, has been utilized.

The flexibility of Sidra Intersection allows its application to many other situations, including uninterrupted traffic flow conditions and merging analysis.

Sidra Intersection employs lane-by-lane and vehicle drive-cycle models coupled with an iterative approximation method to provide estimates of capacity and performance statistics (delay, queue length, stop rate, etc). Although Sidra Intersection is a single intersection analysis package, a traffic signal analysis can be performed as an isolated intersection or as a coordinated intersection by specifying platooned arrival data. The platoon is a group of vehicles or pedestrians travelling together because of signal control, geometric condition or other factors.

Figure 1.1 explains the position of Sidra Intersection in the traffic model hierarchy². The Y axis of the diagram represents the traffic stream, from the least detailed to the most detailed model. In a similar way the X axis represents the road geometry.

¹ Sidra Intersection Guide – Introduction, Part.1-3.

² Sidra Intersection, Training Workshop, Introduction Examples & Notes, Oslo, Norway, 2011. Akcelik & Associates Pty Ltd.

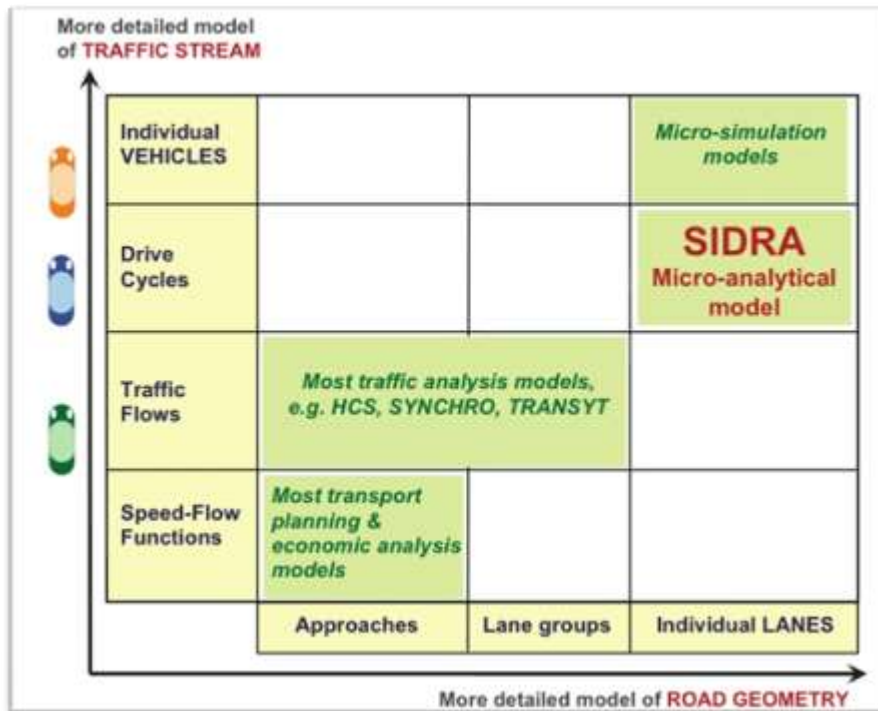


Fig. 1.1

I. 2. What Sidra Intersection can do

The Sidra Intersection uses are several and in Chapter II some of them will be analyzed. Anyway in the following list, it will be shown what Sidra Intersection can do, according to the user manual:

- analyze a large number of intersection types including signalized intersections (fixed-time/pretimed and actuated), signalized pedestrian crossings, single point interchanges (signalized), roundabouts, metered roundabouts, two-way stop sign control, all-way stop sign control, and give-way/yield sign-control;
- obtain estimates of capacity and performance characteristics such as delay, queue length, stop rate as well as operating cost, fuel consumption and pollutant emissions for all intersection types;
- analyze many design alternatives to optimize the intersection geometry, signal phasing and timings specifying different strategies for optimization;
- handle intersections with up to 8 legs, each with one-way or two-way traffic, one-lane or multi-lane approaches, and short lanes, slip lanes, continuous lanes and turn bans as relevant;

- determine signal timings (fixed-time/pretimed and actuated) for any intersection geometry allowing for simple as well as complex phasing arrangements;
- carry out a design life analysis to assess impact of traffic growth;
- carry out a parameter sensitivity analysis for calibration, optimization, evaluation and geometric design purposes;
- design intersection geometry including lane use arrangements taking advantage of the unique lane-by-lane analysis method of Sidra Intersection;
- design short lane lengths (turn bays, lanes with parking upstream, and loss of a lane at the exit side);
- analyze effects of heavy vehicles on intersection performance;
- analyze complicated cases of shared lanes and opposed turns (e.g. permissive and protected phases, slip lanes, turns on red);
- analyze oversaturated conditions making use of the time-dependent delay, queue length and stop rate models used in Sidra Intersection.

For all types of intersection, Sidra Intersection uses advanced models and methods, including lane-by-lane analysis (rather than analysis by lane groups), modeling of short lanes, detailed modeling of geometric delays, and the use of drive cycles (cruise, acceleration, deceleration and idling) for detailed modeling of delay and travel time components as well as operating cost, fuel consumption and emission estimation.

For signalized intersections, in addition to the general features mentioned above, advanced signal timing methods are available, and the use of two green periods for modeling slip lanes, RTOR and permitted-protected left-turns provides more accurate capacity estimates.

The HCM (Highway Capacity Manual), Sidra Intersection capacity and performance models are compatible in their basic structures and principles (e.g. the HCM back of queue model for signalized intersections was derived from the Sidra Intersection model), and although Sidra Intersection is a more detailed model than the HCM, Sidra Intersection works like an advanced version of the HCM by incorporating the HCM defaults in its HCM version.

The HCM version of Sidra Intersection is based on the calibration of most model parameters using the HCM defaults as applicable. HCM 2010 defaults have been adopted in Sidra Intersection Version 5.1.

Sidra Intersection includes various configuration options to allow the user to choose between the HCM and SIDRA standard model options, e.g. the HCM Delay and Queue model options.

The HCM Delay Formula and HCM Queue Formula options in Sidra Intersection will cause delays and queues for signalized intersections, roundabouts and two-way stop-sign control to be calculated using the HCM equations regardless of the model setup chosen. Otherwise, the standard Sidra Intersection delay and queue equations will be used in all cases.

The signalized intersection chapter of the Highway Capacity Manual includes a back of queue model which was developed by Akçelik (1995, 1996). The HCM back of queue model for signalized intersections will be used instead of the standard Sidra Intersection model when the HCM Queue Formula option is selected. The two models are based on the same modeling methodology and give close results.

The operation of the Sidra Intersection system is shown in Figure 1.2.

A Project system helps the user to manage various activities with ease. Many Sites can be created under a Project, like in the following examples in Chapter II. The first step is to prepare input for a site under the project, then process the site.

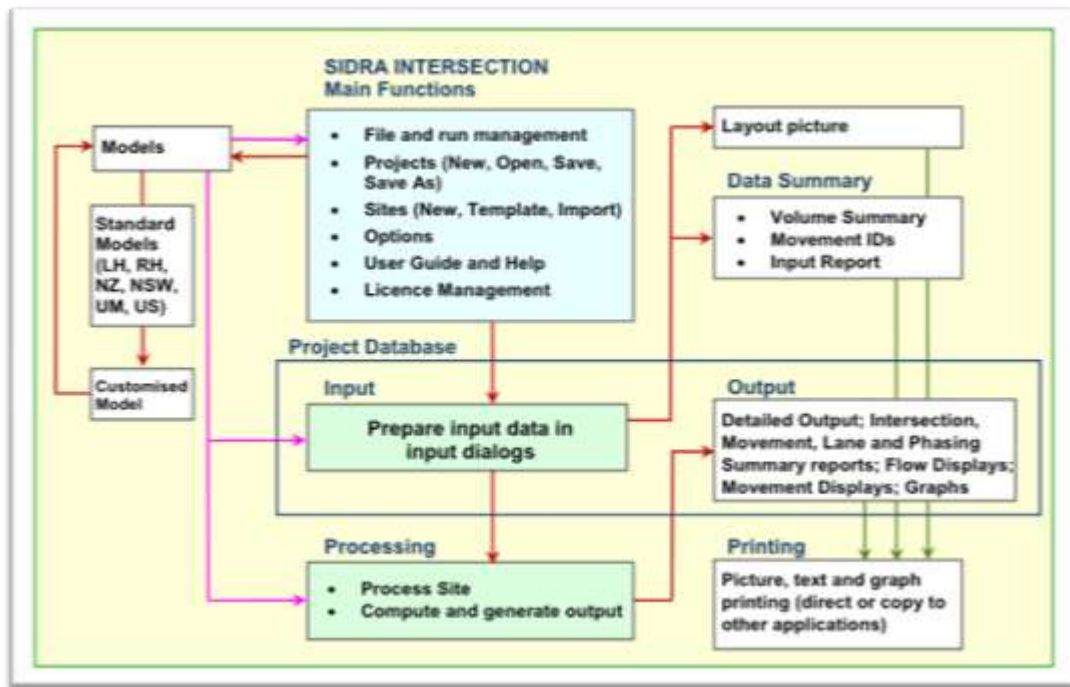


Fig. 1.2

Considering that in this thesis Sidra Intersection version 5.1 was used, for the sake of completeness, some new features introduced in this last version will be listed below:

- Export DAT File function introduced;
- German roundabout capacity models removed;
- API (application-programming interface) expanded to include Priorities data and computation, Phase Sequence data, Lane Discipline and Lane Type, Lane addition and deletion, Movement Turn Designation and Movement status;
- Substantial updates to all parts of the User Guide and the Help system including Troubleshooting topics.

I. 3. Sidra Utilities

Various API applications and other programs, that are available as part of the Sidra Utilities group of products, will be described in this section.

I. 3. 1. VOLUMES

The Volumes utility for Sidra Intersection is a macro-enabled Excel application that allows specification of volumes and related data within the Excel file, and

processes a selected site in a Sidra Intersection project using data given in the project file or in the Excel file, providing Intersection Summary, Movement Summary, Lane Summary and Pedestrian Movement outputs in Excel sheets.

The Volumes utility has two purposes:

- to enable volume data to be written from Excel into the Project file, thus:
 - facilitating the running of several sites with the same set of volumes,
 - allowing the volume data to be transferred from one Site to another,
 - allowing programmatically-generated volumes to be passed into site data without retyping;
- to enable the user to have the output in the Excel file, and also copy and paste the output into a Word document if desired.

I. 3. 2. ANNUAL SUMS

The Annual Sums utility for Sidra Intersection is a macro-enabled Excel application that allows determining yearly total values of various performance statistics (cost, fuel consumption, CO₂ and other emissions, delay, effective stops, travel time, etc.) for several flow periods and for two design options/scenarios, and gives comparison statistics and charts.

I. 3. 3. OUTPUT COMPARISON

The Output Comparison 5.1 utility, the most used tool, is an API program for Sidra Intersection 5.1 written in C#.

The program processes two Sites providing Intersection Summary output (for vehicle movements only) and comparing the results for the two Sites. The two Sites can be selected either from the same Project or from two different Projects.

The Output Comparison program has a simple interface for ease of use (Fig. 1.3).

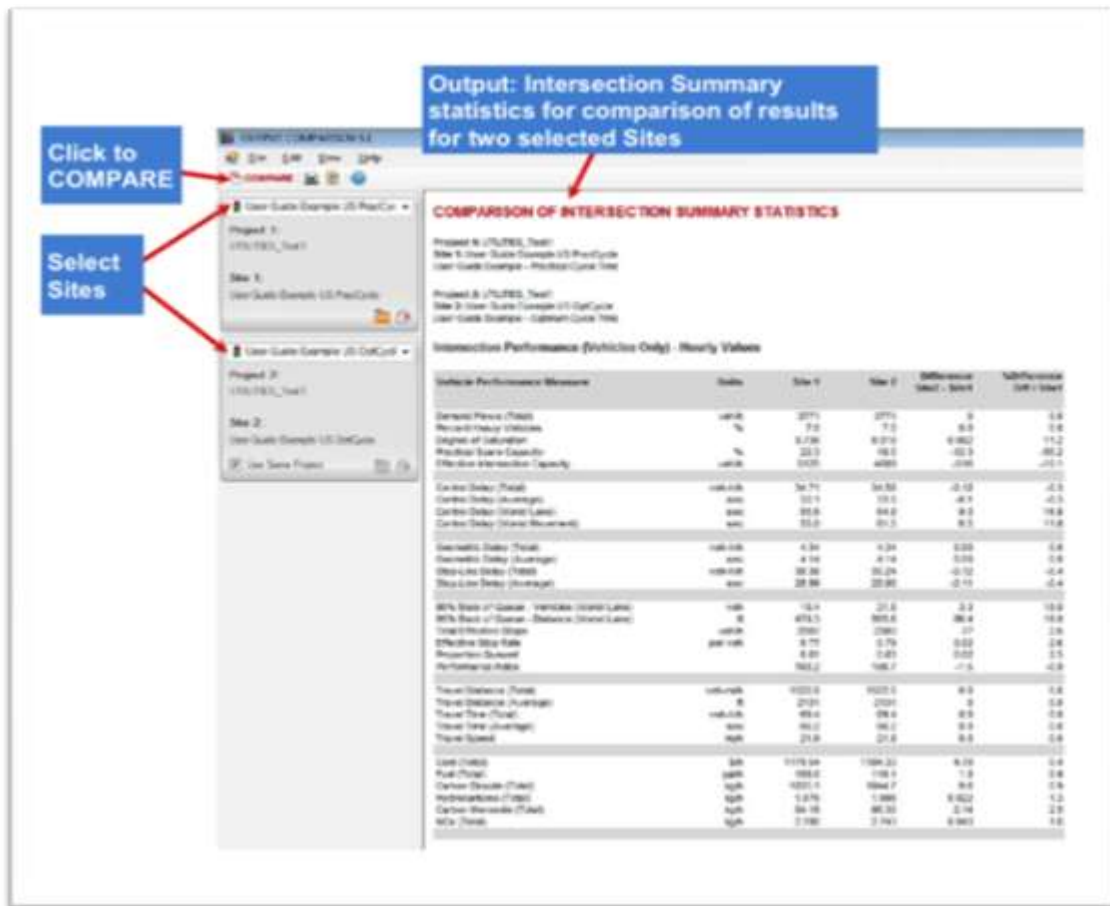


Fig. 1.3

The output can be printed directly, or easily copied and pasted into Word or Excel files.

Initially, the user interface will display:

- two empty drop-down lists for the selection of Site 1 (under Project 1) and Site 2 (under Project 2) on the left-hand side;
- an empty Output pane on the right-hand side.

Once selected the two different sites to compare, the COMPARE button should be clicked to obtain the output.

The two selected Sites will be processed using Sidra Intersection and the output statistics and comparisons for the two Sites will be shown in HTML format in the Output window.

Intersection Summary statistics will be shown in two tables (Hourly Values and Annual Values).

The comparison of statistics for Sites 1 and 2 is based on the use of Site 1 as representing base conditions. Thus, the percentage difference values are calculated from:

$$\% \text{ Difference} = 100 (x_2 - x_1)/x_1$$

where x_1 is the Site 1 value and x_2 is the Site 2 value.

I. 3. 4. VARIABLE RUN

The Variable Run 5.1 utility is an API program for Sidra Intersection 5.1 written in C#. The program processes a selected Site in a Sidra Intersection Project, providing Intersection Summary output for variable run results when an Optimum Cycle Time, Design Life, Flow Scale, or Sensitivity Analysis option is used.

I. 4. Input in Sidra Intersection

In this section the main procedures (modality) to insert the input data and to find out the correct parameters in order to calibrate the model will be shown. In addition, to collect good data from a real site visit, the suggestions proposed by the user guide will be listed.

Tab. 1.4 shows the input dialogs in Sidra Intersection.

• Intersection
• Geometry (includes Approach Data, Roundabout Data, Lane Configuration, Lane Data and Movement Definitions)
• HCM 2010 (Optional Roundabout Data)
• FHWA 2000 (Optional Roundabout Data)
• Freeway (for Single Point Interchange))
• Roundabout Metering
• Volumes
• Path Data
• Movement Data
• Priorities
• Gap-Acceptance
• Phasing & Timing (includes Phase Data, Vehicle Movement Timing Data, Pedestrian Movement Timing Data and Sequence Data)
• Pedestrians
• Model Settings (includes General Options, Roundabout Model Options and Cost Parameters)
• Demand & Sensitivity

Tab. 1.4

I. 4. 1. Input Data Preparation Form

It's helpful to summarize all relevant data in the Input Data Preparation Form as a first step in preparing input data. This is not essential but may be useful for organizing data collection in a formal way.

The required information is summarized below.

1) Intersection layout:

- a description such as existing or proposed;
- any turn bans, one way approaches or exits;
- all lanes (exclusive or shared) marked with clear indication of lane disciplines;
- slip lanes and continuous (uninterrupted traffic) lanes shown;

- upstream and downstream short lanes shown (turn bays, approach parking, and loss of a lane at the downstream side);
- lane widths and median widths given;
- pedestrian crossings indicated (full or staged);
- grade information given if available;
- any data related to adjacent parking, buses stopping, trams, etc.
- direction of North;
- roundabout island diameter, circulating road width, number of circulating lanes and other relevant data.

Volumes:

- volume counts in vehicles per 30 minutes, 60 minutes, etc.;
- heavy vehicle data for each turn (origin-destination) if available;
- the method of counting heavy vehicles: Separate LV and HV, Total Vehicles & HV (%), or Total Vehicles & HV (veh);
- pedestrian volume data if available (or relevant).

Signal phasing:

- phase descriptions and phase sequences showing movements which have right of way in each phase;

Other features:

- non-default total and peak flow periods and peak flow factor, flow scale, etc.;
- intersection control, i.e. Actuated or Fixed-Time Signals, Roundabout, Two-Way Stop or Giveaway/Yield, All-Way Stop;
- signal coordination and arrival type information;
- phase change times (if known);
- non-default timing data (yellow and all-red times, start loss and end gain, minimum and maximum green time, etc.);
- basic saturation flows, restricted turns, etc.;
- free queues for shared lanes;
- other special notes such as capacity losses due to blockage by downstream queues.

Once all the relevant data are summarized, the input coding may be performed.

I. 4. 2. Model Calibration

Important model parameters need to be identified for calibrating Sidra Intersection to reflect local road and driver characteristics and particular intersection conditions. Capacity and performance characteristics (delay, queue length, stops, etc) of a traffic facility are influenced by both the intersection geometry and driver behavior.

To a great extent, all input parameters related to intersection geometry and driver behavior are therefore important for calibrating the Sidra Intersection traffic model to represent particular intersection conditions. For practical purposes, the most important parameters for calibrating capacity and performance models are:

- saturation flow rate for signalized intersections,
- gap-acceptance parameters (especially follow-up headway and critical gap) for roundabouts and other unsignalized intersections.

Sidra Intersection, as reported in the user guide, provides various tools to help the user in model calibration effort. These include:

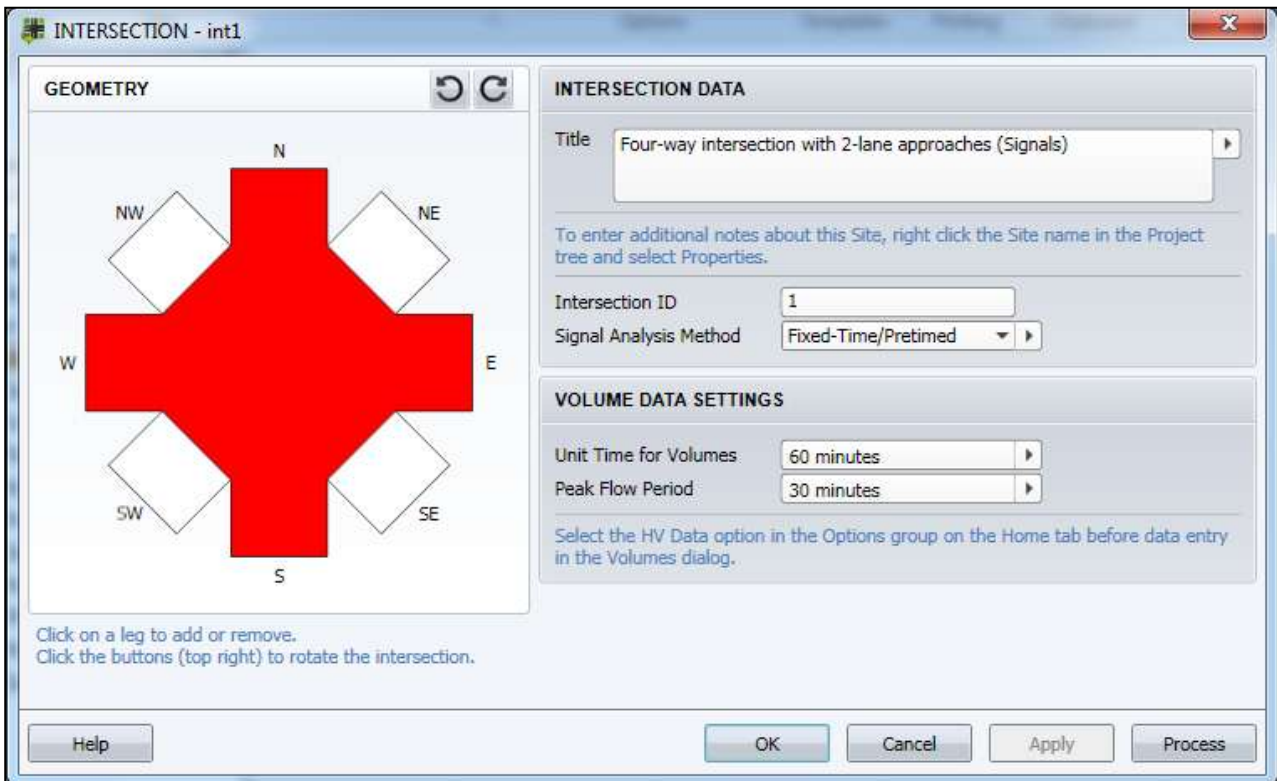
- the sensitivity analysis facility for all intersection (or site) types (see also I. 4. 14.);
- specific roundabout calibration parameters;
- lane utilization factor, and various other facilities.

I. 4. 3. Intersection Dialogue

The following list is required as a minimum in the intersection dialogue:

- a descriptive title of the intersection to be provided including location;
- Peak Flow Period and Unit Time for Volumes should be dependent on the data in the intersection counts where the Maximum Unit Time for Volumes and the Maximum Peak Flow Period are 60 minutes;
- geometry should closely resemble actual alignment and orientation of the intersection;
- Signal Analysis Method should reflect the actual or proposed intersection operation (only for signalized intersection).

The screen shot 1.5 shows the Intersection Dialogue.



Screen Shot 1.5

I. 4. 4. Geometry Dialogue

The following is required as a minimum in the Approaches & Lanes Dialogue:

- in the approach and exit lane data the name, the medians, the lane width, the lane length, the grade, the short lane, the lane type, the lane discipline and the approach control;
- if slip or continuous lanes are present then the appropriate selection is required in this dialogue;
- the maximum Basic Saturation flow (parameter for the calibration);
- values for Extra Bunching should be used if there are upstream signals in close proximity. Extra Bunching should only be applied to sign-controlled and roundabout intersections. A rough indication (Figure 1.6), reported from the user guide, gives the values that can be used to specify extra bunching as a function of the distance to upstream signals and the amount of platooning.

- Utilization Ratio, Saturation Speed & Capacity Adjustment data should only be manually overwritten if the appropriate intersection data has been collected or for calibration reasons;
- the turn designation should be as per the existing or proposed operation of the intersection;
- for signalized intersections, the parameters for Buses Stopping, Parking Maneuvers, Short Lane Green Constraints and Free Queue should only be inputted and included in the model if the parameter has a significant impact on the performance of the intersection;
- in the presence of roundabouts, island diameter, circulating width and number of circulating lanes should be as per the existing or proposed intersection geometry. This data must be specified for each approach.

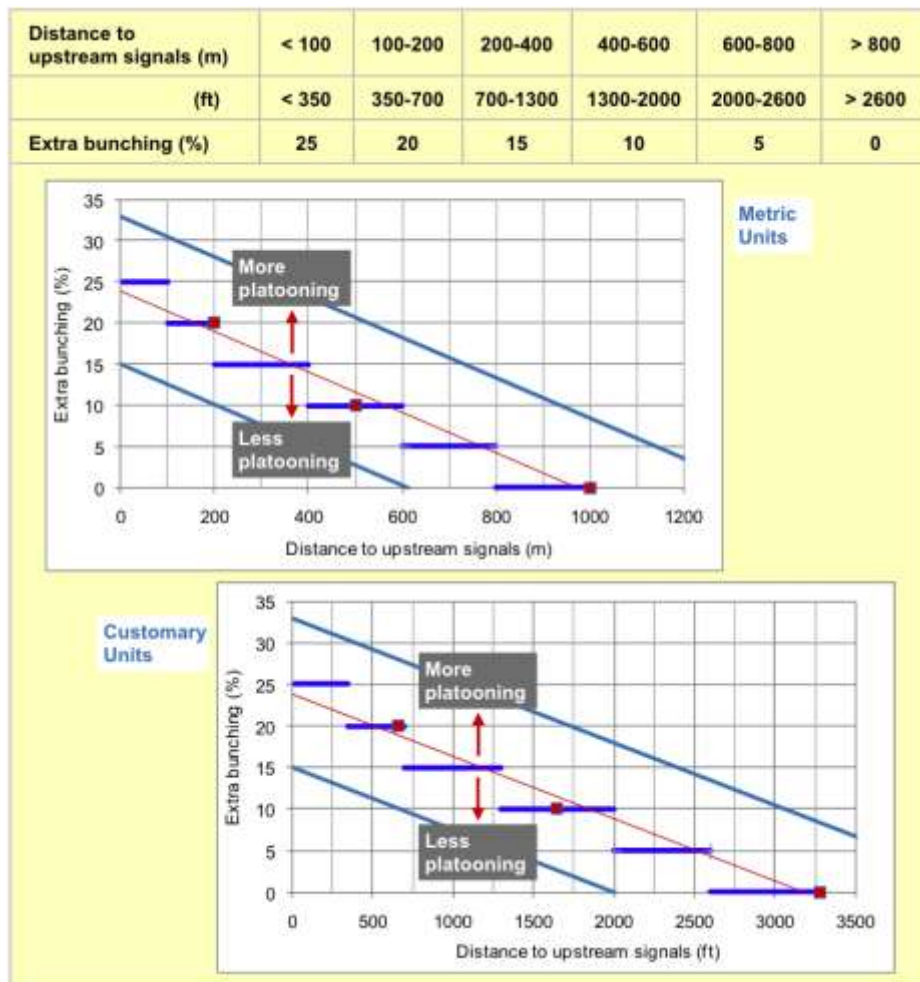


Fig. 1.6

Fig. 1.7 is a screen shot of the Geometry Dialogue for roundabouts, with the Lane and Movements tab open.

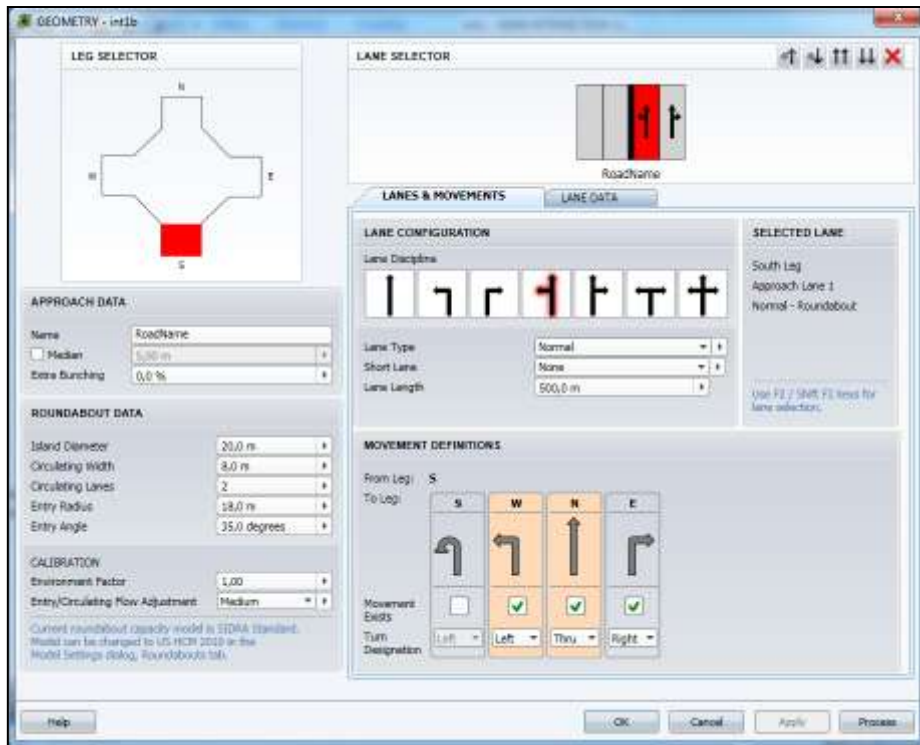


Fig. 1.7

In the same way, Fig. 1.8 is a screen shot of the Geometry Dialogue but for signalized intersections, with the Lane Data tab open.

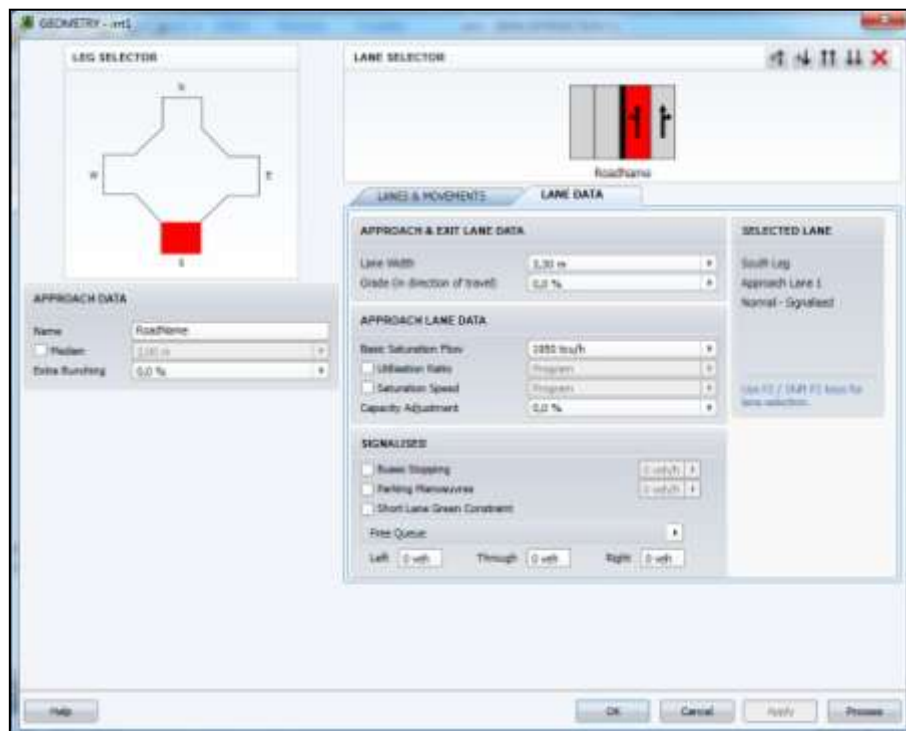


Fig. 1.8

I. 4. 5. Volumes Dialogue

The Volumes input dialog in the Movements group is based on vehicle movements selected by origin-destination (O-D). Volumes for pedestrian movements are given in the Pedestrians dialog (see Section I. 4. 13.) where applicable.

Vehicle Volumes are to be based on the most current data collected from an intersection survey (or count). The characteristics of the analysis of that data are to dictate the Peak Flow Factor used.

As shown in Figure 1.9, the Volumes dialog has two data groups, namely Volumes and Volume Factors.

The Volume Data Method (HV option) that can be set in the Options group in ribbon, and the Unit Time for Volumes and Peak Flow Period parameters specified in the Intersection dialog are relevant to the volume data given in the Volumes dialog. Vehicle demand volumes are specified in vehicles per unit time (in minutes) in the Volumes dialog.

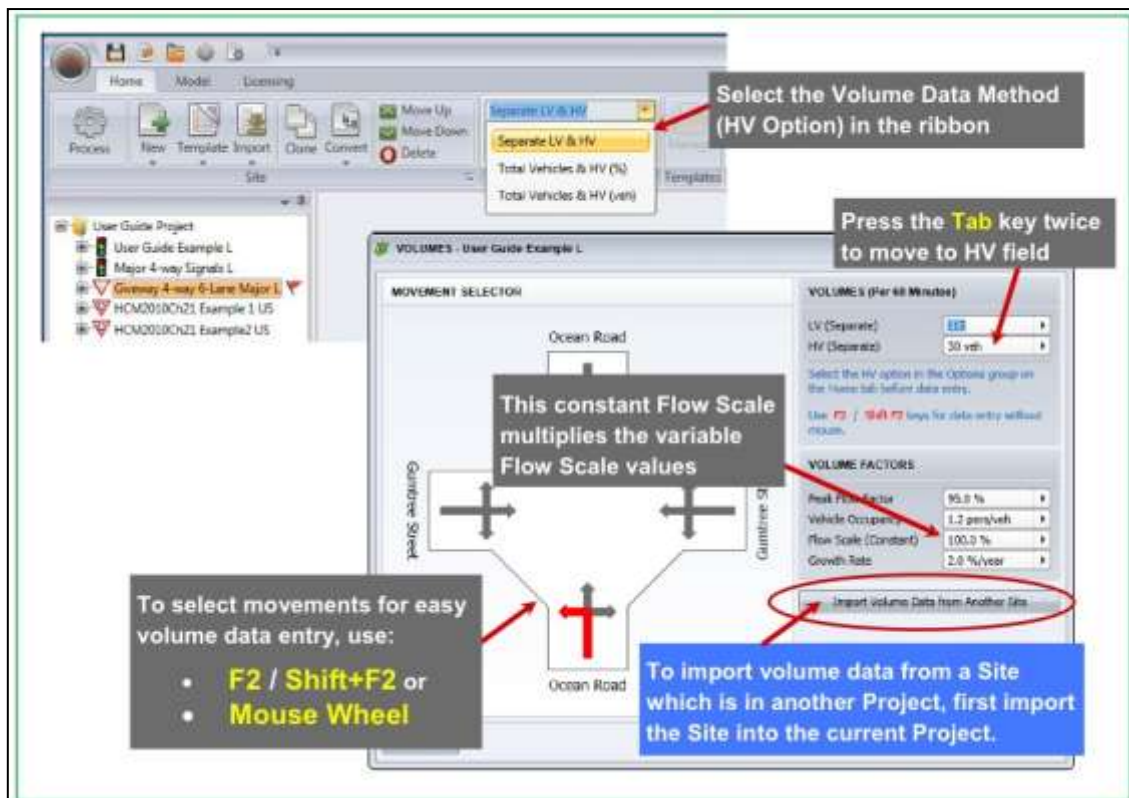


Fig. 1.9

The parameters in the Volume factors group are Peak Flow Factor, Vehicle Occupancy, Flow Scale (Constant) and Growth Rate. These are explained below.

Peak Flow Factor (PFF) is the ratio of the average arrival flow rate during the Total Flow Period (q_a) to the average arrival flow rate during the Peak Flow Period (q_p):

$$PFF = 100 q_a / q_p$$

where both q_a and q_p are flow rates (veh/h) converted from volume counts to flow rates. PFF data are given as percentage values. The standard default is PFF=95% and it means that a peak flow rate q_p which is about 5 per cent above q_a will be used in Sidra Intersection analysis.

The *Peak Flow Factor* is used to estimate the peak flow rate (the average flow rate q_p during T_p) from the known value of average flow rate q_a during T (using PFF a percentage value):

$$q_p = 100 q_a / PFF$$

PFF is equivalent to the more traditional term *Peak Hour Factor* (PHF) when $T=1h$. PFF<100% is used only when the peak demand volumes are not known. Otherwise, use Peak Flow Period Unit Time for Volumes ($T_p = T_v$) and PFF=100%. We can specify also the vehicle occupancy value for each vehicle movement (persons per vehicle including the driver). Vehicle Occupancy values are used for calculating various performance statistics in terms of persons rather than vehicles or pedestrians (e.g. intersection delay in sec/person), and are important in determining the Operating Cost per vehicle allowing for the number of persons per vehicle in calculating time cost per vehicle.

The Flow Scale (Constant) is specified as a percentage value. The demand volume will be increased or decreased using Flow Scale (Constant) given for each movement converting it to a factor calculated as [Flow Scale (Constant)/100].

For example, Volume = 200 veh/h, Flow Scale (Constant) = 110 % will result in increased value of Volume = 1.10 x 200 = 220 veh/h to be used by the program.

When Design Life or Flow Scale analysis is used through the Demand & Sensitivity dialog, the demand volumes are increased using the Growth Rates given in the Volumes dialog. In this case, the factor [Flow Scale (Constant)/100] will multiply the variable flow scale resulting from Design Life or Flow Scale analysis.

Growth Rates specified as percentage values will be used when Design Life or Flow Scale analysis is carried out through the Demand & Sensitivity dialog. The demand volume will be increased using the Growth Rate given for each movement converting it to a factor calculated as $[1 + \text{Growth Rate}/100]$.

For example, Volume = 500 veh/h and Growth Rate = 3% will result in Volume = $1.03 \times 500 = 515$ veh/h.

If Growth Rate is zero, this will mean "No Growth" for the movement demand volume. The variable flow scale (factor) used in Design Life or Flow Scale Analysis value will be 1.0 for the movement for all steps of Demand Analysis in this case.

Negative values of Growth Rate cannot be specified.

The factor $[\text{Flow Scale (Constant)}/100]$ will multiply the variable flow scale resulting from Design Life or Flow Scale analysis. If Growth Rate is zero, the demand volume of such a movement will be constant but increased or decreased by factor $[\text{Flow Scale (Constant)}/100]$.

I. 4. 6. Path Data Dialogue

The Path Data dialog is based on vehicle movements specified by origin-destination (O-D).

The Path Data dialog includes Approach and Exit Cruise Speeds, Approach Travel Distance, Negotiation Radius, Negotiation Speed and Negotiation Distance and Downstream Distance data (Figure 1.10).

Definitions of some of these parameters are shown in Figure 1.11. All data in this group are specified by O-D movement.

The approach and exit cruise speeds (kilometers per hour) can be specified for each O-D movement. The Exit Speed is the downstream speed in the movement path considering the destination of each O-D movement.

The cruise speed is the average uninterrupted travel speed, i.e. the speed of a vehicle without the effect of delay at the intersection. For continuous movements, the cruise speed is used as the zero-flow (free-flow) speed. For normal movements, it can be defined in a similar way.

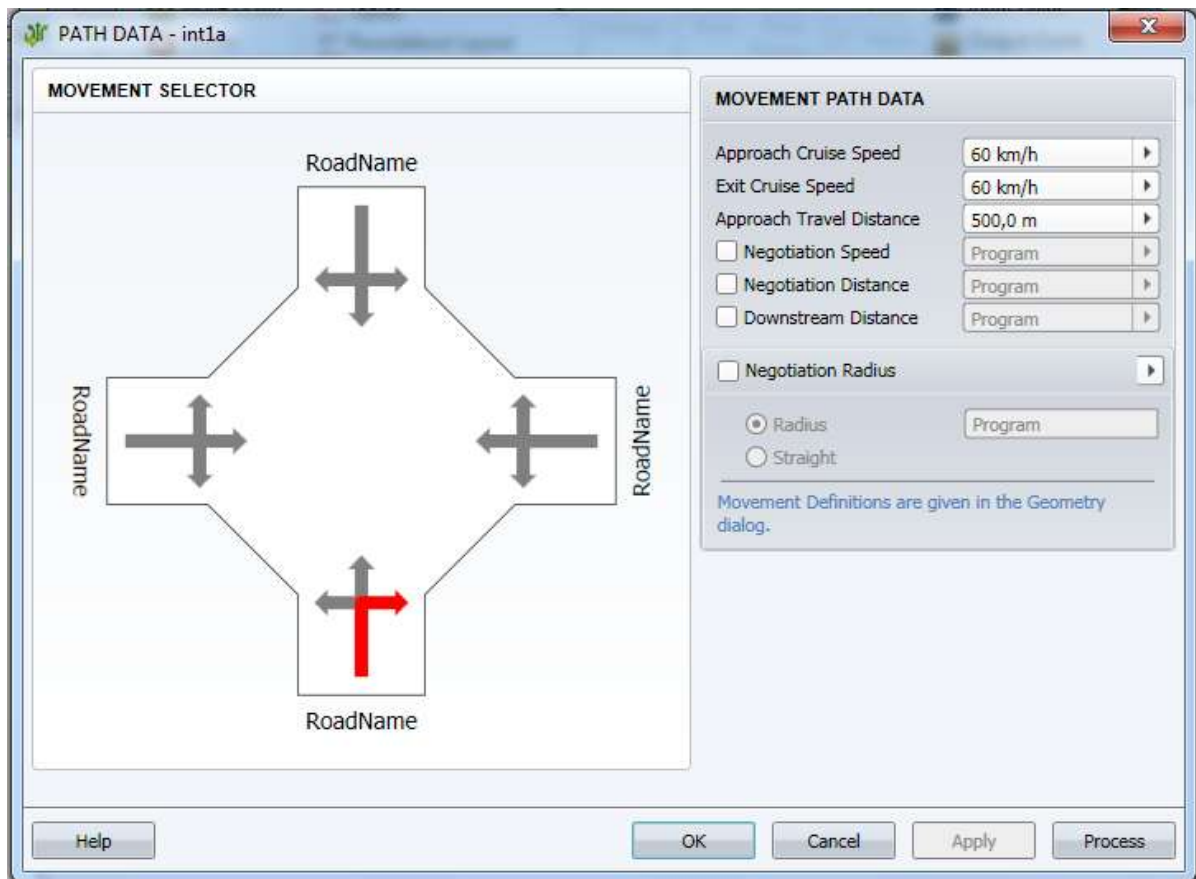


Fig. 1.10

The cruise speed affects the geometric delays, the average speed including the effect of delay at the intersection, the uninterrupted travel time component of the performance index, as well as fuel consumption, operating cost and emissions.

The Approach Cruise Speed and Exit Cruise Speed for existing intersections should reflect the present conditions.

As indicated in Figure 1.11, the approach travel distance is measured from the point of entry to the road section to the stop line of the approach under consideration, and it can be changed to reflect the existing/proposed operation of the intersection.

The intersection negotiation data (negotiation radius, negotiation speed and negotiation distance) are specified for each O-D movement through the intersection, and are calculated by the program when the respective check boxes are unchecked. The Negotiation Radius and Negotiation Distance can be manually overwritten to reflect the physical parameters for cases where an intersection has unusual geometry features.

All other items in this dialogue should be as per the default values or calculation methods.

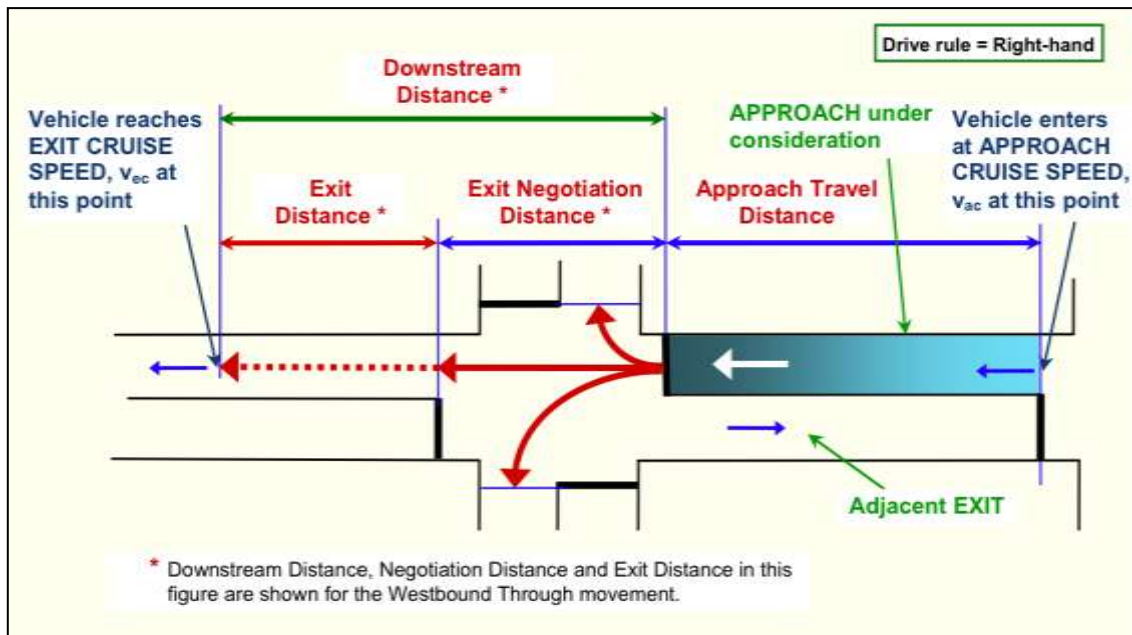


Fig. 1.11

I. 4. 7. Movement Data Dialogue

The Movement Data input dialog is based on vehicle movements specified by Left, Through, Right (L, T, R) movement designations. All default values in the Movement Data Dialogue shall be used unless evidence can be provided which indicates a different level is appropriate. In the project under analysis, for example, all the parameters for heavy vehicles were changed, due to the buses' dimensions. Defaults are as per the screen shot shown in Figure 1.12.

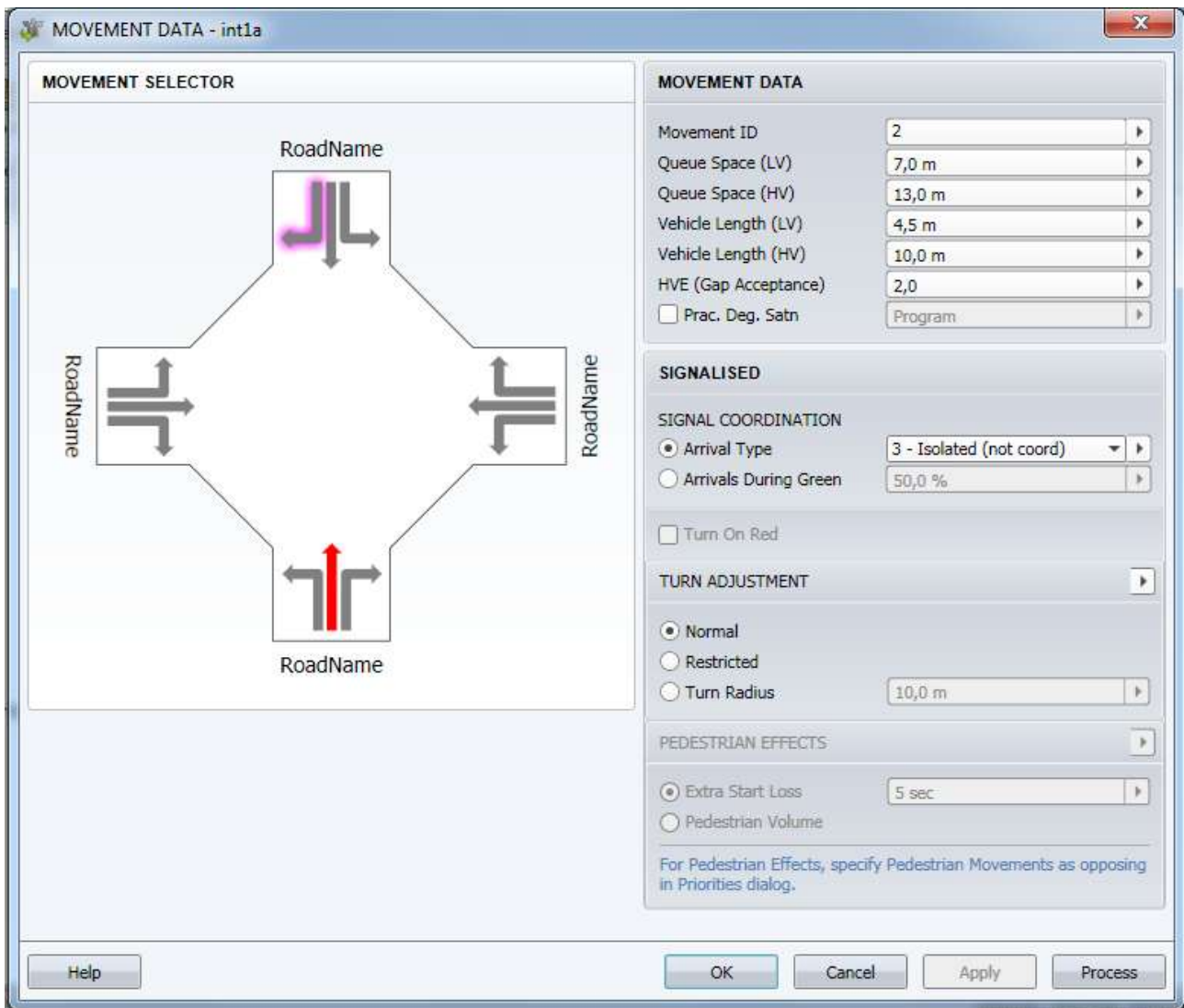


Fig. 1.12

Data group named Signalized is available when the Site type is Signals. For other Site types, this group is hidden.

Signal Coordination allows the user to introduce the effects of platooned arrivals at coordinated or closely-spaced signalized intersections.

Signal Coordination data can be specified for some movements in order to emulate platooned arrivals even though the intersection is not part of a coordinated signal system.

When the Signal Analysis Method specified in the Intersection dialog is Actuated, Signal Coordination data can be given for individual movements irrespective of being Actuated or Non-Actuated.

Arrival Type is specified by selecting one of the codes 1 to 6 (default: 3) in the drop-down list.

Alternatively, the Arrivals During Green (%) parameter can be used to specify the percentage of traffic arriving during the green period (range: 10 to 95 per cent). Figure 1.13 shows the platooned arrivals model used in Sidra Intersection for signal coordination effects, reported from the user guide.

Arrival Type	Progression Quality	Signal Spacing (ft / m)	Conditions under Which Arrival type is Likely to Occur (HCM 2010)	Platoon Description (HCM 2000)
1	Very poor	≤ 1600 ft (500 m)	Coordinated operation on a two-way street where the subject direction does not receive good progression.	Dense platoon containing over 80 per cent of the traffic volume, arriving at the start of the red period. This may be a result of conditions such as overall network signal optimisation.
2	Unfavourable	> 1600 to 3200 ft (>500 to 1000 m)	A less extreme version of Arrival Type 1.	Moderately dense platoon arriving in the middle of the red period or dispersed platoon containing 40 to 80 per cent of the traffic volume, arriving throughout the red period.
3	Random Arrivals	> 3200 ft (> 1000 m)	Isolated signals or widely-spaced coordinated signals	Random arrivals in which the main platoon contains less than 40 per cent of the traffic volume. This arrival type is representative of operations at isolated or non-coordinated signalised intersections characterised by highly dispersed platoons. It may also be used to represent coordinated operation in which the benefits of progression are minimal.
4	Favourable	> 1600 to 3200 ft (>500 to 1000 m)	Coordinated operation on a two-way street where the subject direction receives good progression.	Moderately dense platoon arriving in the middle of the green period or dispersed platoon containing 40 to 80 per cent of the traffic volume, arriving throughout the green period.
5	Highly favourable	≤ 1600 ft (500 m)	Coordinated operation on a two-way street where the subject direction receives good progression	Dense to moderately dense platoon containing over 80 per cent of the traffic volume, arriving at the start of the green period. This may occur on routes with low to moderate side-street entries and which receive high priority treatment in the signal timing plan.
6	Exceptional	≤ 800 ft (250 m)	Coordinated operation on a one-way street in dense networks and central business districts	Very dense platoons progressing over a number of closely-spaced intersections with minimal or negligible side-street entries. This represents routes with near-ideal progression characteristics.

Fig. 1.13

The Basic Saturation Flow Rate specified in the Geometry dialog is reduced for turning vehicles according to the Turn Adjustment option selected. The options available are Normal, Restricted and Turn Radius.

The recommended method by the user guide is to use the Turn Radius method for saturation flow adjustment.

Finally, the effects of pedestrians may be included in the Pedestrian Effects section of this dialogue.

I. 4. 8. Priorities Dialogue

This dialog establishes the Opposing movements for each selected movement (Figure 1.14). If opposing movements are specified for the selected movement, the program will identify and treat it as an Opposed movement. At signals, the opposing movement must run in a common phase with the opposed movement for the movement to be treated as opposed.

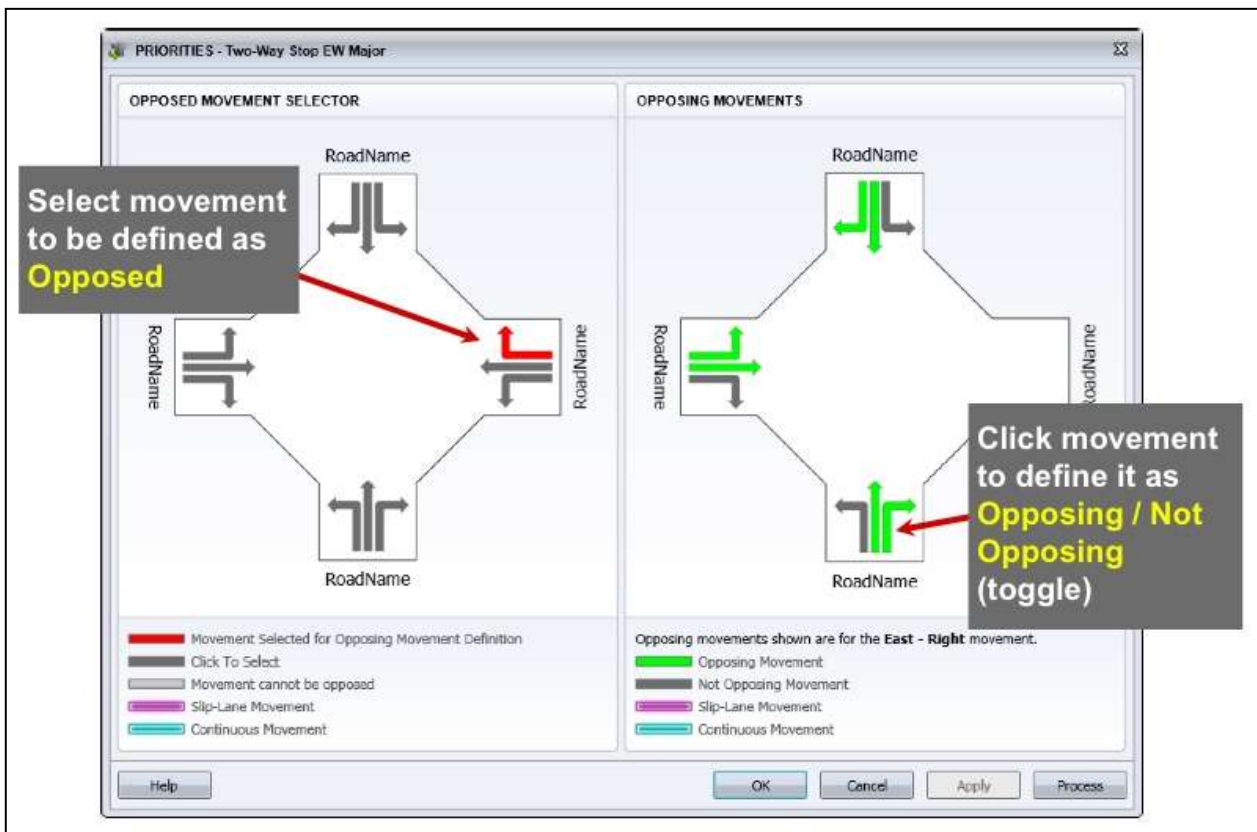


Fig. 1.14

Default opposing movements are to be used unless evidence can be provided to show the actual opposing movements are different. This may be the case for intersections with unusual geometry, turn designations or specialized treatments.

I. 4. 9. Gap-Acceptance Data Dialogue

The Gap-Acceptance Data dialog is used for specifying Gap-Acceptance Data for opposed movements as defined in the Priorities dialog. Data fields vary according to the intersection (Site) type. All-way stop controlled intersections do not use a gap-acceptance capacity model, and therefore, this dialog is not available.

Data fields will be available for opposed movements only.

Gap-Acceptance Data include the Critical Gap, Follow-up Headway, End Departures (signals) or Minimum Departures (roundabout or sign control), and Exiting Flow Effect (%). These parameters represent the give-way/yield behavior of opposed traffic.

The Critical Gap is the minimum time (headway) between successive vehicles in the opposing (major) traffic stream that is acceptable for entry by opposed (minor) stream vehicles.

The Follow-up Headway is the average headway between successive opposed (minor) stream vehicles entering a gap available in the opposing (major) traffic stream.

The End Departures parameter represents the maximum number of vehicles (n_{fm}) that can depart after the end of the displayed green period (“sneakers”) at signalized intersections.

The parameter that ensures a minimum capacity for opposed turns at roundabouts and two-way sign-controlled intersections, is the minimum number of departures per lane per minute. This parameter is similar to the number of departures at the end of the green period at signalised intersections.

The default values of minimum departures per lane are 2.5 vehicles/minute for roundabouts and 1.0 vehicles/minute for two-way stop or Giveway/Yield sign-controlled intersections. These default values ensure minimum capacities of 150 veh/h and 60 veh/h per lane, respectively, subject to a demand flow constraint (minimum capacity cannot exceed the demand volume).

Finally a percentage of exiting flow to be added to the circulating/opposing flow can be specified for all types of intersection although this parameter is more relevant to roundabouts and two-way sign-controlled intersections.

I. 4. 10. Pedestrian Dialogue

The Pedestrians input dialog is for specifying data for pedestrian movements crossing in front of each intersection leg (Figure 1.15). This dialog does not appear for sign-controlled intersections.

For signals (intersections and signalized pedestrian crossings), pedestrian movement data are used for estimating the effect of pedestrians on vehicle movement capacities and signal timings as well as estimating pedestrian performance. For roundabouts, pedestrian movement data are used for estimating the effect of pedestrians on vehicle movement capacities only.

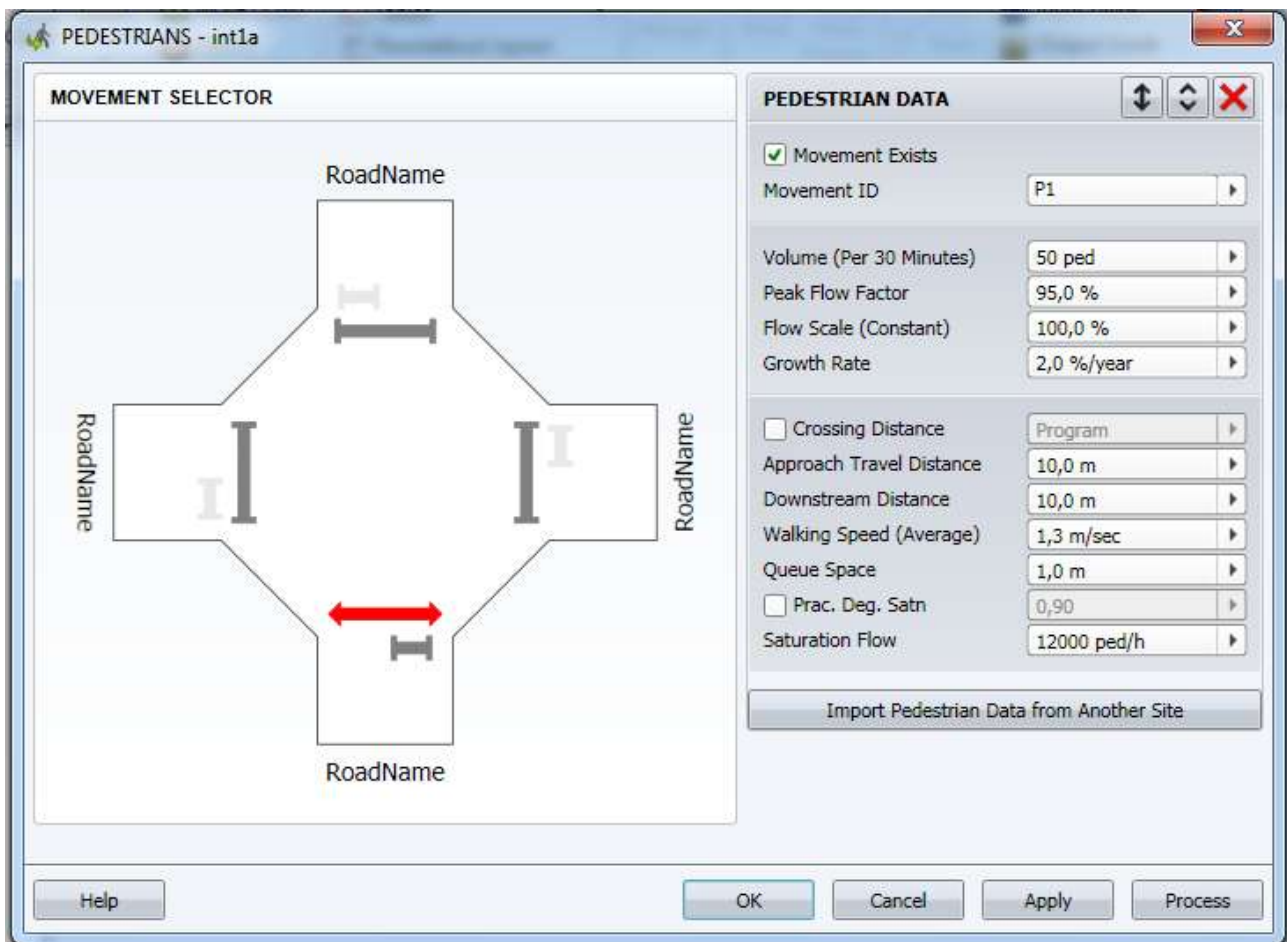


Fig. 1.15

I. 4. 11. Phasing & Timing Dialogue

The Phasing & Timing input dialog displays signal sequences and phases for graphics-based editing. The main dialog has the following sub-dialogs that can be opened in the sequence title bar:

- Phase Data dialog;
- Vehicle Movement Timing Data dialog;
- Pedestrian Movement Timing Data dialog;
- Sequence Data dialog.

The Phase Data dialog allows the user to edit a phase (defining movements that run in the phase) and enter data for the phase.

In this dialog, the movements that are stopped are shown in red, the movement that have right of way are shown in green, the Slip-lane movements are shown in magenta and Continuous movements are shown in light blue.

When conflicting movements run in the same phase, the program will identify the opposed (permitted) movements automatically according to the data given in the Priorities dialog.

In the Vehicle Movement Timing Data dialog, the Start Loss, End Gain, Minimum Green and Maximum Green parameters can be specified. These parameters are specified per Sequence.

In the Pedestrian Movement Timing Data dialog, the following parameters can be specified: Minimum Green, Maximum Green, Crossing Speed, Minimum Walk Time, Minimum Clearance Time, Clearance Time Overlap, Start Loss and End Gain. The Sequence Data dialog includes the Cycle Time Option, Green Split Option, and Actuated Signal Data groups for signal timing data.

Figure 1.16 shows the main dialog and the foreground Sequence Data open.

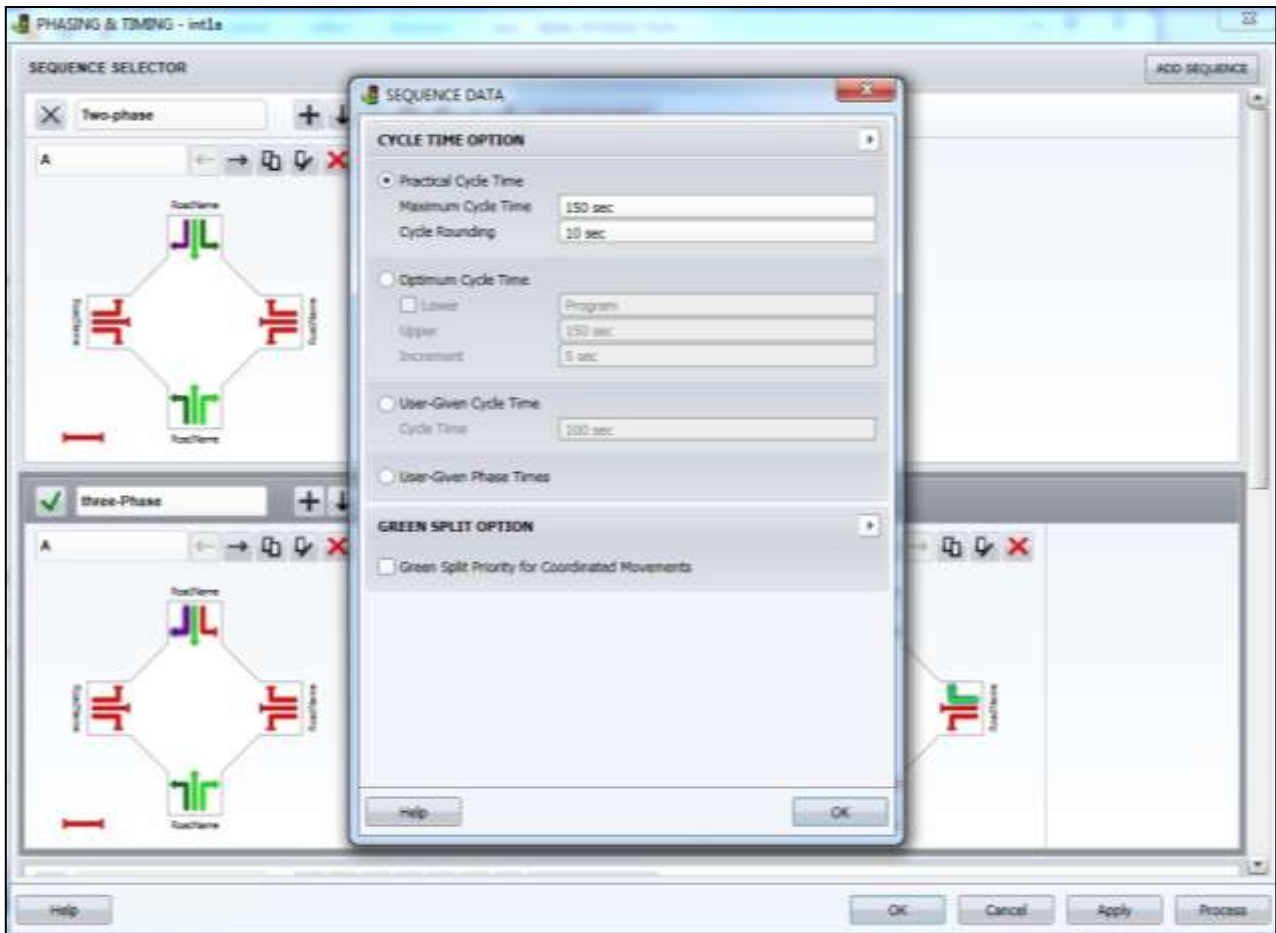


Fig. 1.16

I. 4. 12. Model Settings Dialogue

The Model Settings input dialog can be used to select various model options and specify some model parameters under the Options, Roundabouts and Cost tabs (Figure 1.17).

The parameters in this dialog apply to the intersection as a whole and most of them are relevant to all Sidra Intersection models. These are important parameters that affect the results significantly. However, default values of these parameters are appropriate generally.

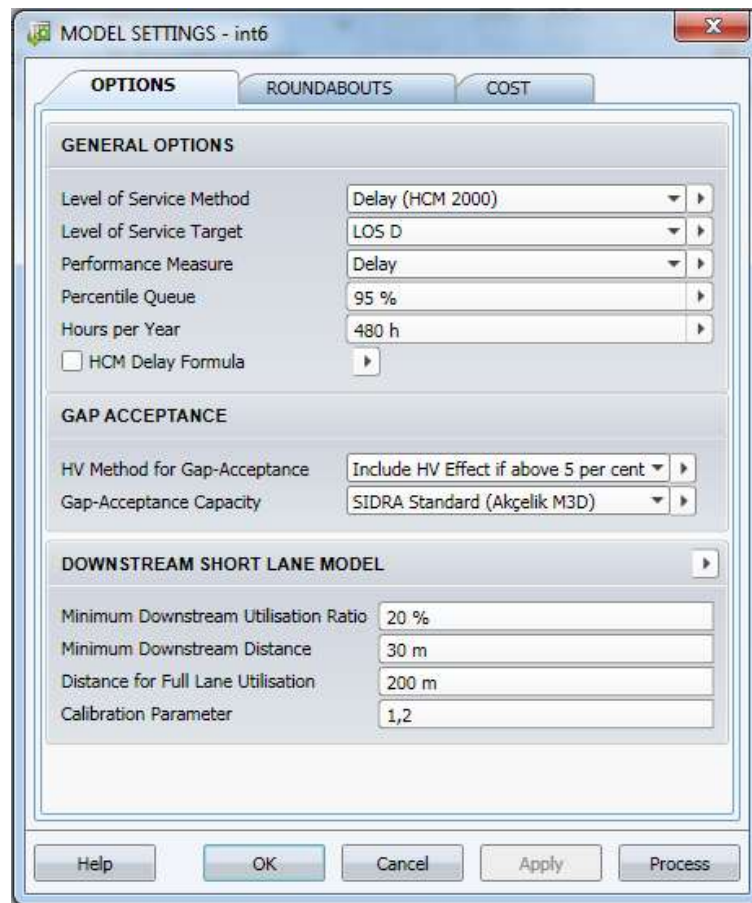


Fig. 1.17

The parameters under the Options tab consist of General Options, Gap-Acceptance and Downstream Short Lane Model options.

The parameters under the Roundabouts tab consist of Roundabout Model Options, US HCM 2010 Roundabout Model settings and Other Roundabout Models options.

The parameters under the Cost tab allow the user to calibrate the operating cost model for local conditions.

These parameters vary from country to country significantly, and need calibration using local data. That's why this part of input data is the most frequently changed from the default values.

I. 4. 13. Demand and Sensitivity Analysis Dialogue

The Demand & Sensitivity dialog includes the Design Life, Flow Scale and Sensitivity options (Figure 1.18). These options are specific to each Site.

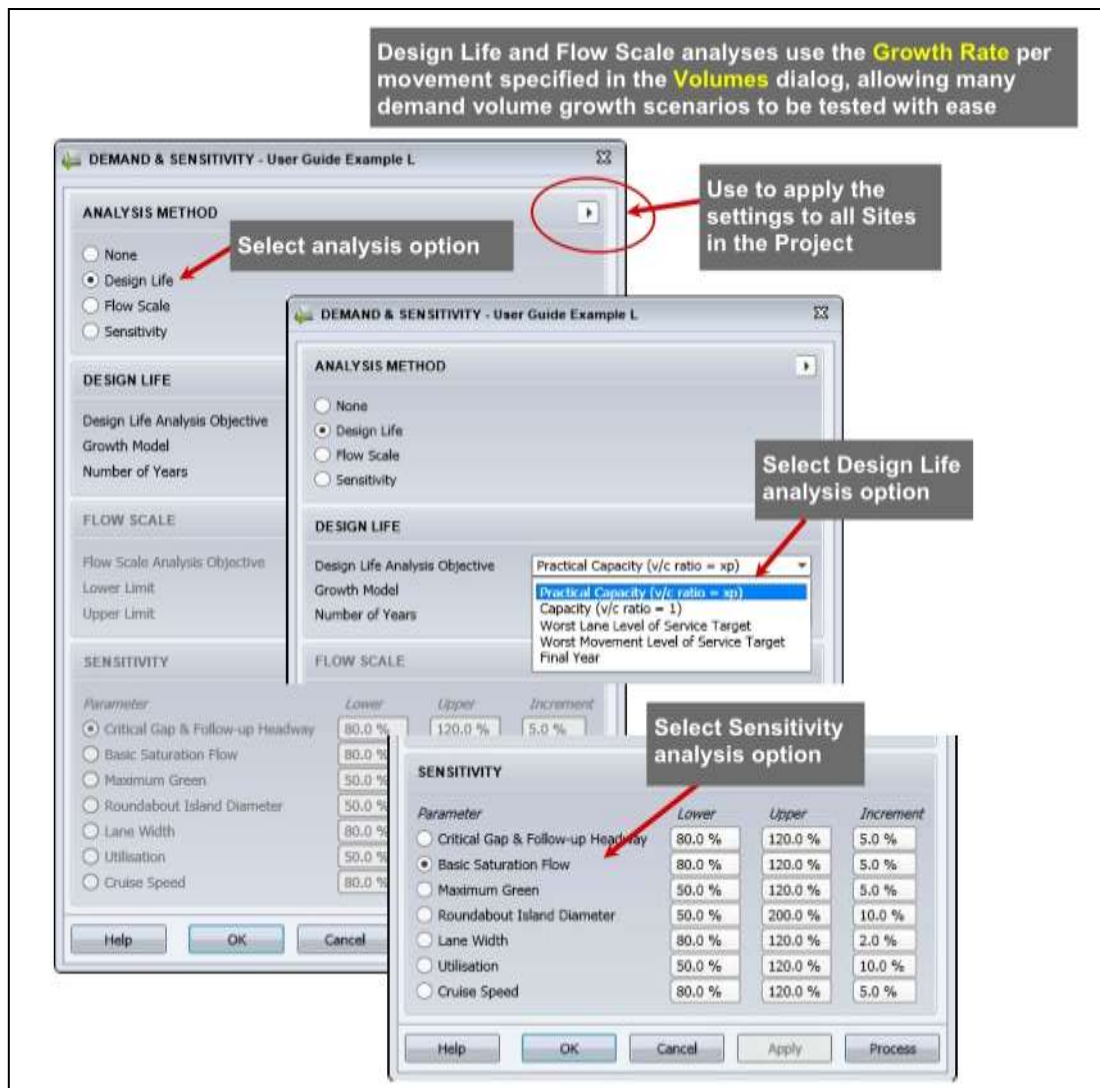


Fig. 1.18

The Demand & Sensitivity input dialog can be used to carry out a Design Life or Flow Scale analysis to determine the amount of increase possible in demand flow rates subject to a target level of performance.

The Design Life analysis helps to investigate the effect of traffic growth with the Uniform and Compound growth options for a given Number of Years using Growth Rates given in the Volumes and Pedestrians dialogs for individual movements (as shown in Chapter II, section *Example Number 1*). The Flow Scale analysis helps to investigate the effect of changes in demand volume levels using varying flow scales.

The Sensitivity Analysis facility can be used to obtain estimates of capacity and performance statistics as a function of parameters representing:

- driver behavior and traffic characteristics (Lane Utilization, Critical Gap & Follow-up Headway, Basic Saturation Flow, Cruise Speed);
- intersection geometry (Lane Width, Roundabout Island Diameter);
- actuated signal timings (Maximum Green).

This facility, as suggested in the user guide, is provided for the purposes of optimization (with maximum green setting for actuated signals and cruise speed) or calibration (with all other parameters).

I. 4. 14. Roundabout Metering Data Dialogue

Roundabout metering signals are used to create gaps in the circulating stream in order to solve the problem of excessive queuing and delays at approaches affected by highly directional flows.

In addition to normal roundabout data, special data required for roundabout metering are specified in the Roundabout Metering input dialog (Figure 1.19).

The Roundabout Metering input dialog includes a graphical data entry box to specify the Metered and Controlling Approaches, and various input data fields which are not tied to specific approaches.

Section 2, in Chapter II, will show an example of metered roundabout, in order to verify if the metering signals help the roundabout in term of performance measures.

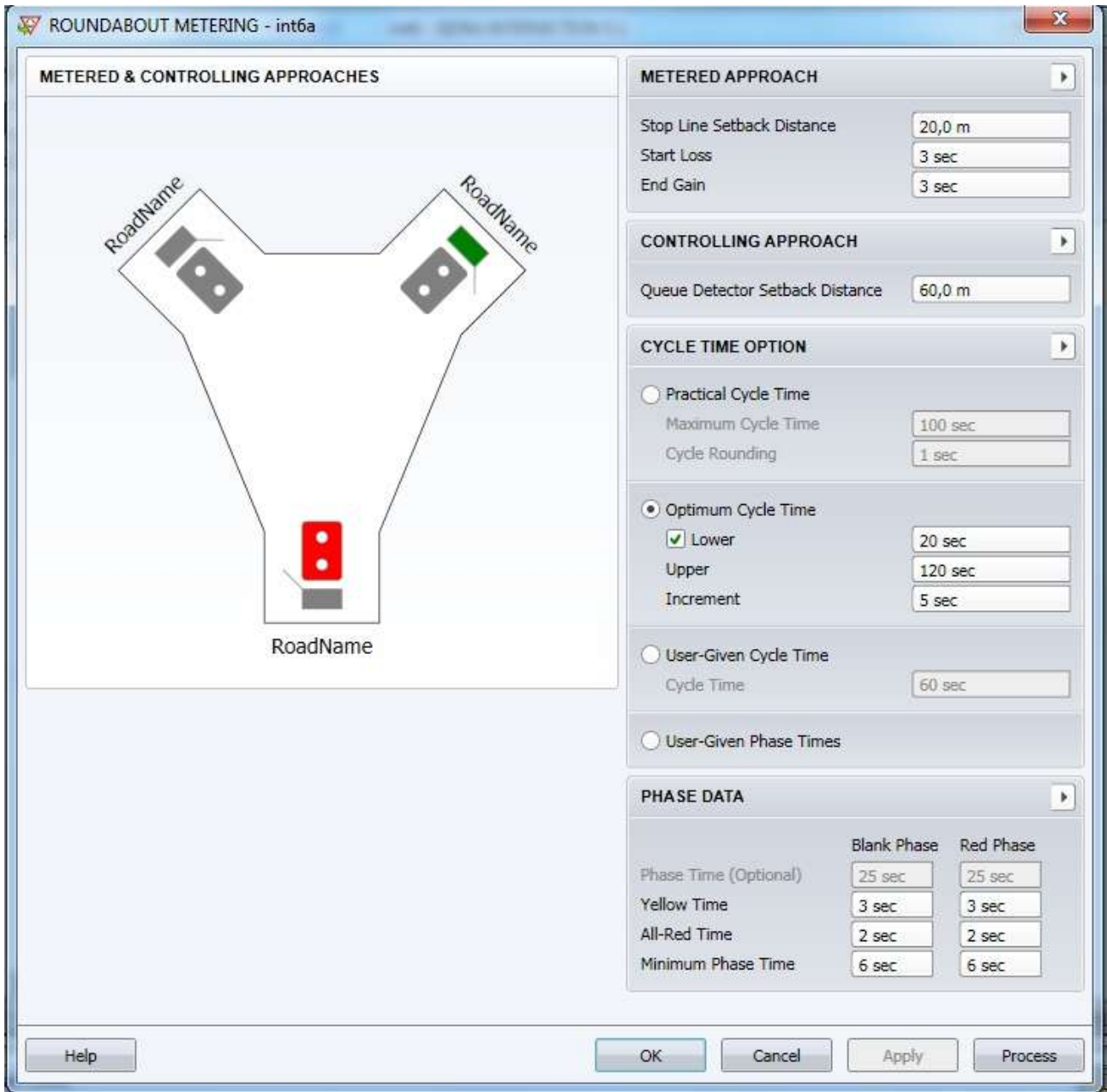


Fig. 1.19

I. 5. Output in Sidra Intersection

The Sidra Intersection output system provides output in both text and graphical format. The program user can inspect the text output (Detailed Output, Intersection Summary, Movement Summary, Lane Summary) and the graphical displays (Layout, Volume Summary, Movement IDs, Phasing Summary, Flow Display, Movement Timing, LOS Summary, Movement Displays, Graphs) by the corresponding nodes in the Output group displayed for each Site open in the Project tree. Figure 1.20 is a screen shoot of the output tree.

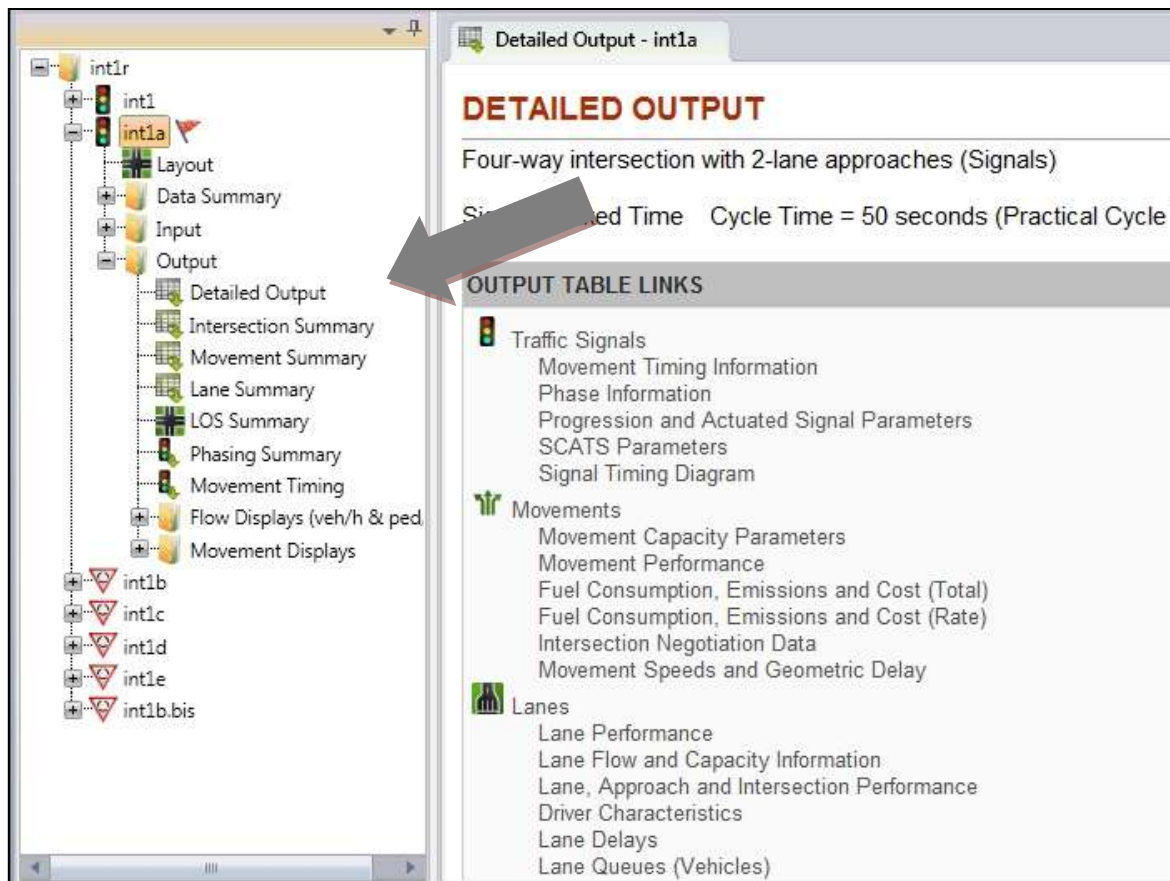


Fig. 1.20

As with input data preparation, Sidra Intersection results are to be analyzed carefully in order to understand the conditions of the particular intersection under study. Capacity and performance data for individual lanes, as we will see in the next chapters, are particularly useful for this purpose.

All output parameters will be explained in the next chapters of the thesis, when they will be used to compare different sites or to make some deductions.

The following list shows a fast roundup of the main parameters taken into consideration during the comparison:

- Capacity (Lane Capacity, Movement Capacity, Sum of Lane Capacities, Effective Intersection Capacity, Effect of the Short Lane and the Signal Coordination on the Capacity);
- Cost (the direct vehicle operating cost and the time cost to driver and passengers);
- Degree of Saturation (ratio of demand flow to capacity, v/c Ratio);
- Delay (for movements, lanes, approaches and the intersection);

- Fuel Consumption and Emissions;
- Geometric Delay;
- Lane Utilization;
- Level of Service (based on the basic concept described in the US Highway Capacity Manual (HCM) and various other publications);
- Practical Spare Capacity;
- Queue Length (Back of Queue and Cycle-average Queue);
- Saturation Flow;
- Speed (average travel speed and average running speed given in various output tables, and approach cruise, average running and average travel speeds given under Movement Displays);
- Stops (Proportion Queued, Effective Stop Rate, Total Effective Stops and Lane Stops);
- Performance Index.

Most of these parameters are reported in the Detailed Output tab which offers a large number of output tables, including detailed information not given in the Movement Summary and Lane Summary output reports.

CHAPTER II

EXAMPLES FROM THE WORKSHOP IN OSLO (NORWAY, 2011)

In this chapter, some interesting examples of possible applications of SIDRA INTERSECTION, presented during a workshop in Oslo (June, 2011), will be described.³

I have chosen two of the several examples of the workshop, in each of which some sites with equal volume flow but different geometric inputs can be found. Indeed the SIDRA INTERSECTION input method allows the user the flexibility to specify a large number of traffic and geometric parameters.

The first intersection has four different data input, corresponding to four sites, while the second just two.

After the description of the input, the output data will be shown, in order to illustrate the differences among the scenarios.

The parameters taken into consideration are intersection parameters with hourly values. Demand flow, degree of saturation, control and geometric delay, level of service (LOS) are just some of the parameters that will be considered.

In addition Output Comparison, a Sidra Intersection 5.1 Utility, was used in order to compare different sites and to obtain clear results.

³ Sidra Intersection, Training Workshop, Introduction and Intermediate Workshop, Oslo, Norway, 2011. Akcelik & Associates Pty Ltd.

II. 1. Example number 1: four-leg intersection.⁴

The purpose of this example is to analyze a quite complex four-leg intersection.

In the beginning the intersection is regulated by a traffic light, later the same intersection will be converted into a roundabout.

II. 1.1. Input data

A - Signalized intersection: fixed-time.

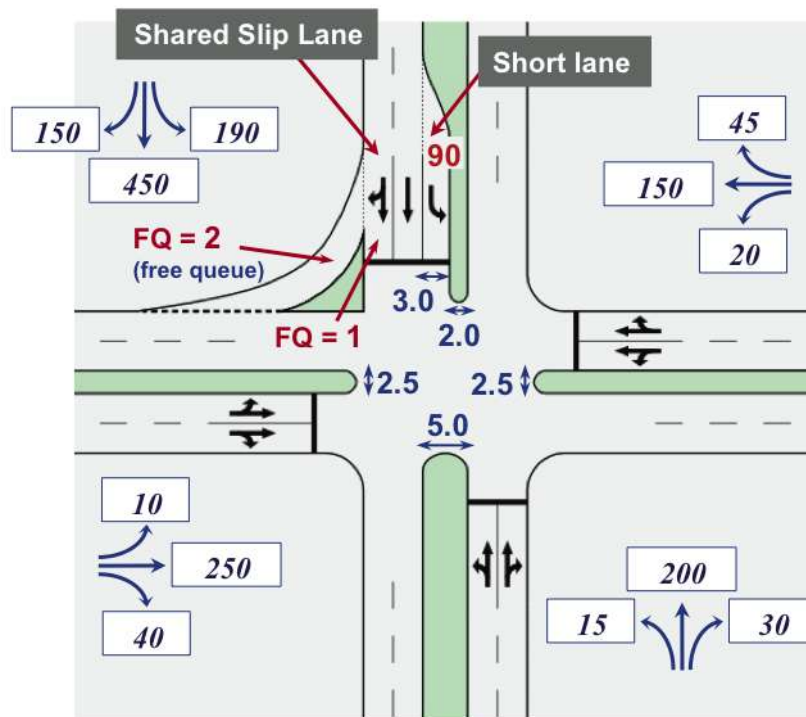


Fig. 2.1

As shown in Fig. 2.1, the first site is a four-way signalized intersection with two-lane approaches. The Signal Analysis Method is **Fixed-Time**.

In the Intersection and Volume dialogs the peaking parameters were specified. The *Peak Flow Period* and *Peak Flow Factor* parameters, together with the *Total Flow Period*, define a typical peaking pattern for the *design (analysis) period* using a simple step-function. In this case the Unit Time for Volumes and the Peak Flow Period are 30 min, while the Peak Flow Factor is 100%.

⁴ Sidra Intersection, Training Workshop, Introduction and Intermediate Workshop, Oslo, Norway, 2011. Akcelik & Associates Pty Ltd (pag. 22-29).

In the same dialog the volumes were specified as shown in Fig. 2.2 (no heavy vehicles).

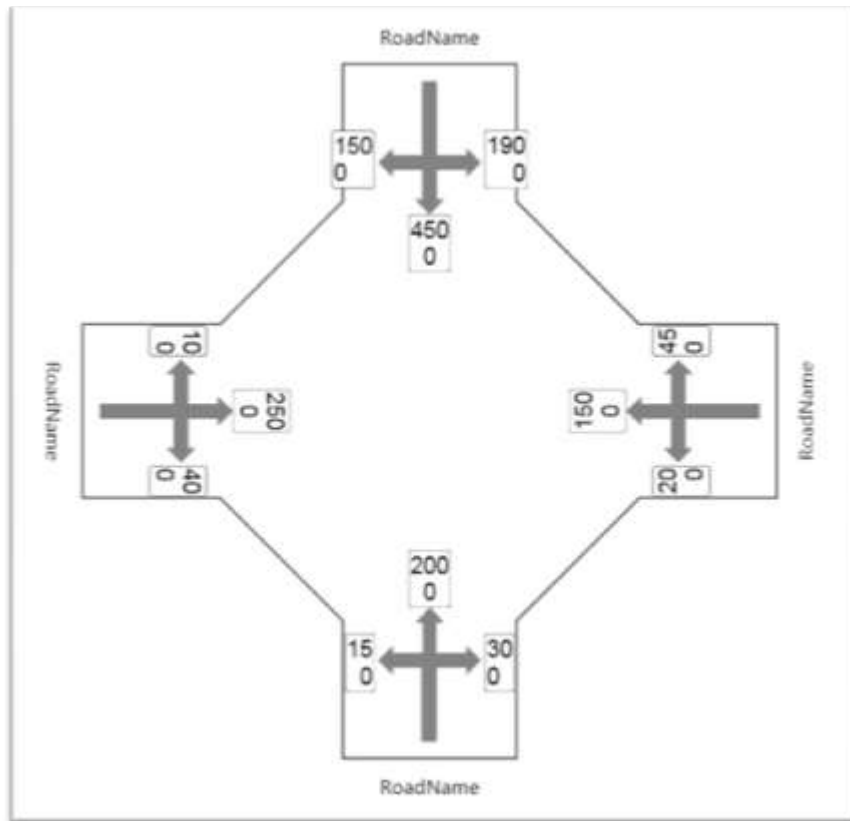


Fig. 2.2

On the north approach a shared right-turn lane was added [Lane Type = Slip (give-way/yield)]. In the lane data dialog, the lane width and the free queue (2 vehicles for the right turn, 1 vehicle for the through direction) were defined. Free queue is the number of vehicles which can queue away from the lane without interrupting the flow of the other movement which shares the lane. This parameter is used for *signalized intersections* only.

A short exclusive left-turn lane (length 90 m and lane width 3 m) was added.

In the geometry dialog all the width of the medians were added as shown in Fig. 2.1.

To simplify matters, in this example pedestrians are not considered.

Fig. 2.3 shows the phasing diagram that has been applied to the intersection. In the Phasing & Timing dialog the following signal phasing was set.

The “Two-Phase” sequence was cloned and renamed as “Three-Phase”. Once selected the “Three-Phase” as the current sequence, a Phase C with a leading left

turn (green arrow) from the North approach and a protected right-turn from East (green arrow) were added and the North-left movement in Phase A was stopped; East-Right movement was specified as Undetected in Phase C, while North-Right movement as Undetected in All Phases; in Phase B, Phase Transition was applied to the East-Right movement.

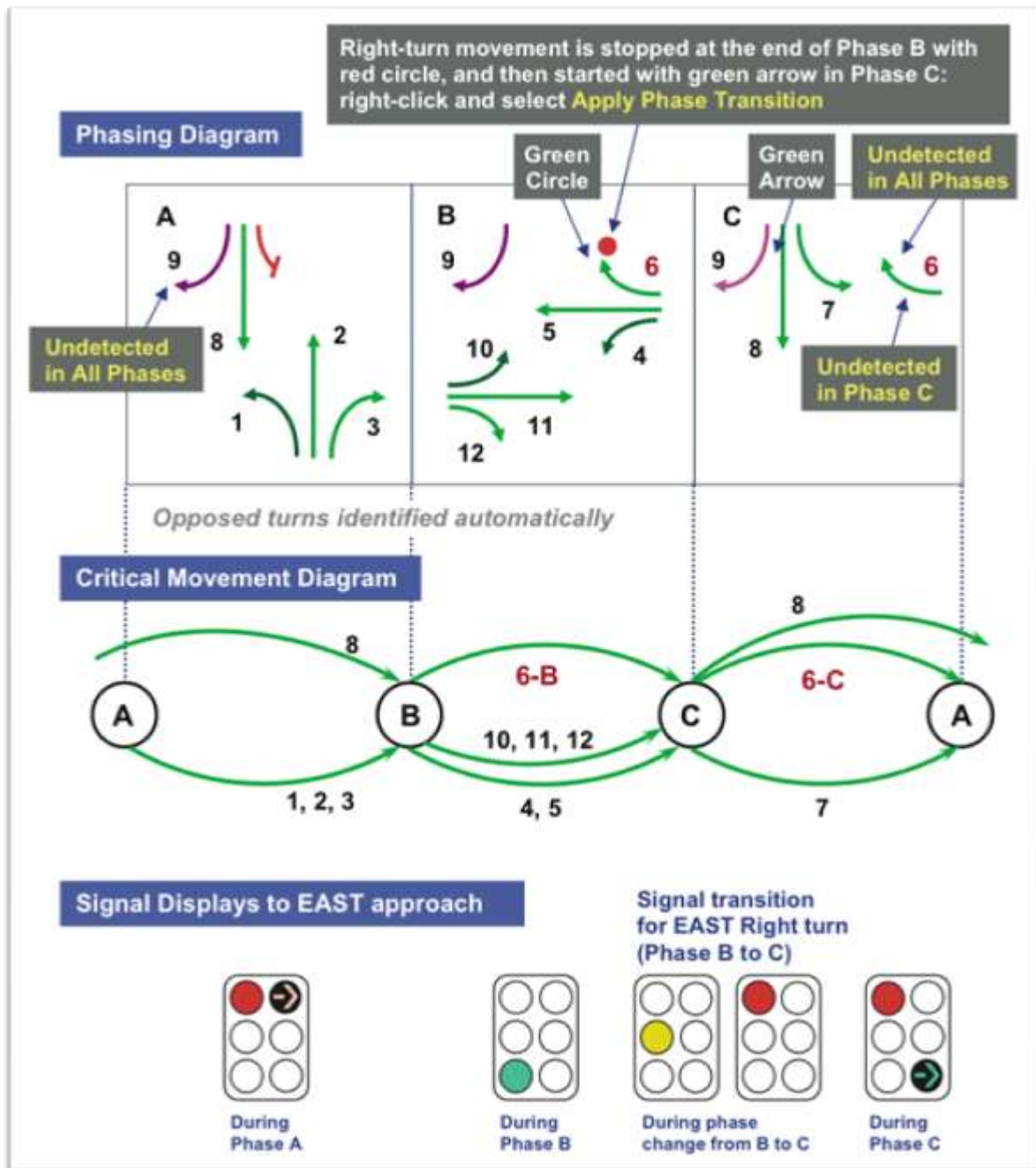


Fig. 2.3

B – Two-lane roundabout alternative

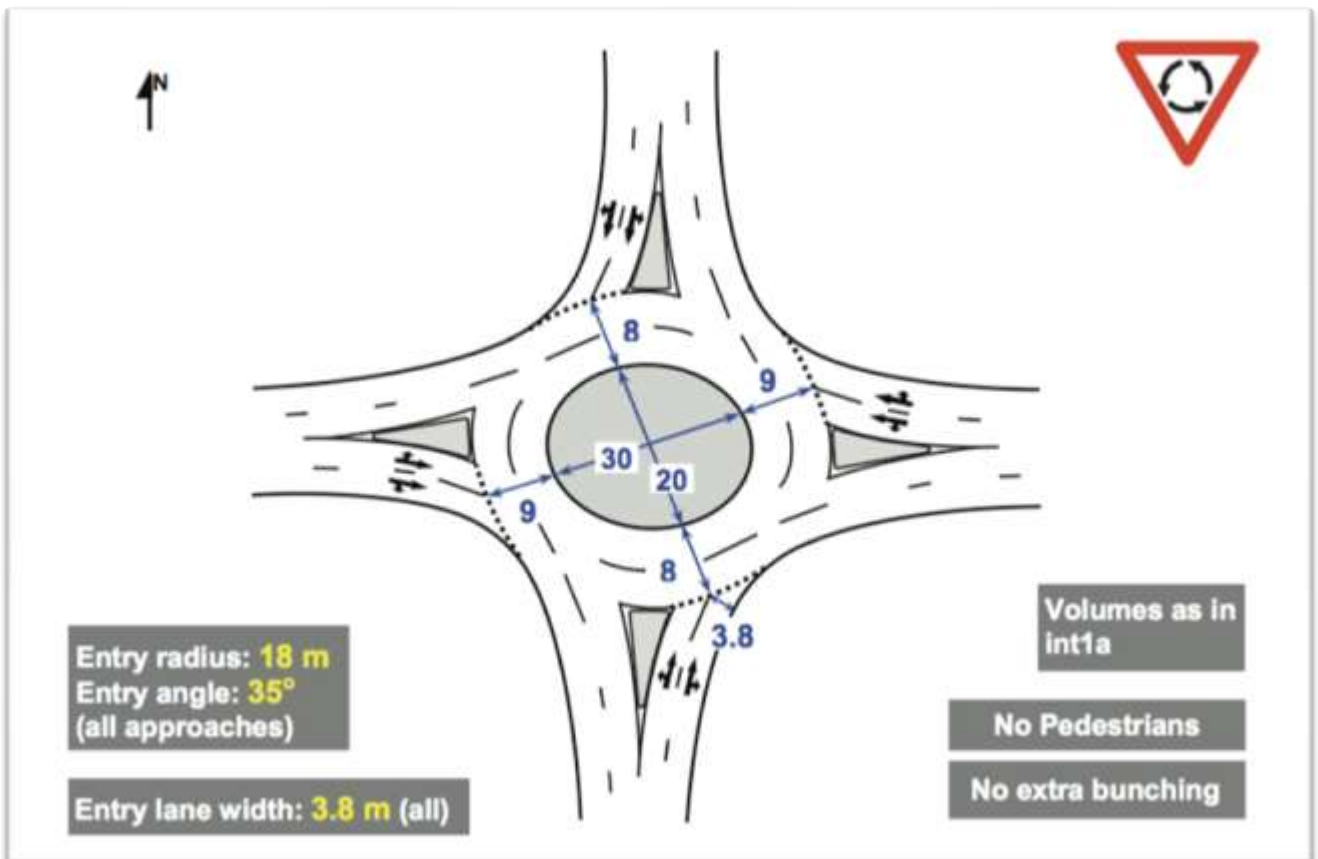


Fig. 2.4

The second site, called B, is intersection A converted into a two-approach roundabout.

The following parameters were changed:

- no short lane or slip lane on the North approach;
- no medians in each approach;
- entry radius = 18 m and entry angle = 35° (all legs);
- entry lane width 3.8 m (all lanes);
- island diameters width and number of circulating lanes as shown in Fig. 2.4.

Traffic Volumes remain the same as in the A-site.

In addition the Design Life Analysis was applied, in the Demand and Sensitivity dialog, to investigate the effects of the traffic growth. The final year (after 10 years) was selected as Design Life Objective, with 2,0% uniform rate of growth per year (in the Volume dialog).

C – Roundabout alternative with more favorable geometry

The third site is the B site with a more favorable geometry aimed at coping with the assumed traffic growth (10 years, with 2,0% uniform growth rate per year).

The following parameters were changed:

- entry radius = 30 m and entry angle = 20°;
- entry lane width = 4.3 m;
- circulating road width = 10 m in South and North approaches and 12 m in East and West approaches;

The traffic volume values at year zero remain the same.

D – Roundabout with different utilization ratio

The fourth site is the C site with a different utilization ratio in lane 2 on South approach. The Utilization Ratio is used to specify an underutilized lane relative to the critical lane of the approach. This is specified as a percentage (range: 1 to 100; default: 100, i.e. full lane utilization). At least one lane of the approach road must have full lane utilization. In our case 30% ratio was applied, as shown in Fig. 2.5.

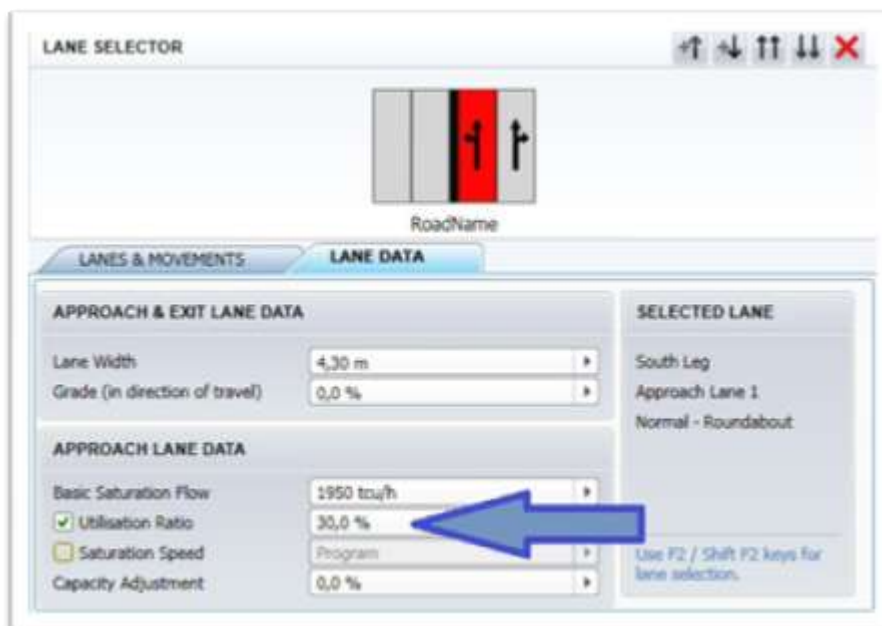


Fig. 2.5

II. 1.2.1 Analysis of the Output Data

A-site and B-site comparison

The results for the two sites have been compared using the Output Comparison utility for Sidra Intersection 5.1 (see also I. 3. 3.).

This comparison is useful to understand if the roundabout intersection works better than the signalized intersection in the case under analysis. In order to obtain significant deduction, the B-site was considered at year zero, when the total demand flows are exactly the same of the A-site.

Table 2.6 shows the parameters produced by Output Comparison and the respective differences between the two sites.

Intersection Performance (Vehicles Only) - Hourly Values (Table 2.6)

Vehicle Performance Measure	Units	Site A	Site B	Difference SiteB - SiteA	%Difference Diff / SiteA?
Demand Flows (Total)	veh/h	3100	3100	0	0,0
Percent Heavy Vehicles	%	0,0	0,0	0,0	0,0
Degree of Saturation		0,813	0,748	-0,064	-7,9
Practical Spare Capacity	%	10,7	13,6	2,9	26,6
Effective Intersection Capacity	veh/h	3814	4142	329	8,6
Control Delay (Total)	veh-h/h	16,93	9,03	-7,90	-46,7
Control Delay (Average)	sec	19,7	10,5	-9,2	-46,7
Control Delay (Worst Lane)	sec	31,4	13,2	-18,2	-58,1
Control Delay (Worst Movement)	sec	34,0	19,0	-15,0	-44,1
Geometric Delay (Total)	veh-h/h	2,23	5,18	2,95	132,7
Geometric Delay (Average)	sec	2,58	6,01	3,43	132,7
Stop-Line Delay (Total)	veh-h/h	14,71	3,85	-10,86	-73,8
Stop-Line Delay (Average)	sec	17,08	4,47	-12,61	-73,8
95% Back of Queue - Vehicles (Worst Lane)	veh	10,2	8,1	-2,0	-20,0
95% Back of Queue - Distance (Worst Lane)	m	71,3	57,0	-14,3	-20,0
Total Effective Stops	veh/h	2577	2668	91	3,5
Effective Stop Rate	per veh	0,83	0,86	0,03	3,5
Proportion Queued		0,86	0,77	-0,10	-11,4
Performance Index		103,1	67,3	-35,8	-34,7
Travel Distance (Total)	veh-km/h	1880,7	1903,5	22,8	1,2
Travel Distance (Average)	m	607	614	7	1,2
Travel Time (Total)	veh-h/h	50,2	41,2	-9,0	-18,0
Travel Time (Average)	sec	58,3	47,8	-10,5	-18,0
Travel Speed	km/h	37,5	46,2	8,8	23,4
Cost (Total)	\$/h	1670,39	1447,22	-223,18	-13,4
Fuel (Total)	L/h	220,8	209,7	-11,1	-5,0
Carbon Dioxide (Total)	kg/h	551,9	524,2	-27,7	-5,0
Hydrocarbons (Total)	kg/h	0,950	0,889	-0,061	-6,4
Carbon Monoxide (Total)	kg/h	41,18	41,25	0,07	0,2
NOx (Total)	kg/h	1,267	1,256	-0,011	-0,9

The highlighted parameters are the main values that were checked and analyzed before drawing conclusions.

The degree of saturation is the ratio of arrival (demand) flow rate to capacity during a given flow period, 30 minutes in the case under analysis.

The Capacity (Q) is the maximum sustainable flow rate at which vehicles reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental, and control conditions; usually expressed as vehicles per hour, passenger cars per hour, or persons per hour. In the case under analysis it is expressed as vehicles per hour.

$$Q = s \cdot u$$

where u = proportion of time when the vehicles can depart from the queue (signals are green or gaps are available in the conflicting stream) and s = saturation (queue discharge) flow rate (veh/h). Sidra Intersection computes the capacity of each approach lane separately and then adds the lane capacities to obtain movement capacities.

The Effective Intersection Capacity is determined as the ratio of the total intersection demand flow to the intersection degree of saturation, where the intersection degree of saturation is the largest lane degree of saturation considering all lanes of the intersection.

The Effective Intersection Capacity is an intersection-based lane utilization ratio, similar to the lane utilization ratio used by Sidra Intersection for determining lane flows in a lane group, and aggregating lane capacities (and saturation flow rates) to movement capacity (or saturation flow rate). Thus, the Effective Intersection Capacity is given by:

$$Q_{INT} = q_{INT} / X_{INT}$$

where

q_i = lane demand flow rate (veh/h),

Q_i = lane capacity (veh/h),

$x_i = q_i / Q_i$ = lane degree of saturation,

$q_{INT} = \sum q_i$ = total intersection demand flow rate (veh/h), where summation is for all intersection lanes,

$X_{INT} = \max (x_i)$ = intersection degree of saturation (highest x_i for any lane),

$\rho_i = x_i / X_{INT}$ = intersection-based lane utilisation ratio,

$Q_{INT} = \sum (\rho_i Q_i) = \sum (x_i Q_i / X_{INT}) = (\sum q_i) / X_{INT} = q_{INT} / X_{INT} = \text{effective intersection capacity.}$

For signalized intersections, u is the green time ratio, $u = g/c$, where g = effective green time (s) and c = cycle time (s). For gap-acceptance processes at roundabouts and sign-controlled intersections, u is the unblocked time ratio related to average durations of block and unblock periods in the conflicting stream.

The Intersection control delay (d_{ic}) is sum of stop-line and geometric delays ($d_{ic} = d_{SL} + d_{ig}$), thus it includes all deceleration and acceleration delays experienced in negotiating the intersection.

Figure 2.7 shows the intersection control delay.

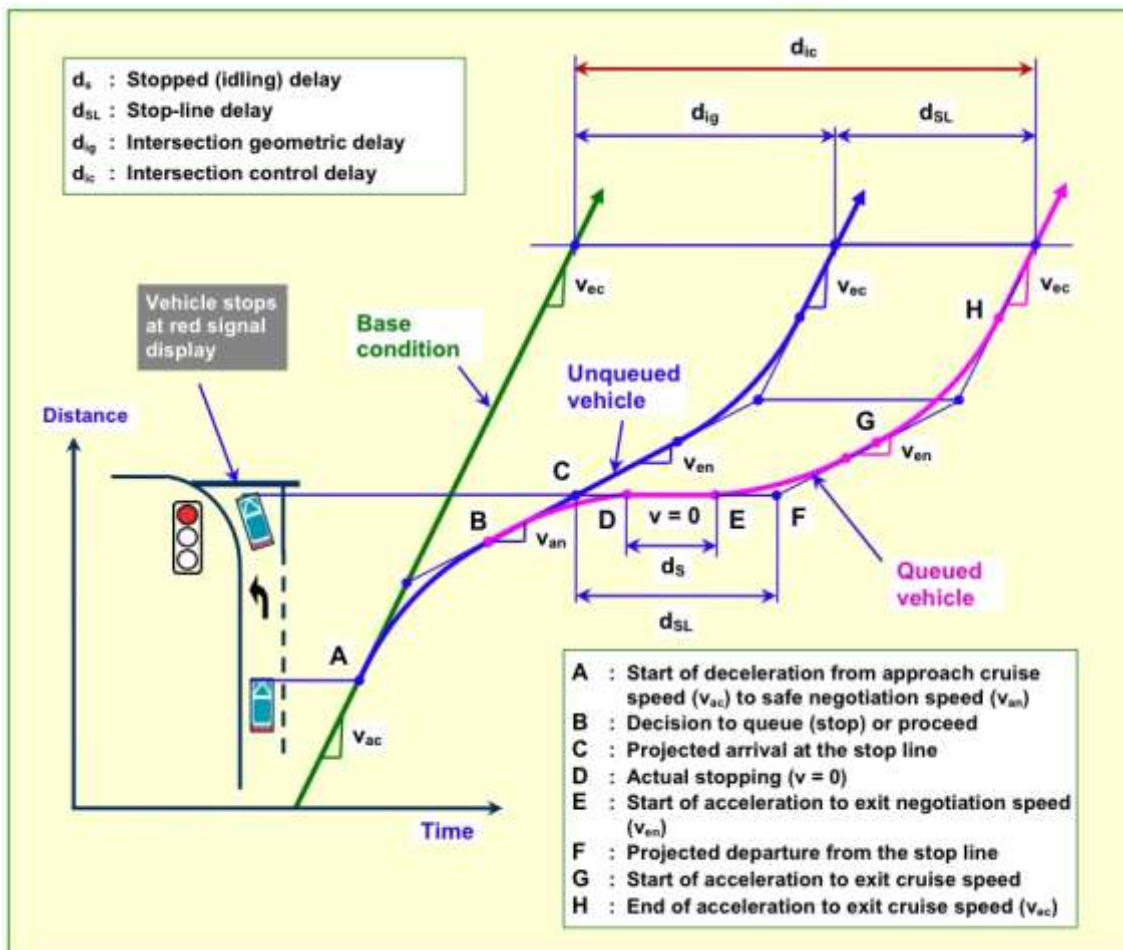


Fig. 2.7

The Stop-line delay (d_{SL}) is calculated by projecting the time-distance trajectory of a queued vehicle from the approach and exit negotiation speeds to the stop line

(or give-way/yield line), which is shown as the time from C to F in Figure 2.7. The stop-line delay is equivalent to queuing delay plus main stop-start delay, and is represented by the first two terms of the delay model ($d_{SL} = d_q + d_n = d_1 + d_2$).

The Geometric delay (d_{ig}) is the delay experienced by a vehicle going through (negotiating) the intersection in the absence of any other vehicles, which is of particular interest for satisfactory modeling of the performance of roundabouts and sign controlled intersections.

Intersection geometric delay is due to a deceleration from the approach cruise speed down to an approach negotiation speed ($v_{ac} \rightarrow v_{an}$), travel at that speed (v_{an}), acceleration to an exit negotiation speed ($v_{an} \rightarrow v_{en}$), travel the rest of exit negotiation distance at constant exit negotiation speed (v_{en}) and then acceleration to the exit cruise speed ($v_{en} \rightarrow v_{ec}$). Thus, this delay includes the effects of the physical (geometric) characteristics of the intersection (negotiation radius and distance, and the associated speeds), as well as the effects of basic control features.

The Back of the Queue, expressed as a distance in meters, is the maximum extent of the queue relative to the stop line or give-way/yield line during a signal cycle or gap-acceptance cycle. The last queued vehicle that joins the back of the queue is the last vehicle that departs at the end of the saturated part of green interval or the available gap interval.

The Percentile Queue parameter (95% in the case under analysis) is used for the percentile queue length value to be included in output reports.

A percentile queue length is a value below which the specified percentage of the average queue length values observed for individual cycles fall. For example, the 95th percentile queue length is the value below which 95 per cent of all observed cycle queue lengths fall, or 5 per cent of all observed queue lengths exceed. With a cycle time of 120 s, a 30-min peak (analysis) period would have 15 cycles. This would mean that the queue length would be larger than the 95th percentile value in $15 \times 0.05 = 0.75$ cycles during the analysis period (i.e. exceeded approximately once).

The Performance Index (PI) is a measure that combines several other performance statistics, and therefore can be used as a basis for choosing between various design options. The smallest value of PI indicates the best design.

The Performance Index is defined as

$$PI = T_u + w_1 D + w_2 K H / 3600 + w_3 N'$$

where

T_u = total uninterrupted travel time (veh-h/h), $T_u = q_a * t_u$ where q_a is the arrival (demand) flow rate and t_u is the uninterrupted travel time per unit distance at a given demand flow rate;

D = total delay due to traffic interruption (veh-h/h);

H = total number of effective stops (veh/h);

K = stop penalty;

N' = sum of the queue values (in vehicles) for all lanes;

w_1, w_2, w_3 = delay weight, stop weight and queue weight values, respectively.

The queue value used in the Performance Index calculation is always the average back of queue.

For continuous (uninterrupted) movements, $N'= 0, D=0$ and $H=0$.

In shared lane cases, the queue length for the lane is split in proportion to flows before summing up for individual movements, and this is the value used in Performance Index calculations.

Sidra Intersection uses a four-mode elemental model for estimating fuel consumption, operating cost and pollutant emissions (see Figure 1.8).

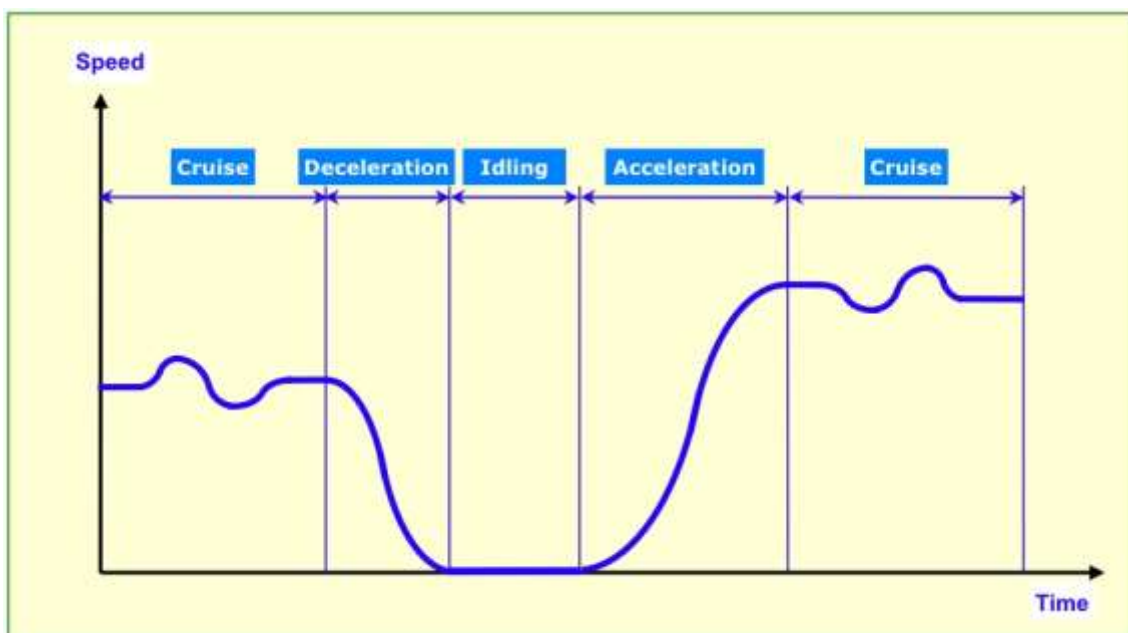


Fig. 21.8

For each lane of traffic, Sidra Intersection constructs drive cycles consisting of a series of cruise, acceleration, deceleration and idling (stopped time) elements. These drive cycles vary according to specific traffic conditions (geometry, traffic control including signal timings, driver characteristics, demand flows). Drive cycles are constructed for stopped and unstopped vehicles, and light and heavy vehicles, separately. Fuel consumption and emissions are calculated for each of the four modes of driving for each drive cycle, namely cruise, acceleration, deceleration and idling (stopped time), and the results are added together for the entire driving maneuver.

Using the fuel consumption and emission values calculated for light and heavy vehicles in each lane of each movement, the total and average values are calculated for each lane.

The average or total values for each movement or approach road are calculated by aggregating the values for the lanes that belong to the movement or approach.

The operating cost estimates include the direct vehicle operating cost (the resource cost of fuel and additional running costs including tire, oil, repair and maintenance as a factor of the cost of fuel), and the time cost to driver and passengers.

The vehicle operating cost factor, k_o (Cost Unit per litre, e.g. \$/L) is calculated from:

$$k_o = f_c f_r P_p$$

where

f_c = an aggregate cost factor used to convert the cost of fuel to total running cost including tyre, oil, repair and maintenance;

f_r = fuel resource cost factor (ratio of the resource price of fuel to the pump price);

P_p = pump price of fuel in "Cost Unit" per liter, e.g. \$/L.

The time cost per vehicle, k_t in "Cost Unit" per hour, e.g. \$/h, is calculated from:

$$k_t = f_o f_p W$$

where

f_o = average occupancy in persons per vehicle;

f_p = time value factor that converts the average income to a value of time;

W = average income (full time adult average hourly total earnings) in "Cost Unit" per hour, e.g. \$/h.

Total operating cost for vehicles, C_t in "Cost Unit" per hour, e.g. \$/h, can be calculated from:

$$C_t = k_o F_t / 1000 + k_t T_t$$

where

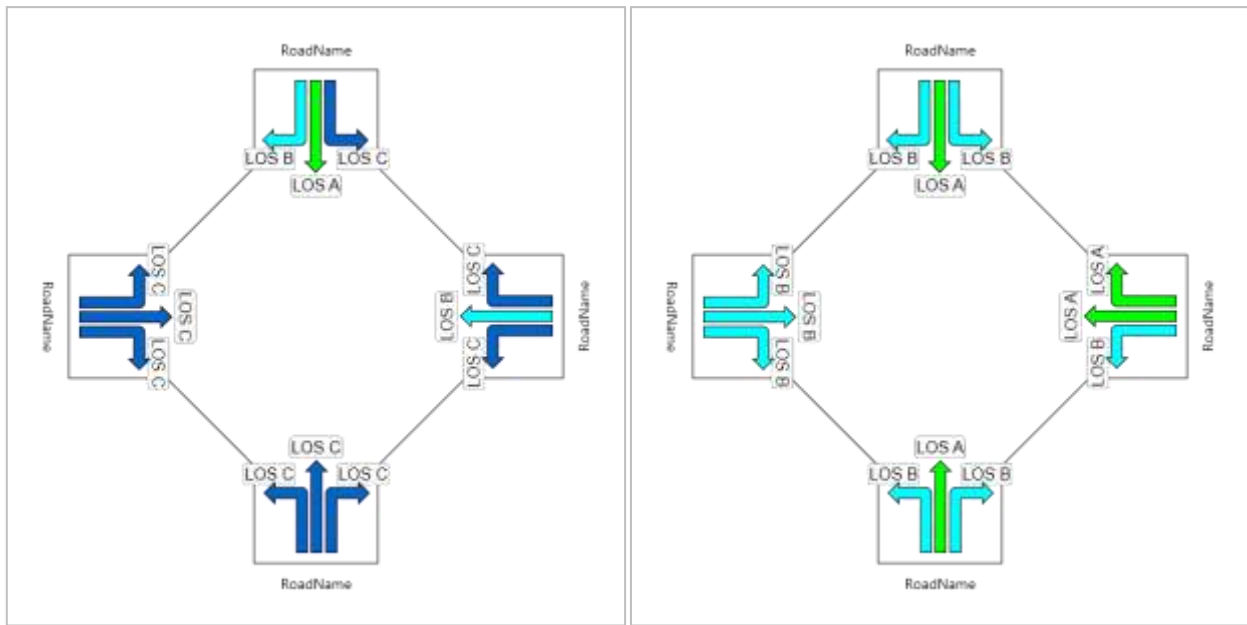
F_t = total fuel consumption (mL/h),

T_t = total vehicle travel time (veh-h/h).

All of these parameters, as shown in Table 2.6, are more favorable for B-site. For example, the degree of saturation changes from 0,813 to 0,748 with an 8% decrease. The control delay, for the worst lane (L, North approach for A-site and LT, West approach for B-site), changes from 31,4 sec to 13,2 sec, with an appreciable decrement (-58,1%), while the performance index decreases from 103 to 67. Even the environmental and energetic parameters, like fuel consumption, operating cost and pollutant emissions, decrease, e.g. the cost changes from 16670,31 \$/h to 1447,22 \$/h and the carbon dioxide changes from 551,9 kg/h to 1447,22 kg/h (only the carbon monoxide remains essentially constant).

Thus the results indicate that the roundabout, with this type of operating conditions, works better than the signalized intersection. In other words, during the peak period, the traffic stream is more fluent with the roundabout, and the level of service results higher. Figures 2.7 and 2.8 show the sites Level Of Service (LOS)⁵. For example, in the south approach the through movement improves from LOS C to LOS A, meaning a more comfortable condition for the users.

⁵ SIDRA INTERSECTION Guide - OUTPUT GUIDE Part 4, pag. 403-411.

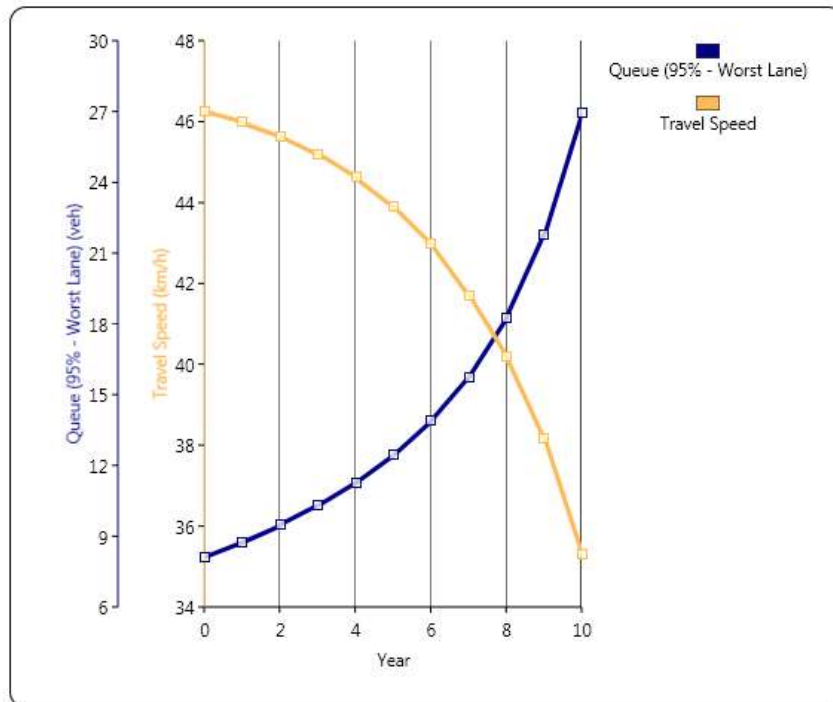


(A-site) Fig. 2.7

(B-site) Fig. 2.8

Growth model, B-site

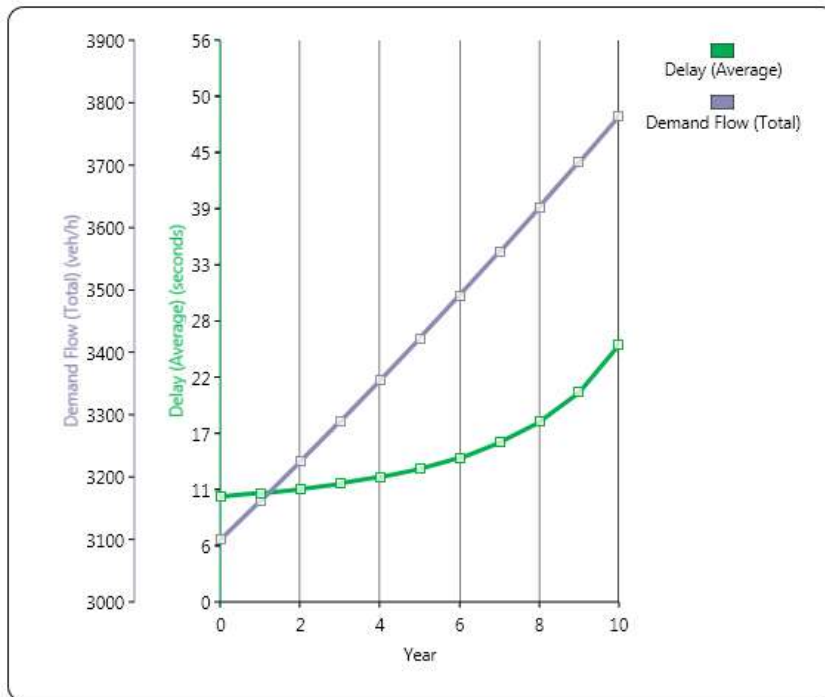
The Design Life analysis helps to investigate the effect of traffic growth with the uniform (or compound) growth options for a given number of years (10 the example under analysis) using growth rates given in the volumes and pedestrians dialogs for individual movements (2% for each movement). The following graphs are two examples of output.



Gra. 2.9

In design life analysis the x axis represents always the "Year", from "year zero" to "year 10" in the studied case.

As shown in Graphic 2.9, the delay (average) and the total demand flow are the parameters correlated with the years. They both increase over time. It means that after ten years, Sidra Intersection calculates that the demand flow will change from 3100 veh/h to 3779 veh/h, and the delay from 10,8 s to 23 s.



Gra. 22.10

Graphic 2.10 shows the back of the queue (95%) and travel speed, in the “y” axis, as a function of time. Once again the queue, like delay and demand flow, increases from 8,6 veh to more than 26 veh. On the contrary the travel speed declines over the forecast horizon. At the end of the study period, the travel speed will be 35 km/h.

B-site and C-site comparison

The B-site, considered at "year zero", was compared with the C-site at the end of the ten-years growth period. The purpose is to understand if the improvements of the geometric parameters could be sufficient to cope with the increase in demand flow.

As written in the input data, the C-site has some parameters, like entry lane width, entry angle, entry radius and circulating road width, more favorable than in the B-site.

Tab. 2.11 shows part of the Sidra Comparison output.

Intersection Performance (Vehicles Only) - Hourly Values (Tab. 2.11)

Vehicle Performance Measure	Units	Site B	Site C	Difference SiteC - SiteB	% Difference Diff / SiteB
Demand Flows (Total)	veh/h	3100	3779	679	21,9
Percent Heavy Vehicles	%	0,0	0,0	0,0	0,0
Degree of Saturation		0,748	0,848	0,100	13,3
Practical Spare Capacity	%	13,6	0,2	-13,4	-98,4
Effective Intersection Capacity	veh/h	4142	4455	313	7,6
Control Delay (Total)	veh-h/h	9,03	12,19	3,16	35,0
Control Delay (Average)	sec	10,5	11,6	1,1	10,7
Control Delay (Worst Lane)	sec	13,2	15,3	2,1	16,2
Control Delay (Worst Movement)	sec	19,0	21,1	2,1	10,8
Geometric Delay (Total)	veh-h/h	5,18	6,35	1,18	22,7
Geometric Delay (Average)	sec	6,01	6,05	0,04	0,7
Stop-Line Delay (Total)	veh-h/h	3,85	5,83	1,98	51,5
Stop-Line Delay (Average)	sec	4,47	5,56	1,09	24,3
95% Back of Queue - Vehicles (Worst Lane)	veh	8,1	11,1	3,0	36,4
95% Back of Queue - Distance (Worst Lane)	m	57,0	77,8	20,8	36,4
Total Effective Stops	veh/h	2668	3572	905	33,9
Effective Stop Rate	per veh	0,86	0,95	0,08	9,9
Proportion Queued		0,77	0,82	0,06	7,5
Performance Index		67,3	86,7	19,4	28,8

As shown before, the total demand flow raises by 21,9% in ten years.

Despite the improvement of the intersection capacity (from 4142 veh/h to 4455 veh/h), the C-site works worse than the B-site.

It means that for example the performance index (PI) increases by 28,8% and the control delay in the worst lane by 16,2%.

However, it is interesting to notice that the LOS in the C-site remains more than satisfactory (except for movement nr. 10), despite the worsening of all the performance parameters. Tab. 2.12 shows the C-site LOS for each movement.

Movement Performance – Vehicles in C-site (Tab. 2.12)

Mov ID	Turn	Demand Flow	HV	Deg. Satn	Average Delay	Level of Service	95% Back of Queue		Prop. Queued	Effective Stop Rate	Average Speed
		veh/h	%	v/c	sec		Vehicles	Distance		per veh	km/h
South: RoadName											
1	L	37	0,0	0,416	16,4	LOS B	2,5	17,2	0,79	1,02	43,4
2	T	488	0,0	0,416	9,5	LOS A	2,7	18,6	0,80	0,87	46,9
3	R	73	0,0	0,416	10,7	LOS B	2,7	18,6	0,81	0,95	47,4
Approach		597	0,0	0,416	10,1	LOS B	2,7	18,6	0,80	0,89	46,7
East: RoadName											
4	L	49	0,0	0,236	12,6	LOS B	1,1	7,6	0,53	0,88	46,1
5	T	366	0,0	0,236	6,1	LOS A	1,1	8,0	0,53	0,54	48,8
6	R	110	0,0	0,236	6,6	LOS A	1,1	8,0	0,52	0,58	48,8
Approach		524	0,0	0,236	6,8	LOS A	1,1	8,0	0,53	0,58	48,5
North: RoadName											
7	L	463	0,0	0,848	17,5	LOS B	10,9	76,5	0,88	1,08	42,0
8	T	1097	0,0	0,848	10,6	LOS B	11,1	77,8	0,86	0,99	45,8
9	R	366	0,0	0,848	11,8	LOS B	11,1	77,8	0,85	0,99	46,1

Approach	1926	0,0	0,848	12,5	LOS B	11,1	77,8	0,86	1,01	44,8
West: RoadName										
10 L	24	0,0	0,653	21,1	LOS C	4,5	31,3	0,92	1,10	40,2
11 T	609	0,0	0,653	13,7	LOS B	5,4	37,6	0,94	1,08	43,5
12 R	98	0,0	0,653	13,5	LOS B	5,4	37,6	0,96	1,09	44,3
Approach	731	0,0	0,653	13,9	LOS B	5,4	37,6	0,95	1,08	43,5
All Vehicles	3779	0,0	0,848	11,6	LOS B	11,1	77,8	0,82	0,95	45,3

D-site utilization ratio

Sidra Intersection defines the *lane utilization ratio* (ρ , or RLU as a percentage value) as the ratio of the degree of saturation of a given lane to the highest (critical) lane degree of saturation for the lane group:

$$\rho = x_j / x_c \text{ and } RLU = 100 \rho = 100 x_j / x_c$$

where x_j is the degree of saturation (demand/capacity ratio) of the j^{th} lane, and x_c is the degree of saturation of the critical lane.

Thus:

- a *fully utilized lane* means $x_j = x_c$, therefore $RLU = 100 \%$ or $\rho = 1.00$;
- an *under-utilized lane* has $x_j < x_c$, therefore $RLU < 100 \%$ or $\rho < 1.00$;
- *equal lane utilization* means equal degrees of saturation for all lanes in the lane group, $x_1 = x_2 = \dots = x_c$, therefore $RLU = 100 \%$ or $\rho = 1.00$ for all lanes.

RLU (Utilization Ratio) values less than 100 %, as it was already seen, can be given for individual lanes in the Geometry dialog (as percentage values) indicating potential lane under-utilization.

Unequal lane utilization reported in SIDRA INTERSECTION output could be a result of a user-specified $RLU < 100 \%$, as in our case, or a program determined $RLU < 100 \%$ due to a "de facto" exclusive lane or due to a limited capacity of a short lane.

The user can specify the lane under-utilization to allow one or more of the following situations:

- a large number of heavy commercial vehicles, buses or trams (moving or stopping) in the lane;
- turning vehicles in the lane subject to heavy pedestrian conflict at the exit;
- heavy interference by parking maneuvers (parking adjacent to the lane);
- opposed (permitted) turns in the lane;

- a short lane;
- a lane that discontinues at the downstream side due to a decreased number of lanes or parked vehicles (downstream short lane);
- a lane with a large proportion of traffic turning left or right at a downstream location (destination effect);
- some interference at the downstream side, e.g. vehicles merging from a slip lane with no clear give-way / yield lane markings.

Tab. 2.13 shows the comparison between the C-site and the D-site. Predictably, the performance parameters show a small decrease due to the reduced capacity (utilization ratio = 30 % in lane 2 on South approach).

That is why the Performance Index changed from 86,7 to 88,5.

Finally the D-site works worse than the C-site.

Intersection Performance (Vehicles Only) - Hourly Values (Tab. 2.13)

Vehicle Performance Measure	Units	C-site	D-site	Difference D-site – C-site	%Difference Diff / C-site
Demand Flows (Total)	veh/h	3779	3779	0	0,0
Degree of Saturation		0,848	0,852	0,004	0,4
Practical Spare Capacity	%	0,2	-0,2	-0,4	-200,7
Effective Intersection Capacity	veh/h	4455	4436	-19	-0,4
Control Delay (Average)	sec	11,6	12,0	0,4	3,5
Control Delay (Worst Lane)	sec	15,3	15,5	0,2	1,2
Geometric Delay (Average)	sec	6,05	6,05	0,00	0,0
Stop-Line Delay (Average)	sec	5,56	5,96	0,40	7,3
95% Back of Queue - Distance (Worst Lane)	m	77,8	79,4	1,6	2,1
Total Effective Stops	veh/h	3572	3677	104	2,9
Effective Stop Rate	per veh	0,95	0,97	0,03	2,9
Performance Index		86,7	88,5	1,8	2,1

II. 2. Example number 2: Roundabout with unbalanced flows.⁶

The second example is based on a real-life case described in AUSTRROADS Traffic Engineering Practice (1993). It deals with a roundabout having an unbalanced flow in one of the approaches, causing traffic problems during the morning peak. In order to solve the problem of excessive queuing and delays at approaches affected by highly directional flows, metering signals can be used to create gaps in the circulating stream.

⁶ Sidra Intersection, Training Workshop, Introduction and Intermemmediate Workshop, Oslo, Norway, 2011. Akcelik & Associates Pty Ltd, pag. 54-57.

The use of metering signals is a cost-effective measure to avoid the need for a fully-signalized intersection treatment. Roundabout metering signals are installed on selected roundabout approaches and used on a part-time basis since they are required only when heavy demand conditions occur during peak periods, during the morning in the case under analysis.

As shown in Fig. 2.14, the term *Metered Approach* is used for the approach stopped by red signals (approach causing problems for a downstream approach), and the term *Controlling Approach* is used for the approach with the queue detector, which is the approach helped by metering signals.

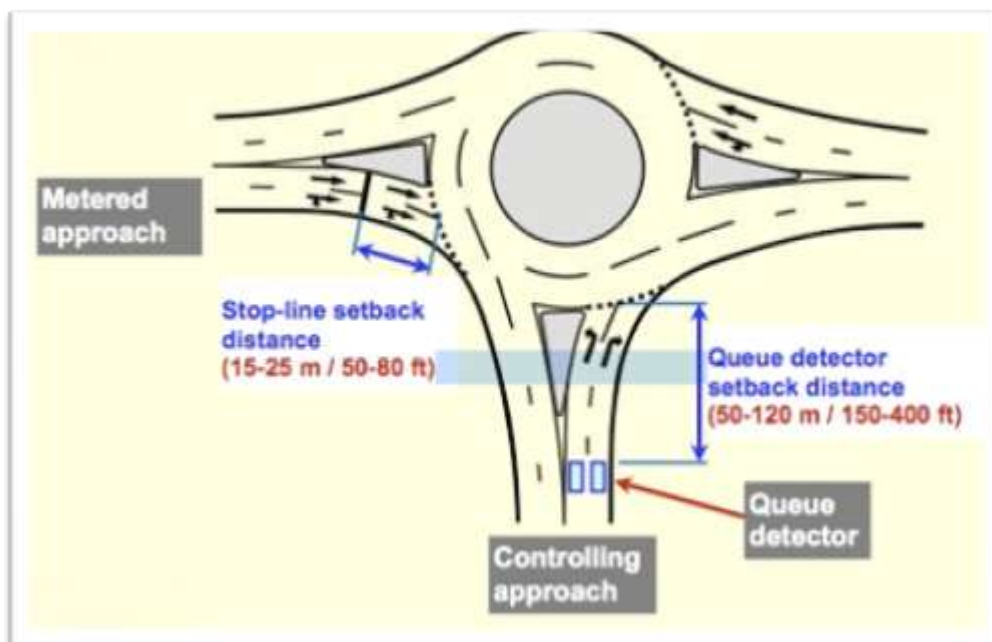


Fig. 2.14

When the queue on the *Controlling Approach* extends back to the queue detector, the signals on the *Metered Approach* display red (subject to signal timing constraints) so as to create a gap in the circulating flow. This helps the *Controlling Approach* traffic to enter the roundabout. When the red display is terminated on the *Metered Approach*, the roundabout reverts to normal operation. The introduction and duration of the red signal on the Metered Approach is determined by the Controlling Approach traffic. The duration of the blank signal is determined according to a minimum blank time requirement, or extended by the metered approach traffic if detectors are used on that approach.

Two-aspect yellow and red signals are commonly used for metering signals. The sequence of aspect display is Off to Yellow to Red to Off. When metering is not required neither aspect is displayed.

Table 2.15 summarizes some design and control parameters used for metering signals at various roundabouts in Australia.⁷

Table 2.15

Metered approach	
Signal stop-line setback distance	15 -25 m
Controlling approach	
Queue detector setback distance	50 - 120 m
Signal Timing	
Minimum blank time setting	20 - 50 s
Maximum blank time setting	50 - 80 s
Minimum red time setting	10 - 20 s
Maximum red time setting	30 - 80 s
Yellow time	3.0 - 4.0 s
All-red time	1.0 - 2.0 s

II. 2.1. Input data

A – Roundabout without metering signal.

Site A is a Y-shaped roundabout, without the metering signal. It represents the base configuration of the intersection, before metering is adopted.

After the processing, the A-site output will be compared with the B-site output (with metering).

⁷ AKÇELİK, R. (2005), “Capacity and Performance Analysis of Roundabout Metering Signals.” (Pag. 10)

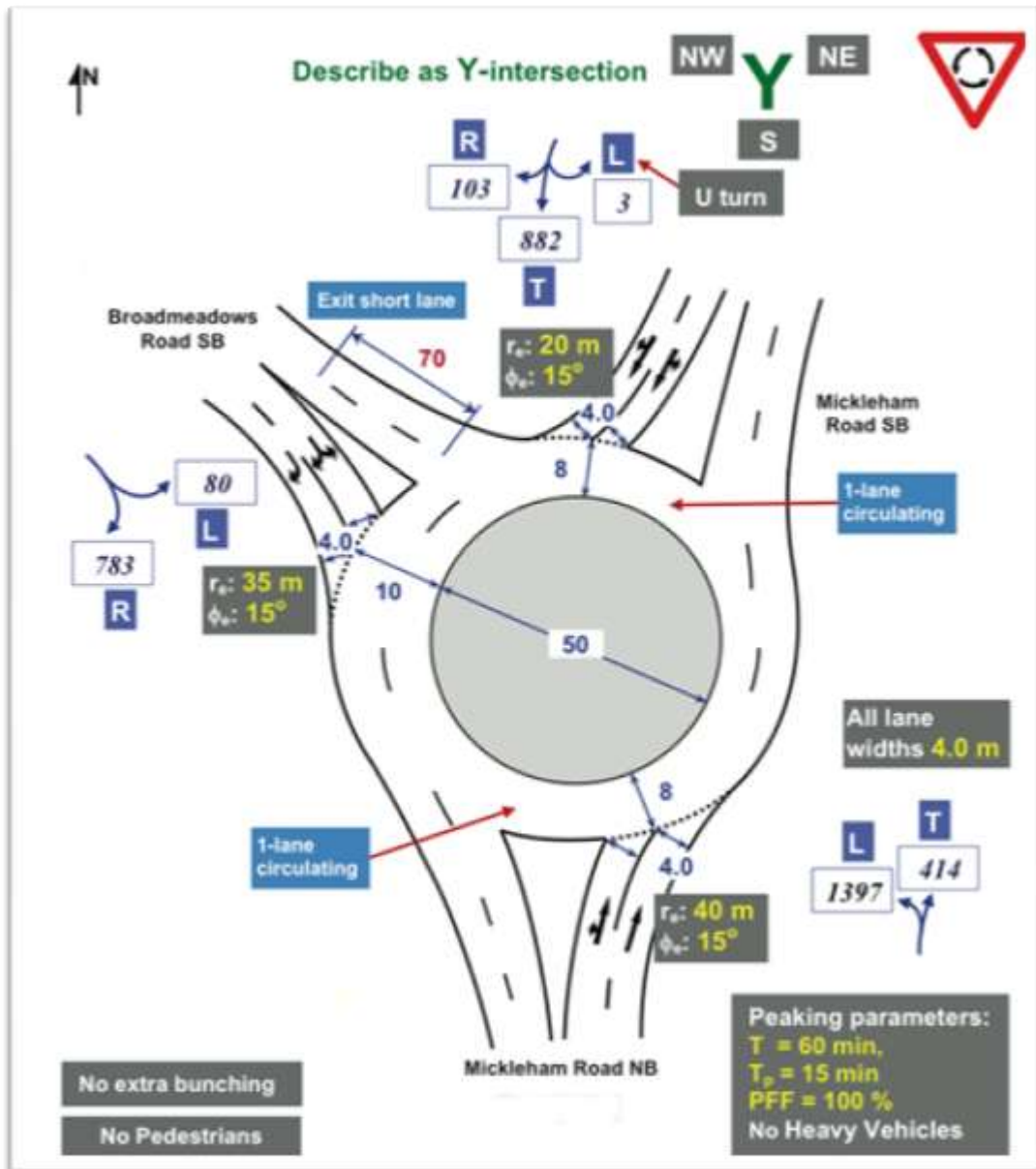


Fig. 2.16

In the intersection dialog the following inputs were set up:

- the shape of the intersection (Y-intersection, 3 legs)
- unit time for volume = 60 min and peak flow period = 15 min

In the geometry dialog:

- entry radius = 40 m and entry angle = 15° (Mickleham Road NB);
- entry radius = 20 m and entry angle = 15° (Mickleham Road SB);
- entry radius = 35 m and entry angle = 15° (Broadmeadows Road SB);
- entry lane width 4 m (all lanes) and movement definitions;
- circulating lane as shown in Fig. 2.16;

Before processing, the Volumes were set as shown in the chart in Fig. 2.16, with the additional specification of no extra bunching and no pedestrians.

B – Roundabout with metering signal

The B-site is the A-site converted into a metered roundabout, with the same volumes and geometric characteristics.

In addition to normal roundabout data, special data required for roundabout metering are specified in the Roundabout Metering input dialog. In that dialog, the Mickleham Road South was specified as metered approach and Mickleham Road North as controlling approach (photographic reproduction in Fig. 2.17).



Fig. 2.17

In addition, in the Cycle Time Option and in the Phase Data tab, I selected Optimum Cycle Time with 35 sec as lower value (Upper=120 sec and Increment=5 sec).

In Sidra Intersection metering signals are based on a simple two-phase operation (Blank Phase and Red Phase). Signal timing data consist of Cycle Time Option and Phase Data for the Blank and Red Phases (Fig. 2.18).

Cycle Time options are similar to those used for normal signalized intersections.

Phase Time (optional) is the sum of Blank Time (or Red Time), Yellow Time and All-Red Time for the subject phase. Yellow time is a nominal setting for the Red Phase as it will be displayed as a red interval.

METERED APPROACH		
Stop Line Setback Distance	20,0 m	
Start Loss	3 sec	
End Gain	3 sec	
CONTROLLING APPROACH		
Queue Detector Setback Distance	60,0 m	
CYCLE TIME OPTION		
<input type="radio"/> Practical Cycle Time		
Maximum Cycle Time	100 sec	
Cycle Rounding	1 sec	
<input checked="" type="radio"/> Optimum Cycle Time		
<input checked="" type="checkbox"/> Lower	35	
Upper	120 sec	
Increment	5 sec	
<input type="radio"/> User-Given Cycle Time		
Cycle Time	60 sec	
<input type="radio"/> User-Given Phase Times		
PHASE DATA		
	Blank Phase	Red Phase
Phase Time (Optional)	25 sec	25 sec
Yellow Time	3 sec	3 sec
All-Red Time	2 sec	2 sec
Minimum Phase Time	6 sec	6 sec

Fig. 2.18

II. 2.2. Analysis of the Output Data

As indicated before, the metering signal helps the roundabout in terms of performance measures, when there are unbalanced flows and high demand flow levels in the intersection.

In order to verify this circumstance, the A-site was compared with the B-site.

Tab. 2.19 is the output of Sidra Output Comparison. It shows, as usual, the main performance parameters of the two sites and the differences between them. The demand flows remain constant, while the effective capacity increases as expected (from 3534 to 4344 veh/h). Due to this capacity increase, the metered intersection works better during the peak:

- 18,6 % is the decrease of the degree of saturation (from 1,036 to 0,843);
- 59,9 % is the decrease of the control delay (total and average);
- 30,3 % is the decrease of the total effective stops (from 3665 to 2555 veh/h);

Despite the back of the queue for the worst lane (controlling approach for the A-site and metered approach for the B-site) remains more or less constant, the performance index decreases by 13,1% (from 138,3 to 120,2), as the above listed parameters.

Regarding the energy consumption and the pollutant parameters, a decrease is observable in the last part of the table 2.19, e.g the cost changes from 2679,85 to 1965,19 \$/h and hydrocarbons from 1,346 to 1,133 kg/h.

All these results demonstrate that the intersection can work better with metering signal, at least in certain ranges of demand flows.

Intersection Performance (Vehicles Only) - Hourly Values (Tab. 2.19)

Vehicle Performance Measure	Units	Site A	Site B	Difference SiteB - SiteA	%Difference Diff / Site A
Demand Flows (Total)	veh/h	3662	3662	0	0,0
Percent Heavy Vehicles	%	0,0	0,0	0,0	0,0
Degree of Saturation		1,036	0,843	-0,193	-18,6
Practical Spare Capacity	%	-18,0	0,8	18,8	-104,6
Effective Intersection Capacity	veh/h	3534	4344	810	22,9
Control Delay (Total)	veh-h/h	41,33	16,59	-24,74	-59,9
Control Delay (Average)	sec	40,6	16,3	-24,3	-59,9
Control Delay (Worst Lane)	sec	134,4	27,2	-107,2	-79,8
Control Delay (Worst Movement)	sec	138,4	23,7	-114,7	-82,9
Geometric Delay (Total)	veh-h/h	7,41	7,41	0,00	0,0
Geometric Delay (Average)	sec	7,29	7,29	0,00	0,0
Stop-Line Delay (Total)	veh-h/h	33,92	9,18	-24,74	-72,9
Stop-Line Delay (Average)	sec	33,34	9,02	-24,32	-72,9
95% Back of Queue - Vehicles (Worst Lane)	veh	46,5	46,9	0,4	0,9
95% Back of Queue - Distance (Worst Lane)	m	325,2	328,0	2,8	0,9
Total Effective Stops	veh/h	3665	2555	-1110	-30,3
Effective Stop Rate	per veh	1,00	0,70	-0,30	-30,3
Proportion Queued		0,63	0,82	0,19	30,6
Performance Index		138,3	120,2	-18,1	-13,1
Travel Distance (Total)	veh-km/h	2375,7	2375,7	0,0	0,0
Travel Distance (Average)	m	649	649	0	0,0
Travel Time (Total)	veh-h/h	82,5	56,9	-25,6	-31,0
Travel Time (Average)	Sec	81,1	56,0	-25,1	-31,0
Travel Speed	km/h	28,8	41,7	12,9	44,9
Cost (Total)	\$/h	2679,85	1965,18	-714,67	-26,7

Fuel (Total)	L/h	301,1	265,2	-35,9	-11,9
Carbon Dioxide (Total)	kg/h	752,7	662,9	-89,8	-11,9
Hydrocarbons (Total)	kg/h	1,346	1,133	-0,213	-15,8
Carbon Monoxide (Total)	kg/h	52,52	50,24	-2,28	-4,3
NOx (Total)	kg/h	1,594	1,529	-0,065	-4,1

CHAPTER III

FIELD OBSERVATIONS IN TRONDHEIM, NORWAY

In this chapter the field observations carried out in Trondheim (Norway) will be explained using charts, tables, computer-aided design reproductions, origin-destination matrices and screenshots.

The following list shows the parameters which will be described and processed in the next thesis sections:

- Geographic location of the intersection;
- Choice of the time span for the observations;
- Traffic flow characteristics during the morning peak;
- Geometric characteristics for each approach and lane;
- Development of the origin-destination matrices for each approach following the traffic flow counting;
- Equivalence coefficients used;
- Signal plan, describing cycle time and phases sequence;
- Total and average delay for each lane of the South Approach;
- Average delay for the South Approach buses, using the difference between interrupted and uninterrupted travel times.

Data like average delay will be used in the next chapters as comparison parameters for the modeling outputs.

III. 1. Intersection description

The field observations were carried out in Trondheim, the third most populous municipality in Norway, in Sør-Trøndelag county.

Figure 3.1 shows the intersection under analysis with a Google Earth screenshot.



Fig. 3.23

This is a three-leg signalized intersection, just outside the city center, in the industrial belt. The main road is Holtermans Veg. (south-north direction) and it is the arterial street connecting the suburbs to the city center. Thus during the peak of the morning, the typical flow in the South Approach is characterized by daily commuters travelling to reach the center. Opposite, during the peak of the afternoon the North Approach has the largest flow due to the daily commuters leaving the city.

The Holtermans Veg. in south direction becomes the Trondheim ring road.

The East Approach is Bratsbervegen and it is a secondary road linking Lerkendal and Sorgenfri quarters to the main road for the city center or for the ring road.

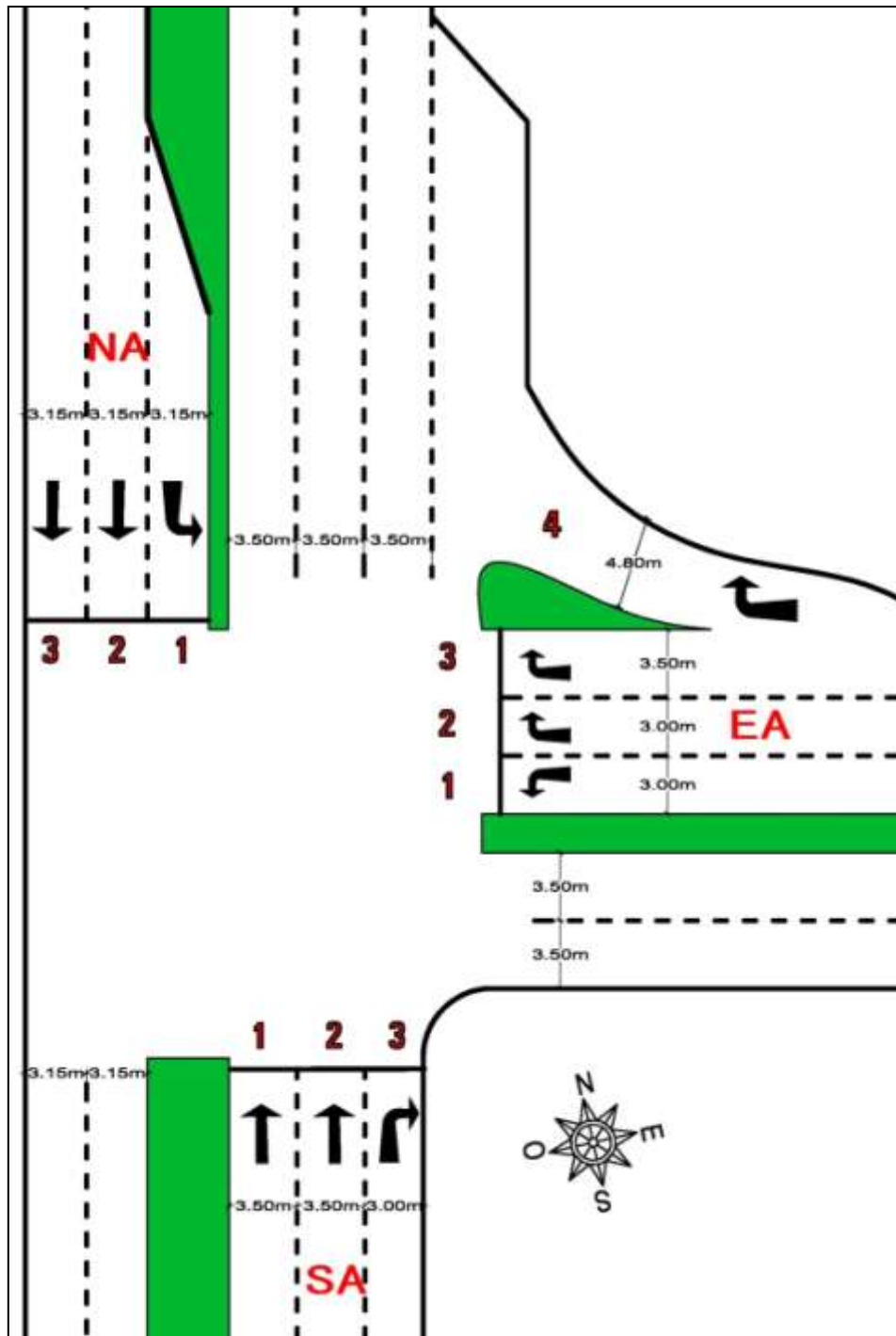


Fig. 3.24

Fig. 3.2 is a computer-aided design reproduction of the intersection. As seen, the South Approach (SA) has three lanes:

- lane 1 and 2 for straight direction,
- lane 3 for right turning.

In the north direction, downstream the intersection, lane 2 becomes a bus priority lane and lane 3 disappears. Thus the cars approaching the intersection

from south tend to choose lane 1, in order to avoid changing lane after the intersection. This behavior of car drivers allows to consider the intersection as a bus priority intersection, even if there is no real priority lane for buses. This type of simplification will imply some essential considerations during the data processing and the comparison with software modeling.

The East Approach (EA) has four lanes:

- lane 1 for left turning;
- lane 2 and 3 for right turning;
- lane 4 is a short continuous lane (22 meters long) for buses coming from Lerkendal and Sorgenfri quarters for the right turning.

This approach presents some problems during the afternoon peak, due to the excessive queuing for the left turning. In order to reduce the negative effects of this type of traffic congestion, in the future lane 2 will be converted into a left turning lane.

The volume of buses in this approach is very low.

The North Approach (NA) has three lanes:

- lane 1 is a short lane for left turning, with a 140 meters turn bay;
- lane 2 and 3 for straight direction.

This approach doesn't show any problem of excessive queuing and delays, neither during the morning peak nor in the afternoon peak. Seldom if ever the queue storage capacity of the short lane is not sufficient to receive the approaching flow, especially when the heavy vehicle flow is high. In this case, the queue in lane 1 reaches lane 2, causing delay for the straight direction.

Figure 3.2 also shows the lane widths expressed in meters.

This intersection was selected for the field observations because of the following reasons:

- it is an isolated intersection, therefore the arrival patterns are not influenced by either signal control or other factors. Thus it will not be necessary to specify platooned arrival data;
- although the intersection doesn't have a real bus priority lane, the drivers' behavior will allow to model it as a priority intersection, even if some considerations will be necessary;

- Holtermans Veg. is one of the roads with the highest bus flow in Trondheim;
- the pedestrian flow is low because of the nature of the location (industrial area), thus pedestrians can be neglected in the intersection modeling.

III. 2. How the field observations were carried out

Two high definition video cameras were placed on the top of the roof, in Tempevegen 22, a secondary street close to the crossroad under analysis. This fifteen-storey building was the perfect location for the recording because of the right distance from the intersection (around 400 meters) and the right height (around 50 meters).

In order to obtain a full view of the intersection, two video cameras were used so that the recording angle was larger. Indeed a larger angle allows to observe the queue length, an important input element to derive delays and other output parameters.

A frame of the recording is shown in Figure 3.3.



Fig. 3.25

The purpose of the field observations is to analyze the flow coming from South to North, especially the bus flow. For this reason the recordings were taken during the morning peak, from 7:15 to 8:15 a.m., in a normal working day without snow (Tuesday May 15, 2012).

Once the recordings were taken, all the data were processed using software like Windows Media Player and Excel, and tools to count the vehicles.

III. 3. Data processing

In this section of the thesis all the processing phases and the outputs will be described through charts and graphs.

III. 3. 1. Vehicular counts

Once the recording was completed, the tape was analyzed using Windows Media Player for the vehicles counting.

The flow has been measured for each lane every 5 minutes, separately for light vehicles (all the motorcycles, low (below 2 meters) 2-axis vehicles, low 3-axis vehicles and high (above 2 meters) 2-axis vehicles), buses (ordinary city buses and intercity buses) and heavy vehicles (neither light vehicle nor buses).

The vehicular counts refer to the period from 7:15 to 8:00 a.m., even if the recording was done from 7:15 to 8:15. This choice was made due to the strong decrease of the flow peak around 8:00 in the morning.

Table 3.4 shows the South Approach traffic flow for each lane, measured about every 5 minutes (in order to have exact cycles) from 7:15 to 8:00 in the morning.

Table 3.4 (TRAFFIC FLOW, SOUTH APPROACH)

	1 - Straight direction			2 - Straight direction			3 - Right turning		
	Light Veh	Heavy Veh	Buses	Light Veh	Heavy Veh	Buses	Light Veh	Heavy Veh	Buses
07:15:10	61	1	0	33	1	2	50	1	2
07:20:21	54	0	0	19	1	4	36	1	2
07:25:32	47	1	0	25	0	4	29	0	2
07:30:30	54	2	0	42	0	3	45	1	4

07:35:55	40	1	0	24	0	4	39	0	1
07:40:49	44	5	0	29	2	3	40	0	2
07:45:47	50	2	0	25	1	2	32	1	0
07:50:39	34	1	0	31	0	3	25	2	3
07:55:52	37	3	0	20	0	2	22	0	2

It is significant to notice that:

- the bus flow reported for the right turning is not a real flow to Bratsbervegen. Sometimes during the daily peaks, the bus drivers choose to occupy lane 3 even if they are headed to the city-center (straight direction), in order to avoid the queue in lane 2 and to be closer to the bus-stop bay just downstream the intersection;
- the lane 1 flow for straight direction is higher than the lane 2 flow because of the drivers behavior. They know that downstream lane 2 becomes a bus priority lane, thus they avoid to change lane later.

Table 3.5, built following the same criteria of Table 3.4, shows the North Approach traffic flow.

Table 3.5 (TRAFFIC FLOW, NORTH APPROACH)

	1 - Left turning			2 - Straight direction			3 - Straight direction		
	Light Veh	Heavy Veh	Buses	Light Veh	Heavy Veh	Buses	Light Veh	Heavy Veh	Buses
07:15:10	10	0	0	6	0	0	10	1	2
07:20:21	8	0	0	20	0	0	19	2	4
07:25:32	19	2	0	18	0	0	21	0	5
07:30:30	14	2	0	24	0	0	25	0	5
07:35:55	21	1	0	24	0	0	22	0	2
07:40:49	14	0	0	27	0	0	13	1	4
07:45:47	12	0	0	20	0	0	11	0	9
07:50:39	17	2	0	11	0	0	15	2	5
07:55:52	8	1	0	12	0	0	11	1	3

It should be noted that:

- no buses travel in lane 1 (no city-bus line to Bratsbervegen);

- no buses travel in lane 2, because of a bus stop bay, 50 meters downstream the intersection. Thus the buses tend to travel in lane 3;
- the traffic flow on the approach is rather low, since during the morning peak there is not much traffic traveling from the city center to outside areas.

Table 3.6, built as the above tables, shows the East Approach traffic flow.

Table 3.6 (TRAFFIC FLOW, EAST APPROACH)

	1 - Left turning			2 - Right turning			3 - Right turning			4 - Right turning		
	Light Veh	HV	Bus	Light Veh	HV	Bus	Light Veh	HV	Bus	Light Veh	HV	Bus
07:15:10	1	0	0	10	1	0	9	0	0	0	0	1
07:20:21	7	0	0	6	0	0	7	0	0	0	0	1
07:25:32	5	0	0	6	0	0	2	0	0	0	0	2
07:30:30	5	0	0	4	0	0	6	0	0	0	0	0
07:35:55	3	0	0	4	0	0	8	0	0	0	0	2
07:40:49	5	0	0	3	1	0	5	0	0	0	0	0
07:45:47	5	0	0	6	0	0	6	0	0	0	0	1
07:50:39	1	0	0	6	1	0	8	0	0	0	0	1
07:55:52	1	0	0	5	1	0	4	0	0	0	0	0

It should be noted that:

- the flow on this approach during the morning peak is very low;
- lane 4 is used just by buses (continuous buses lane);
- the Heavy Vehicle flow is almost nonexistent on this approach, due to the traffic composition in the morning peak.

Based on the previous three tables, Origin-Destination matrices can be built.

The values in the following matrices are expressed in equivalent vehicles per 15 minutes. Every Heavy vehicle and Bus was counted as 2,5 times a Light vehicle, e.g. if the hourly flow is 100 light vehicles, 20 buses and 60 heavy vehicles, the equivalent flow is 300 eqveh/h ($1,0 \cdot 100 + 2,5 \cdot 20 + 2,5 \cdot 60 = 300$). For the sake of simplicity, and since heavy vehicles flow is quite low, the same equivalence coefficient was used for HV and buses.

Tables 3.7, 3.8 and 3.9 are three origin-destination matrices that will be used later to identify the worst 15 minutes, in terms of flow, during the morning peak. Indeed, the sum of the O/D matrix values gives the total vehicular volume crossing the intersection in the considered period.

Table 3.7 (O-D Matrix, flow from 7:15 to 7:30, expressed in equivalent vehicles/15 minutes)

<i>O/D</i> 7:15-7:30	South Approach	North Approach	East Approach
South Approach	--	274	135
North Approach	129	--	42
East Approach	13	52,5	--

Table 3.8 (O-D Matrix, flow from 7:30 to 7:45, expressed in equivalent vehicles/15 minutes)

<i>O/D</i> 7:30-7:45	South Approach	North Approach	East Approach
South Approach	--	283	144
North Approach	165	--	56,5
East Approach	13	37,5	--

Table 3.9 (O-D Matrix, flow from 7:45 to 8:00, expressed in equivalent vehicles/15 minutes)

<i>O/D</i> 7:45-8:00	South Approach	North Approach	East Approach
South Approach	--	232	99
North Approach	130	--	44,5
East Approach	7	45	--

III. 3. 2. Cycle and phases

After counting the traffic flow, the signal operation was analyzed, measuring the length of the cycle and the phase sequences.

The following table (3.10) shows how intervals and indications work at the signalized intersection under analysis. Essentially the table shows a signal plan for the intersection. The time is the length of the interval, while R (Red) and G (Green) refer to the indication during the specific interval. An interval is a period of time during which none of the indications changes.

Because of the small number of pedestrians in this industrial area, the pedestrian movements, crossing in front of South and East Approaches, were ignored in the counting. In addition the signal plan is not influenced by the pedestrian crossing movements.

Table 3.10 (Signal Plan for three cycles)

Interval (Cycle)	Time (sec)	South Approach			North Approach			East Approach			
		1(T)	2(T)	3(R)	1(L)	2(T)	3(T)	1(L)	2(R)	3(R)	4(R)
1 (I)	20	R	R	R	G	G	G	R	G	G	G
2 (I)	3	R	R	R	R	G	G	R	R	R	G
3 (I)	28	G	G	G	R	G	G	R	R	R	G
4 (I)	4	R	R	R	R	R	R	R	R	R	G
5 (I)	8	R	R	R	R	R	R	G	G	G	G
6 (I)	3	R	R	R	R	R	R	R	G	G	G
7 (II)	15	R	R	R	G	G	G	R	G	G	G
8 (II)	3	R	R	R	R	G	G	R	R	R	G
9 (II)	35	G	G	G	R	G	G	R	R	R	G
10 (II)	4	R	R	R	R	R	R	R	R	R	G
11 (II)	10	R	R	R	R	R	R	G	G	G	G
12 (II)	3	R	R	R	R	R	R	R	G	G	G
13 (III)	16	R	R	R	G	G	G	R	G	G	G
14 (III)	3	R	R	R	R	G	G	R	R	R	G
15 (III)	24	G	G	G	R	G	G	R	R	R	G
16 (III)	4	R	R	R	R	R	R	R	R	R	G
17 (III)	16	R	R	R	R	R	R	G	G	G	G
18 (III)	3	R	R	R	R	R	R	R	G	G	G

The 18 intervals shown in Table 3.10 represent just three whole cycles even if all cycles from 7:15 to 8:00 (about 45 cycles) were analyzed. Every cycle is composed by 3 phases, each of which is separated by an all-red time. For the sake of simplicity the yellow time was ignored.

All-red time between the phases is a fixed value, while phases time changes each cycle due to the presence of vehicle loop detectors. Although this traffic signal is designed to work like a fully-actuated signal, the cycle time remains more or less the same for all the cycles during the morning peak. Later, for this reason, the intersection will be modeled as a pre-timed signal (phases time will be the average of the phases times in the period of analysis).

Figure 3.11 shows a phasing summary chart, where green arrows represent normal movement with green light while red arrows stopped movement. The chart is closely correlated with Table 3.10 because phase A coincides with intervals 1,7 and 13, phase B with intervals 3,9,15 and phase C with intervals 5,11,17.

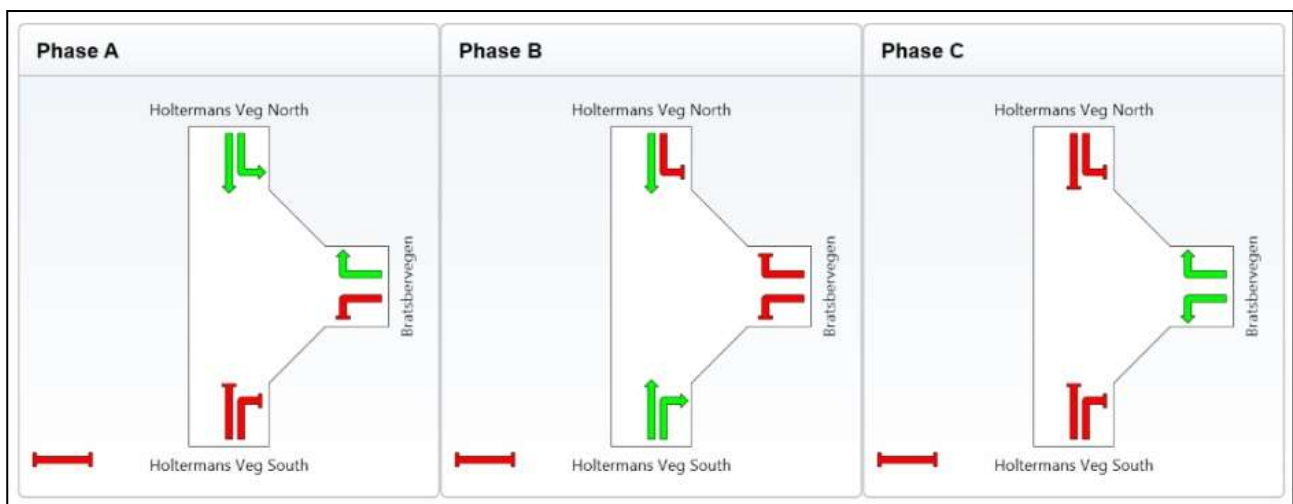


Fig. 3.11 (Intersection Phases)

III. 3. 3. Delay on South Approach

As written in the introduction, the purpose of this thesis is to analyze and model bus priority lanes. In this section, for this reason, the South Approach will be analyzed in order to obtain total and average delay for each lane (bus priority lane belongs to South Approach).

Figure 3.12 shows the queue length as a function of time for a typical cycle at a traffic signal. In the following list all symbols appearing in the graph are defined:

- **q**: arrival flow rate [veh/sec];
- **s**: saturation flow rate [veh/sec];
- **s-q**: queue discharge rate [veh/sec];

- **L(t)**: queue length [veh];
- **D_c**: total delay per cycle [veh* sec];
- **c**: cycle time [sec];
- **r**: effective red time [sec];
- **g**: effective green time [sec];
- **g_s**: saturated green time [sec];
- **g_u**: unsaturated green time [sec].

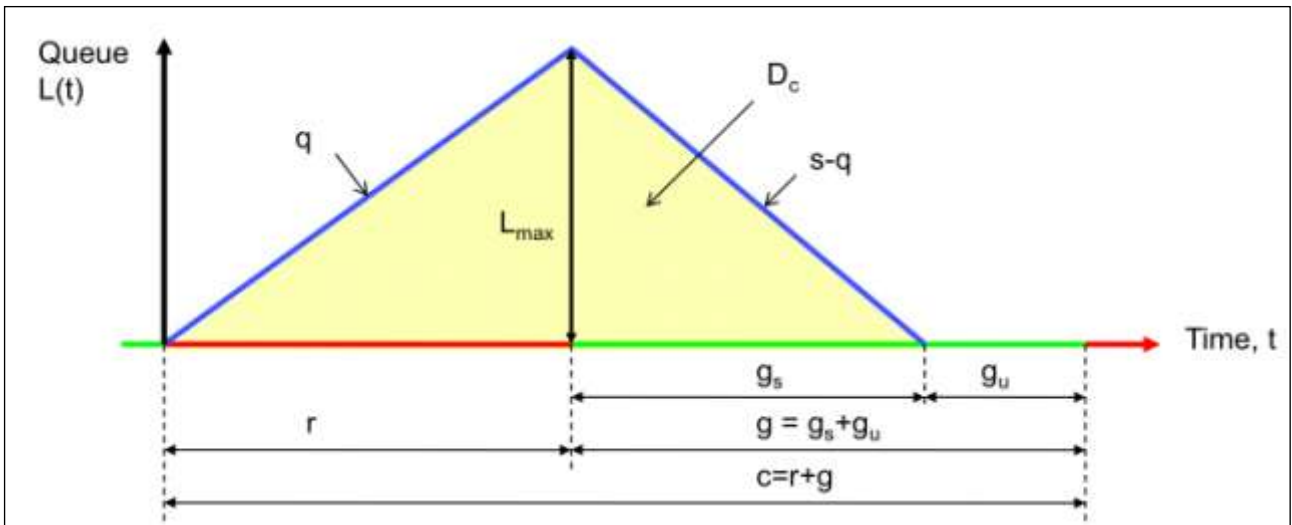


Fig. 3.12

Traffic arrives during the cycle time ($c=r+g$) and it passes the stop line during the green time. If the ratio of the flow ($q \cdot c$), arriving during the cycle, to the maximum flow which is able to pass the stop line during the green time ($s \cdot g$) is bigger than 1, the lane is oversaturated. If the ratio is less than 1, the unsaturated green time is positive and this is the case represented in figure 3.12. If the ratio is equal to 1, the unsaturated green time (g_u) will be naught.

Just this last case will be used as a simplifying assumption when delays (total and average) will be calculated for each lane of the South Approach.

Figure 3.13 shows the shape of the graph for one cycle for a lane assuming this simplification.

The Y axis represents the queue length, expressed in number of equivalent vehicles, as a function of time. At 07:16:03 the cars start to queue with red on the traffic light, at 07:16:34 the queue starts to dissolve until the new red at

07:17:08. The unsaturated green time (g_u) is equal to zero and the queue is dissolved just at the beginning of the new cycle ($q \cdot c = s \cdot g$).

It should be noted that assuming this simplification in the case under analysis, the Total and Average Delay will be overestimated, since the observations shows that the oversaturated cycles are less than the under saturated ones.

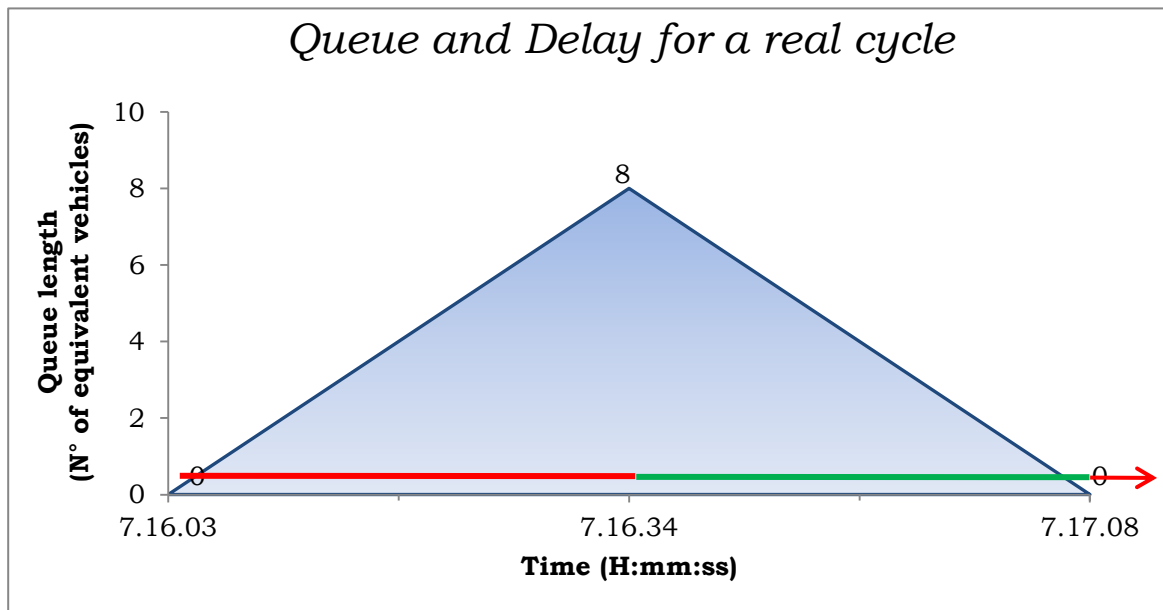


Fig. 3.13

Once this graph has been built for each cycle, the sum of total delay per cycle (D_c), represented by the area of the triangle, could be calculated, while the average delay per vehicle will be calculated as ratio of total delay to total arrivals in the chosen time span.

The time span was chosen finding the half-hour in the recording period with the highest flow in the South Approach, in other words the period with the worst average delay and the longest queues.

In this time span, that goes from 7:15 a.m. to 7:45 a.m., the cycles are 29.

To build these 29 graphs for each lane, the following indications were adopted:

- the counting of the vehicles queued was done for each lane when the first car in the queue had completely passed the stop line;
- in that very second was noted down the time (H:mm:ss) of the recording;
- once known the number of the buses, the light and heavy vehicles queued, the equivalent vehicles were determined;

- to calculate the blue area under the curve (Total Delay) the time was expressed in seconds;
- for the sake of simplicity all the 29 triangles were lined up in only one graph.

Figure 3.14 shows lane 1 (straight direction) queuing in the time span chosen. The blue area under the curve, as written before, represents the Total Delay and it is equal to 5050 seconds, while the Total Flow is equal to 325 equivalent vehicles per 30 minutes. Thus the Average Delay per vehicle is 15,54 seconds.

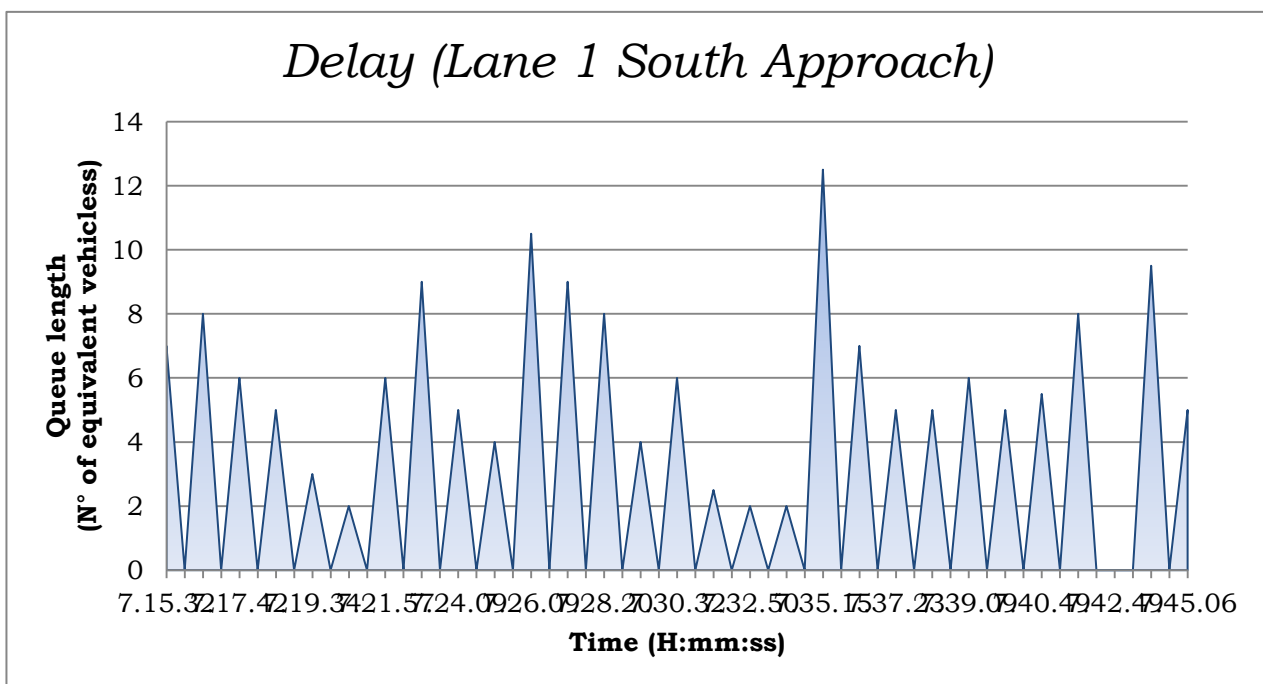


Fig. 3.126

Figure 3.15 shows the queue length for lane 2 (straight direction) as a function of time, as before.

Total Delay is equal to 2799 seconds, while the Total Flow is 232 equivalent vehicles per 30 minutes. Thus the Average Delay for lane 2 is 12,07 seconds per vehicle.

This value as expected is lower than Lane 1 delay, since as written before the drivers tend to fill up Lane 1 to avoid to change lane later and to leave Lane 2 for the buses.

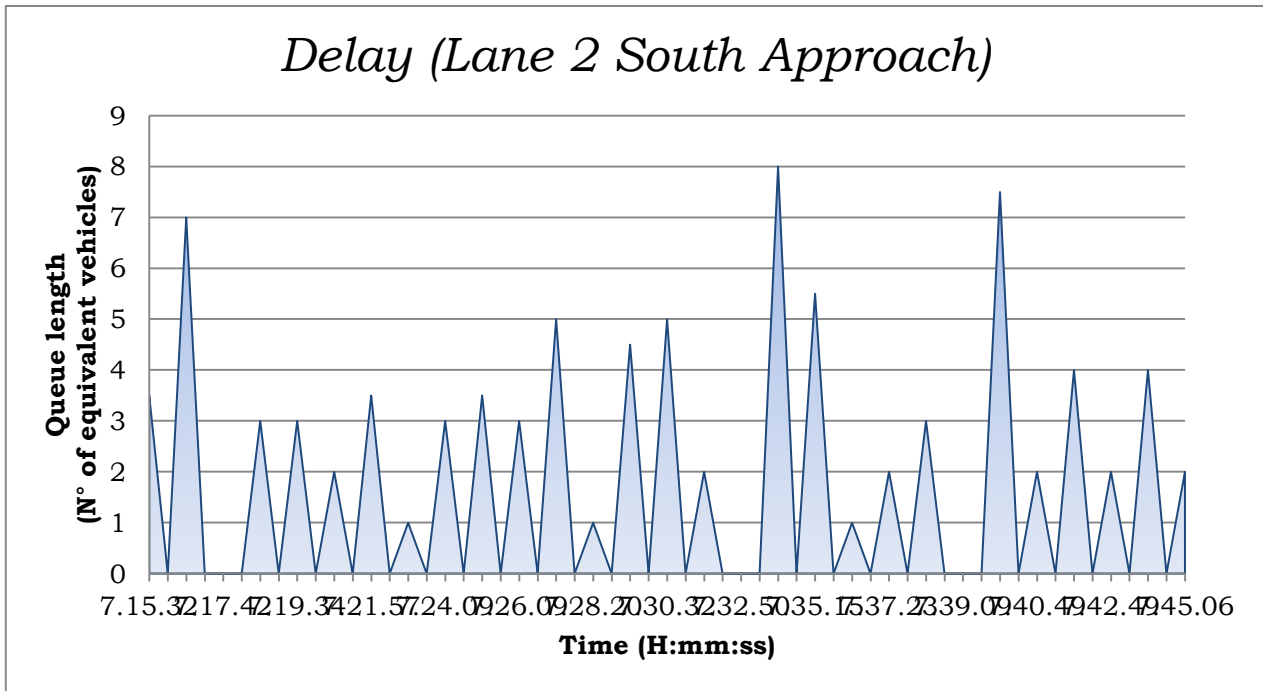


Fig. 3.127

Figure 3.16, as the above two, shows the lane 3 (right direction) queue length as a function of the time.

Total Delay is equal to 4698 seconds, while the Total Flow is 279 equivalent vehicles per 30 minutes. Thus the Average Delay for lane 3 is 16,84 seconds per vehicle.

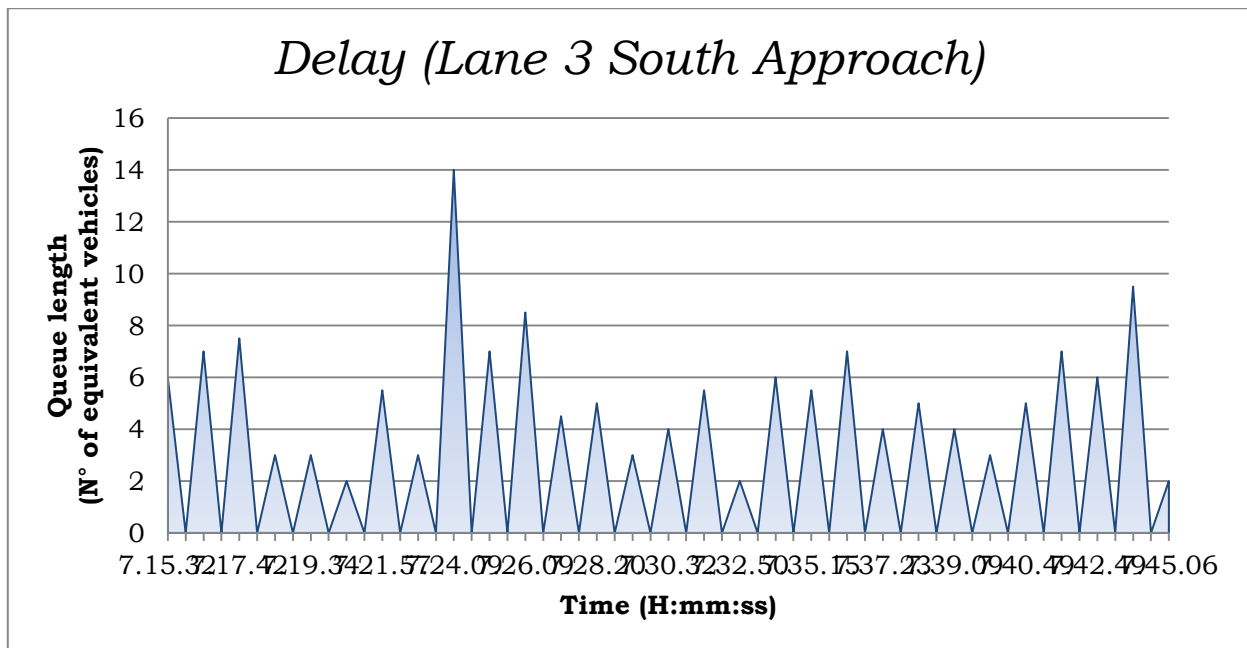


Fig. 3.128

Lane 3, for the right turn, appears to be the worst lane considering the Average Delay per vehicle, while Lane 2 is the best lane, as expected, due to the drivers behavior.

Although lane 3 delay is the highest in South Approach, it's interesting to notice that lane 3 has a relevant part of geometric delay out of total delay, due to the right turning. Indeed the effects of physical characteristic of the intersection cause a higher deceleration from the approach cruise to an approach negotiation speed, than the deceleration for a straight direction.

III. 3. 4. Bus Delay on South Approach

In this section the Average Delay for buses on South Approach will be calculated, and in the next chapters this parameter will be used as a value to compare with modeling outputs from Sidra Intersection 5.1 (and LinSig 3.1).

This element will be determined in the time span used previously to obtain Total and Average Delay for any South Approach lane. In that considered period (from 7:15 a.m. to 7:45 a.m.) 33 buses have passed the intersection (from South to North) and the crossing time for all the buses, from Section I to Section II, was noted down.

In screenshot 3.17 and 3.18 these two sections are shown in the instant when the same green city bus reaches them with the front.



Fig. 3.129

“Section I” was fixed just under the road arch sign, exactly 63,5 meters before the stop line. This cross-section was chosen considering it as a good point to set off the chronometer.

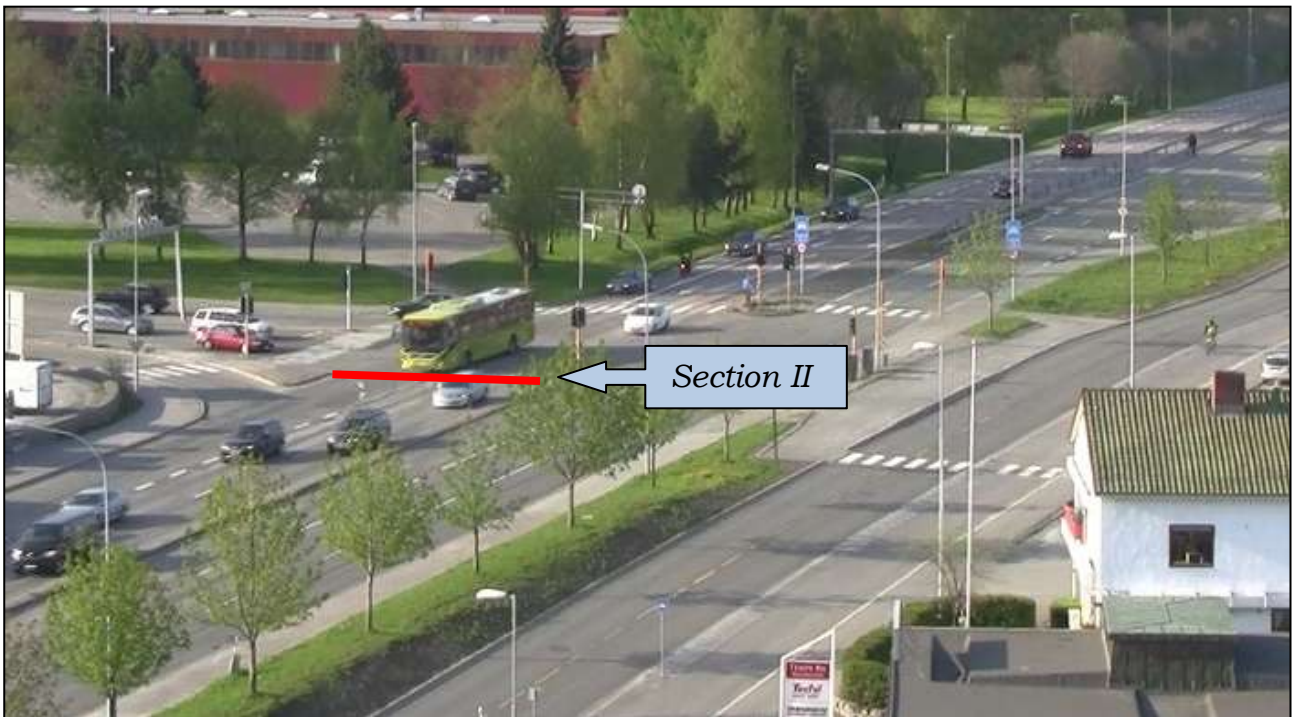


Fig. 3.130

“Section II” was fixed just after the East Approach extension towards the middle of the intersection, 40 meters downstream the South Approach stop line. The chronometer was stopped when the bus front had passed Section II.

Once obtained the crossing time expressed in seconds, the delay could be calculated for all buses in the time span.

Delay to a vehicle is the difference between interrupted and uninterrupted travel times through the intersection as seen in Figure 3.19, which shows the delay experienced by a through vehicle stopping and starting at traffic signals (time-distance and speed-time diagrams representing the acceleration and deceleration maneuvers of the vehicle are shown).

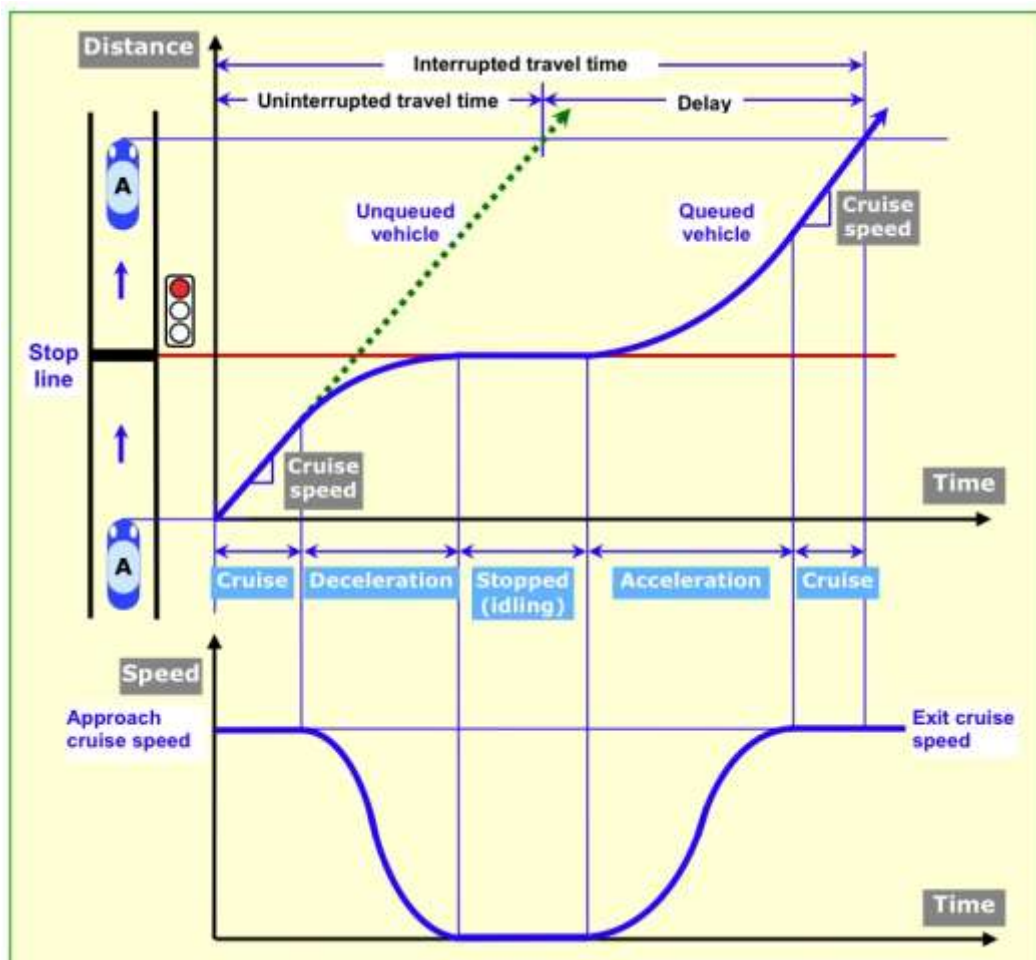


Fig. 3.19

The uninterrupted travel time for crossing Section I to Section II, in the case under analysis, is 8 seconds, value represented by the red line in the Bar Chart 3.20.

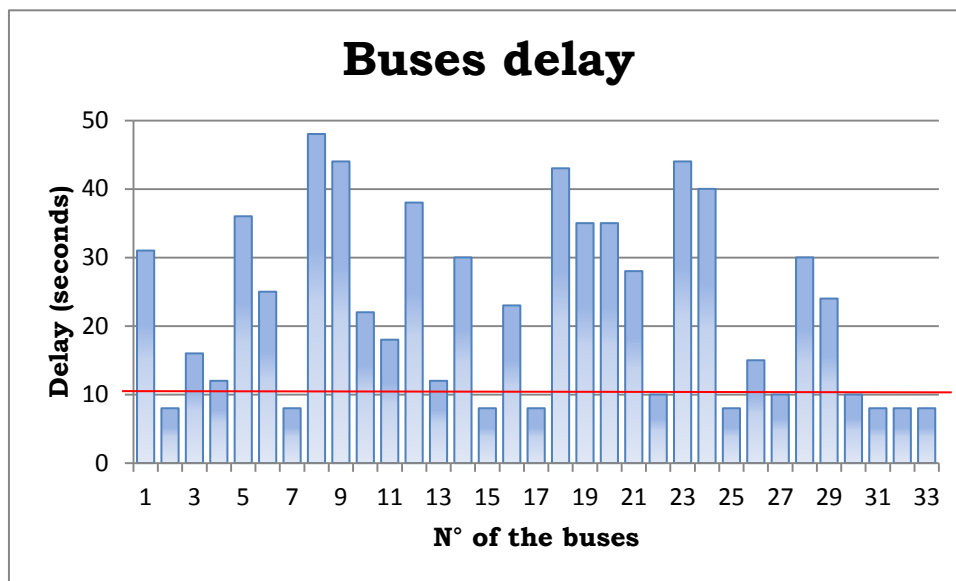


Fig. 3.20

As seen, 8 out 33 buses have passed the sections in 8 seconds without queuing, while the other 25 buses have lost velocity due to traffic flow and signal control. The following formula (3.21) was used to calculate Bus Average Delay:

(Formula 3.21)

where:

- T_i = interrupted travel time;
- T_u = uninterrupted travel time;
- N = number of observations (33 in the case under analysis).

Therefore:

As expected this value is between Lane 3 (16,84 sec) and Lane 2 (12,07 sec) delays. Indeed, as written before, bus drivers sometimes tend to choose during

the morning peak lane 3 instead of lane 2, to avoid excessive queuing and to be closer to the bus-stop bay.

However this type of behavior, that seems to be a reasonable choice, analyzing the results, causes an increase of delay for the buses. Probably this drivers' wrong evaluation is caused by the underestimation of the geometric delay associated with the right turns in Lane 3.

CHAPTER IV

SIDRA INTERSECTION 5.1 MODELING

In this chapter the procedure used in Sidra 5.1 to model the intersection analyzed in field observation, will be described, so all the inputs will be shown and the calibration explained. The modeling details will be often traced out through Sidra screenshots, figures and tables.

The intersection will be modeled with reference to two different scenarios: “Trondheim 1” without the bus priority lane and “Trondheim 2” with it.

Once shown the inputs, Sidra outputs will be used to draw deductions through comparisons and analysis:

- “Trondheim 1” and field observation will be compared mainly in terms of delay parameters of South Approach. In addition outputs regarding the cycle time will be evaluated;
- “Trondheim 2” and field observation will be compared using bus delays;
- “Trondheim 1” and “Trondheim 2” will be compared using Output Comparison (Sidra Utility). Moreover a new parameter will be used to show the benefits induced by the implementation of the bus priority lane.

IV. 1. Inputs

In this section of the thesis all the inputs necessary to model the field observation intersection (see Ch. 3), will be listed and described.

It should be noted that in this chapter buses (ordinary city buses and intercity buses) will be considered as Sidra Heavy Vehicles, while the commercial heavy vehicles, like high (above 2 meters) 3-axis vehicles and so on, will be converted to Sidra Light Vehicles using the corresponding equivalence coefficient . Moreover all the motorcycles, low (below 2 meters) 2-axis vehicles, low 3-axis vehicles and high (above 2 meters) 2-axis vehicles, will be considered as Sidra Light Vehicles like in the previous chapters. This simplification is necessary because Sidra Intersection 5.1 cannot model three different categories of vehicles.

The intersection of Holtermans Veg. and Bratsbervegen (Trondheim, Norway) analyzed in Chapter 3, will be modeled following two different criteria:

- the first site, called “Trondheim 1”, will reproduce the intersection without the bus priority lane on the South Approach. The intersection will be considered as a normal 3-leg signalized junction;
- the second site, called “Trondheim 2”, will be modeled using the "oblique leg technique", explained later, in order to represent the bus priority lane on the South Approach. Moreover, all the bus traffic (Sidra Heavy Vehicles flow, as written before) on this approach, will be loaded just in the oblique leg.

IV. 1.1. “Trondheim 1” (no bus priority lane)

Figure 4.1 shows a screenshot of the first site layout, “Trondheim 1”. It is a 3-leg signalized intersection that represents faithfully the field observation junction.

To notice the 140 meters turn bay on the North Approach and the short continuous lane (22 m) for buses coming from the East Approach. Moreover, all the median widths separating the approach lanes from the adjacent exit lanes, measured at the stop line, have been specified, even if pedestrian flow was omitted from the analysis.

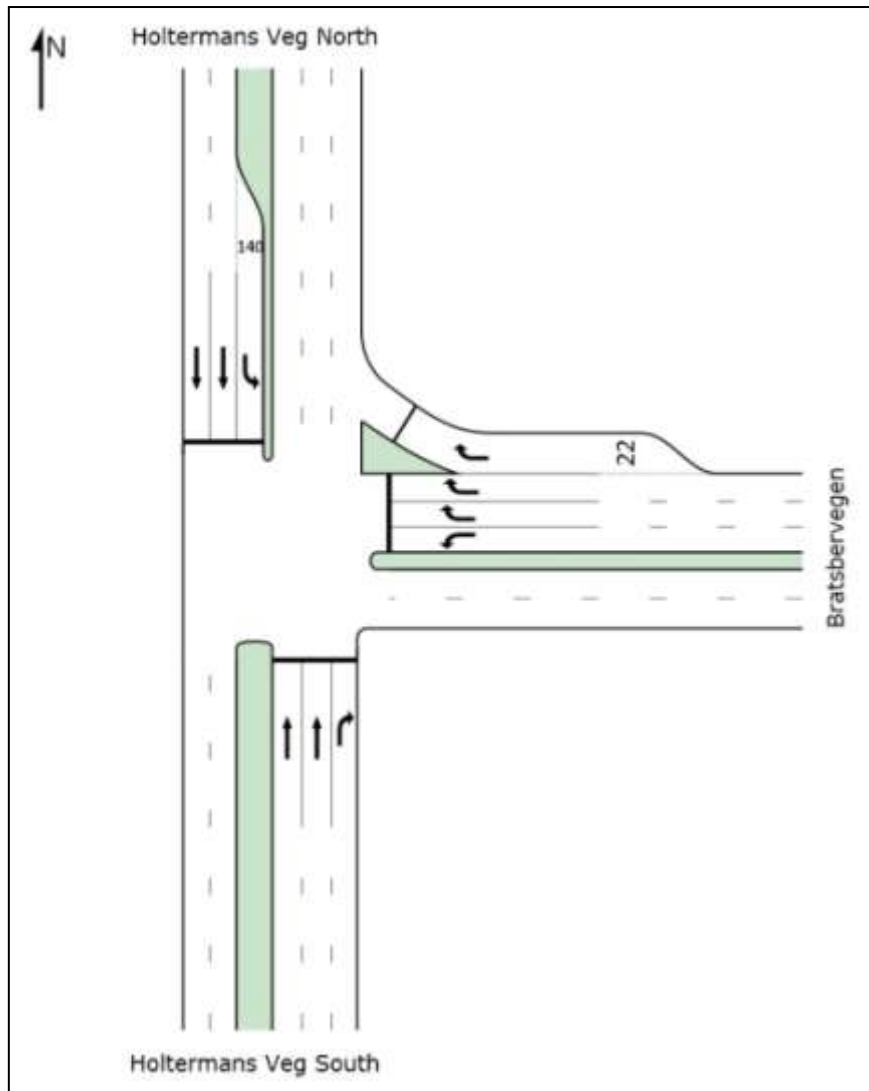


Fig. 4.31

In the Intersection dialog of SIDRA the following data were added:

- the *Geometry* as a 3-leg signalized junction;
- *signal analysis method* has been set as fixed-time;
- the *Peak Flow Period* has been set to 30 minutes while the *Unit Time for Volumes* to 60 minutes.

In the Geometry dialog the following details were specified:

- the continuous short lane length (22 m) for right turn on East Approach;
- the short lane bay length (140 m) for left turn on North Approach;
- all lane widths and movement definitions, for each approach;
- the median widths for each approach.

In addition in Lane Data (Geometry dialog tab), shown in Figure 4.2, the first adjustment has been performed: the utilization ratio of South Approach lane 2 (see Fig. 3.2) was reduced to 60% in order to take into account the drivers' behavior pattern observed during the field survey.

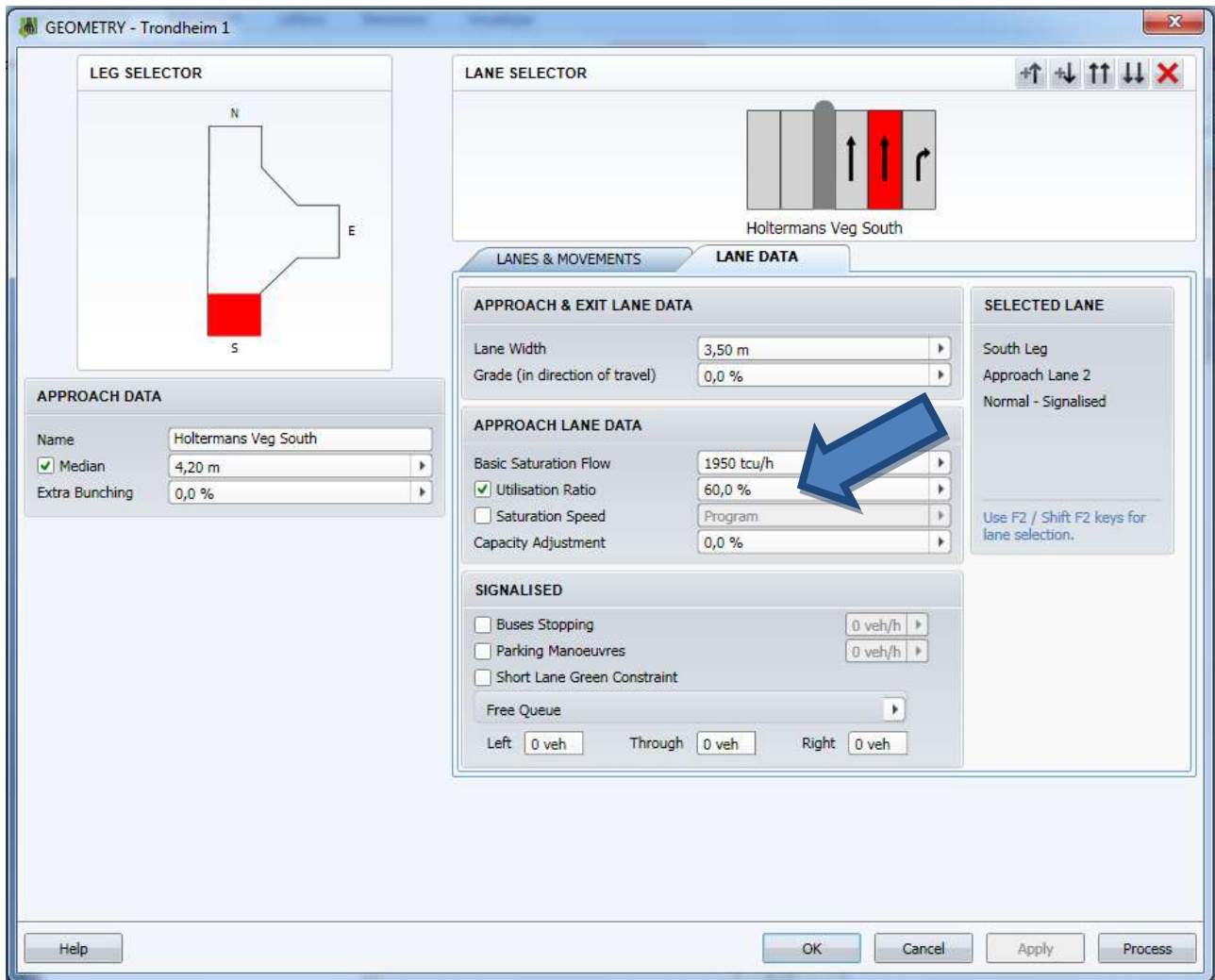


Fig. 4.32

In the Volumes Dialog the flow for each movement was added according to the measures observed during the 30 minutes peak from 7:15:10 to 7:45:47 a.m. (see Tables 3.4, 3.5 and 3.6).

South-North movement:

- Sidra Light Vehicles = $(n^{\circ} \text{ of light vehicles} + 2.5 \times n^{\circ} \text{ of heavy vehicles}) \times 2 =$
1014 vehicles per 60 minutes;
- Sidra Heavy Vehicles = $n^{\circ} \text{ of buses} \times 2 =$ **66** vehicles per 60 minutes.

South-East movement:

- Sidra Light Vehicles = $(n^{\circ} \text{ of light vehicles} + 2.5 \times n^{\circ} \text{ of heavy vehicles}) \times 2 =$
493 vehicles per 60 minutes;
- Sidra Heavy Vehicles = **0** (no buses for this movement).

East-South movement:

- Sidra Light Vehicles = **52** vehicles per 60 minutes;
- Sidra Heavy Vehicles = **0**.

East-North movement:

- Sidra Light Vehicles = **150** vehicles per 60 minutes;
- Sidra Heavy Vehicles = **12** vehicles per 60 minutes.

North-South movement:

- Sidra Light Vehicles = **478** vehicles per 60 minutes;
- Sidra Heavy Vehicles = **44** vehicles per 60 minutes.

North-East movement:

- Sidra Light Vehicles = **197** vehicles per 60 minutes;
- Sidra Heavy Vehicles = **0**.

In the short formulas used to calculate the flows, the multiplying factor “2” is applied to get the right Sidra unit of measure (vehicles per 60 minutes).

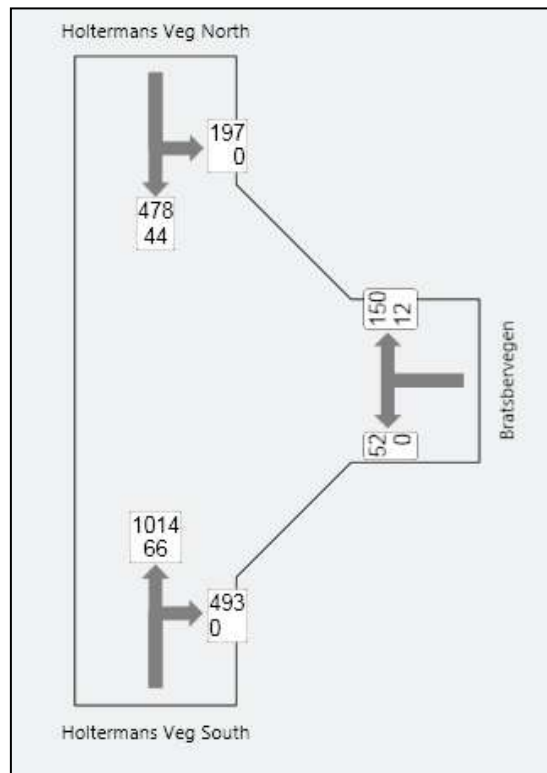


Fig. 4.33

Figure 4.3 shows the “Trondheim 1” volume summary.

In addition, in the same dialog the *Peak Flow Factor* was set to 100%, meaning that the peak demand volumes are known.

It is necessary to remark that in Sidra Intersection 5.1 it is not possible to specify volume flows for each lane, but only for each movement, as just seen. This software limitation will cause the requirement to handle the modeling with the "oblique leg technique", explained in “Trondheim 2”, in order to represent the bus priority lane.

In the Path dialog the approach and exit cruise speeds were modified, introducing into the model the speed restriction in Holtermans Veg. and Bratsbervegen.

South-North movement:

- Approach cruise speed: 60 km/h;
- Exit cruise speed: 50 km/h.

South-East movement:

- Approach cruise speed: 60 km/h;
- Exit cruise speed: 30 km/h.

East-South movement:

- Approach cruise speed: 30 km/h;
- Exit cruise speed: 60 km/h.

East-North movement:

- Approach cruise speed: 30 km/h;
- Exit cruise speed: 50 km/h.

North-South movement:

- Approach cruise speed: 50 km/h;
- Exit cruise speed: 60 km/h.

North-East movement:

- Approach cruise speed: 50 km/h;
- Exit cruise speed: 30 km/h.

These speed values will be very important in “Trondheim 2” modeling (see IV.1.2.), especially for the oblique leg.

In the Movement Data dialog Sidra Heavy Vehicles characteristics were modified since the default data correspond to normal heavy vehicles. Therefore the Length

was set to 12 meters (average length of the buses in Trondheim), while the Queue Space was set to 15 meters. The default values have been maintained for Light Vehicles characteristics.

Moreover, in the Signalized tab of the Movement Data dialog it would have been possible to add platooned arrival, but, as explained in Chapter 3, the field intersection was chosen to avoid the effects of signal coordination on vehicle arrival patterns. Then default data were not modified.

In the Priorities and Gap Acceptance dialogs, all inputs were set as default data, while in the Pedestrians dialog all the pedestrian movements were omitted, as already explained.

Figure 4.4 shows part of the Phase and Timing dialog, where the signal operations, like phases sequence and length of the cycle, were set according to the analysis in Chapter 3 (see Table 3.10 and Figure 3.11).

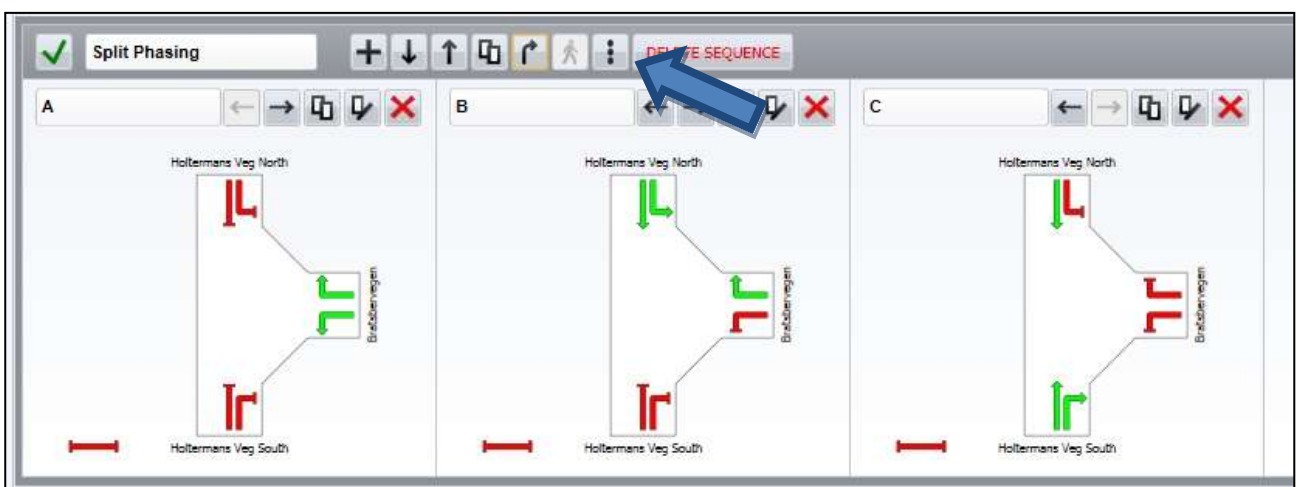


Fig. 4.34

In addition, in the Sequence Data tab, accessible thanks to the button indicated by the arrow in Fig. 4.4, the cycle time settings were specified in order to have the desired method of cycle time calculation: Optimum Cycle Time option was selected, with 70 seconds as the Upper value, 45 seconds as the Lower value, and 5 seconds as the Increment. It is interesting to remark that the program, under

the "Optimum Cycle Time" option, will calculate a cycle time that optimizes a performance measure (minimum delay in the case under analysis).

In the Model Settings dialog the following settings were added:

- 95% as percentile queue (see II.1.2.1, where the value meaning is explained);
- delay has been selected as value for performance measure (just written above);
- heavy vehicle mass (18.000 kg as Gross Vehicle Weight Rating) and heavy vehicle power (200 kW) according to the technical characteristics of the ordinary buses in Trondheim;
- other parameters were left as default values.

IV. 1.2. "Trondheim 2" (bus priority lane modeled)

"Trondheim 2" is the new site representing the field intersection modeled with a bus priority lane, and Figure 4.5 shows a layout of it through a screenshot.

This site is represented as a 4-leg signalized intersection, where a new leg is introduced and used as a bus priority lane in the South-East direction. As written before, all the buses approaching the intersection from South will be assigned to this new lane, allowing only the movement from South-East to North. The new leg, not existing in reality, will be indicated as "Oblique Leg".

Furthermore, the South Approach has been modified compared to the "Trondheim 1" site: now the approach has been modeled with only two lanes (straight direction and right turn) because the third lane is represented by the new oblique leg.

The North and East approaches remain unchanged compared to the "Trondheim 1" site.

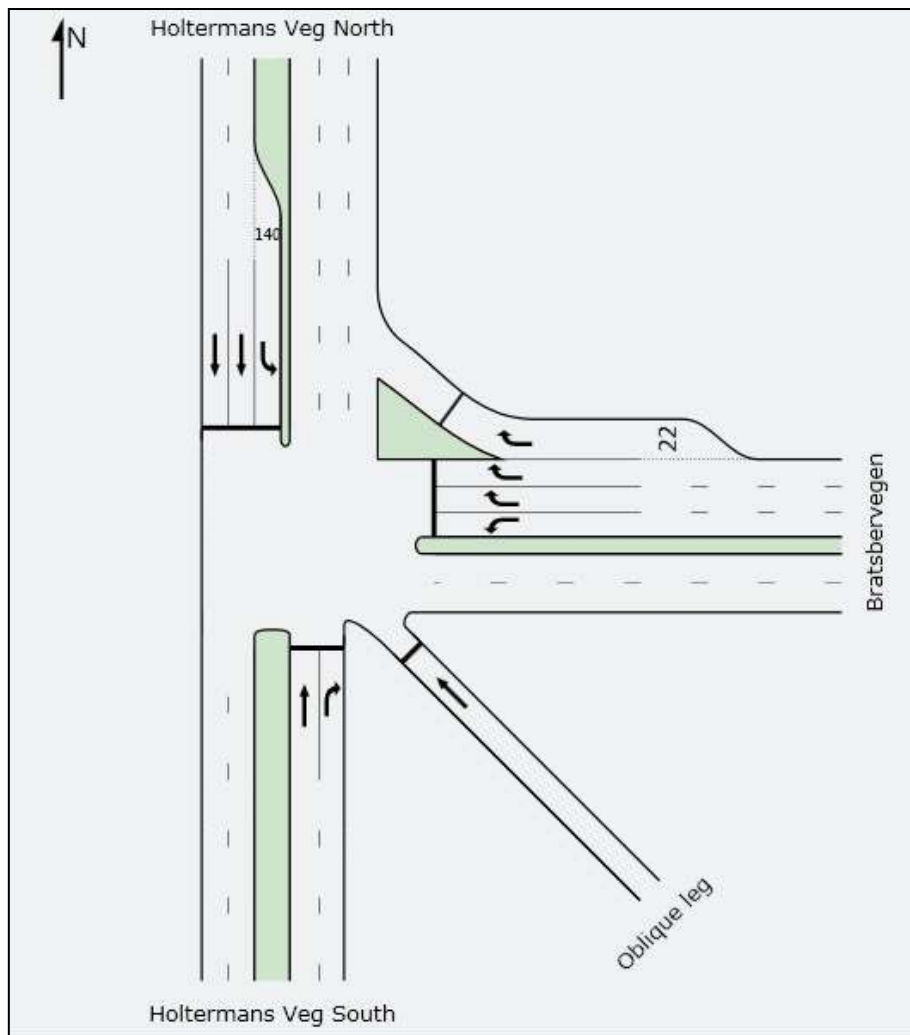


Fig. 4.35

In the following paragraphs all the inputs, modified compared to “Trondheim 1” site, will be listed and commented; the inputs not mentioned through the dialog tabs examples, will remain unchanged.

In the Intersection dialog the 4th leg has been added, so the intersection becomes a 4-leg signalized junction.

In the Geometry dialog the following parameters were set, for a reasonable calibration:

- geometric characteristics for the new oblique lane (3,30 meters width and South-East to North movement definition);
- Basic Saturation Flow of South Approach lane 1 (straight direction) has been modified to 2800 tcu/h. This value, derived after several attempts, represents the parameter that adjusts the degree of saturation for lane 1,

reaching the same value of degree of saturation in “Trondheim 1”. This change gives the possibility to compare “Trondheim 2” outputs and field observation results.

In the Volumes Dialog the flows were added according to the measures observed from 7:15:10 a.m. to 7:45:47 a.m., as for “Trondheim 1”.

South-North movement:

- Sidra Light Vehicles = (n° of light vehicles + 2.5 • n° of heavy vehicles) • 2 = **1014** vehicles per 60 minutes;
- Sidra Heavy Vehicles = n° of buses • 2 = **0** (no buses, all the flow in diagonal leg).

South-East movement:

- Sidra Light Vehicles = (n° of light vehicles + 2.5 • n° of heavy vehicles) • 2 = **493** vehicles per 60 minutes;
- Sidra Heavy Vehicles = **0**.

South/East-North movement:

- Sidra Light Vehicles = **0** vehicles per 60 minutes;
- Sidra Heavy Vehicles = **66**.

All the other movements remain unchanged.

In addition in the Volume Factors tab (Volumes dialog), the vehicle occupancy for the bus priority lane was set. The value was chosen according to the type of passenger flow during the morning peak: from 6:30 to 8:30 a.m. the flow is characterized by students and workers, and the buses occupancy degree is quite high. An average value was assumed around 40 pers/veh, according also to a value used in some examples during the advanced Sidra Intersection workshop in Melbourne (November 2011).

It should be noted that Sidra Intersection doesn't allow the user to set vehicle occupancy per single type of vehicle, but just for movement.

Figure 4.6 is a screenshot of the Volume Factors tab and the blue arrow points to the vehicle occupancy parameter.

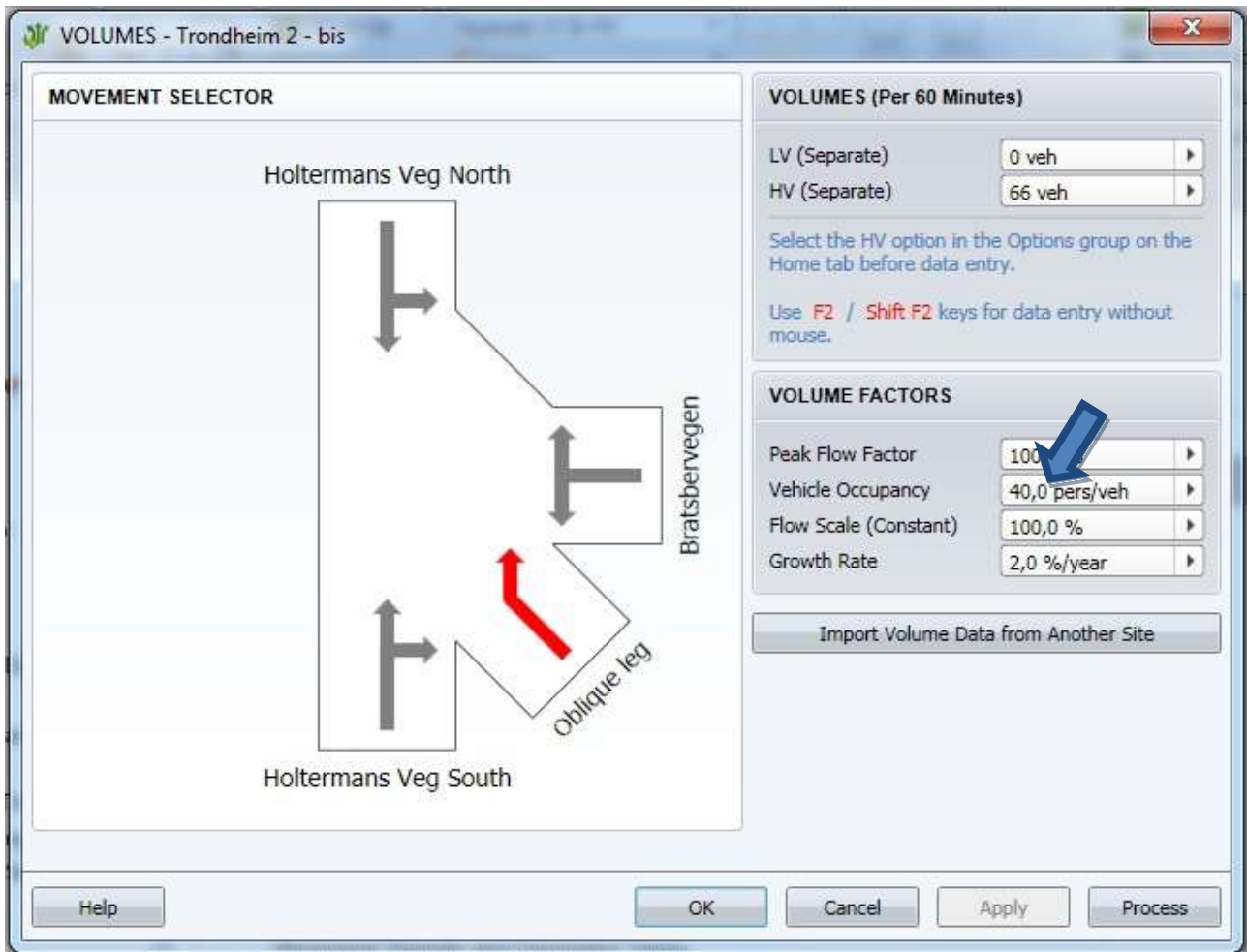


Fig. 4.36

In the Path dialog only the South/East Approach parameters have been modified, while all the other movement data remain unchanged:

- Approach Cruise Speed is 60 km/h, and Exit Cruise Speed is 50 km/h (the cruise speeds both correspond to South Approach cruise speed);
- Negotiation Speed has been added to convey to the software that the priority lane belongs to South Approach with a straight direction, and to reduce the geometric delay to the value of South Approach lane 1. Blue arrow in Figure 4.7 shows the new parameter value (50 km/h).

This calibration was necessary to obtain understandable outputs (using the negotiation speed default value for the South/East Approach would cause the control delay to be double than after the calibration).

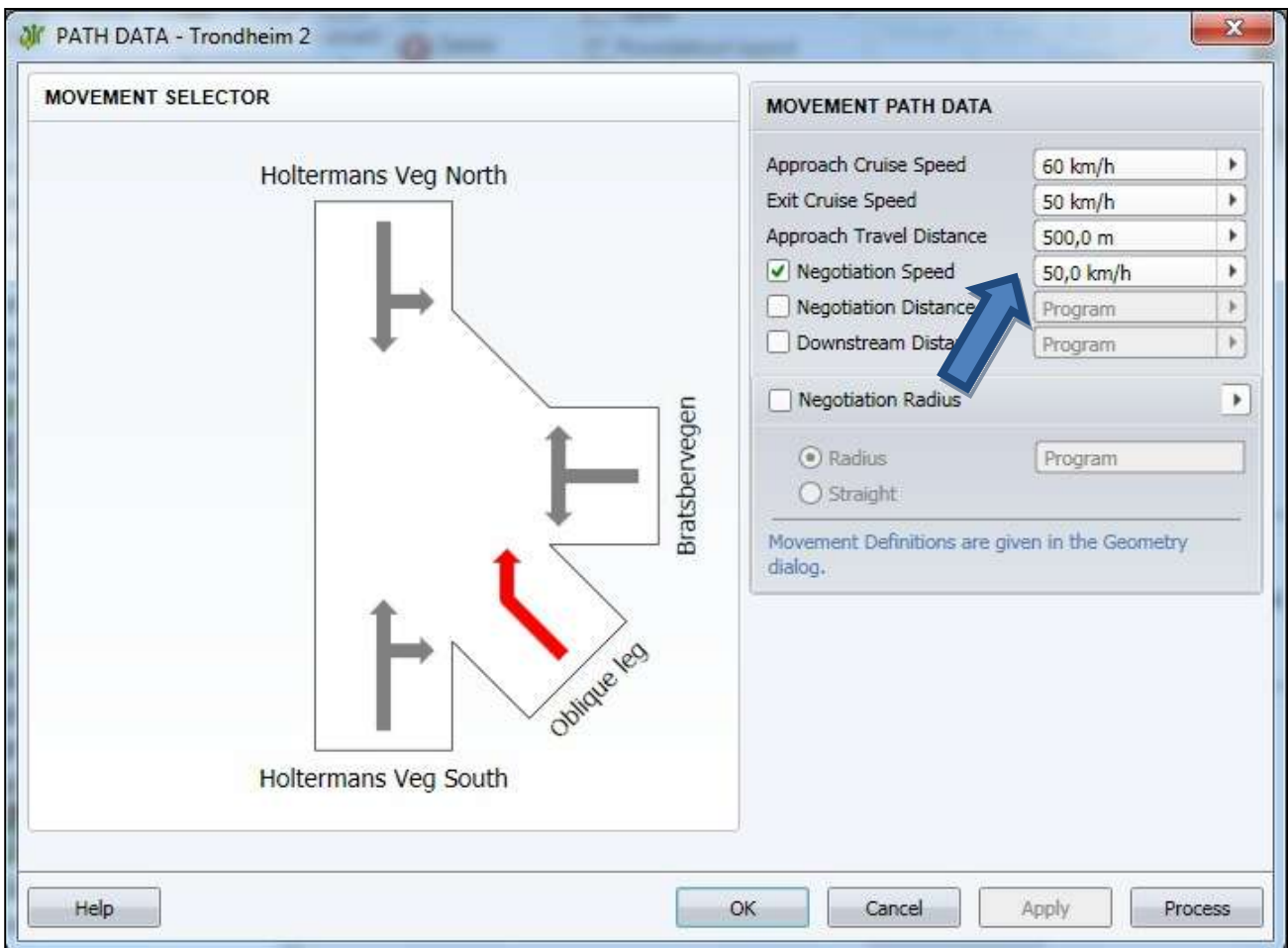


Fig. 4.37

The Priorities dialog, as written in Ch. 1, establishes the Opposing movements for each selected movement. In the case under analysis it is necessary to convey to the software that the South-East movement has no Opposed movement in the Oblique leg. Then once selected the South-East movement (as shown in Figure 4.8 by the circlets), the green arrow in South/East Approach (default selection) had been deleted.

It should be remembered that if opposing movements are specified for the selected movement, the program will identify and treat it as an Opposed movement. This is the case shown in Figure 4.8, where the North-East movement is an Opposed movement for South-North, South-East and South/East-North movements (green arrows).

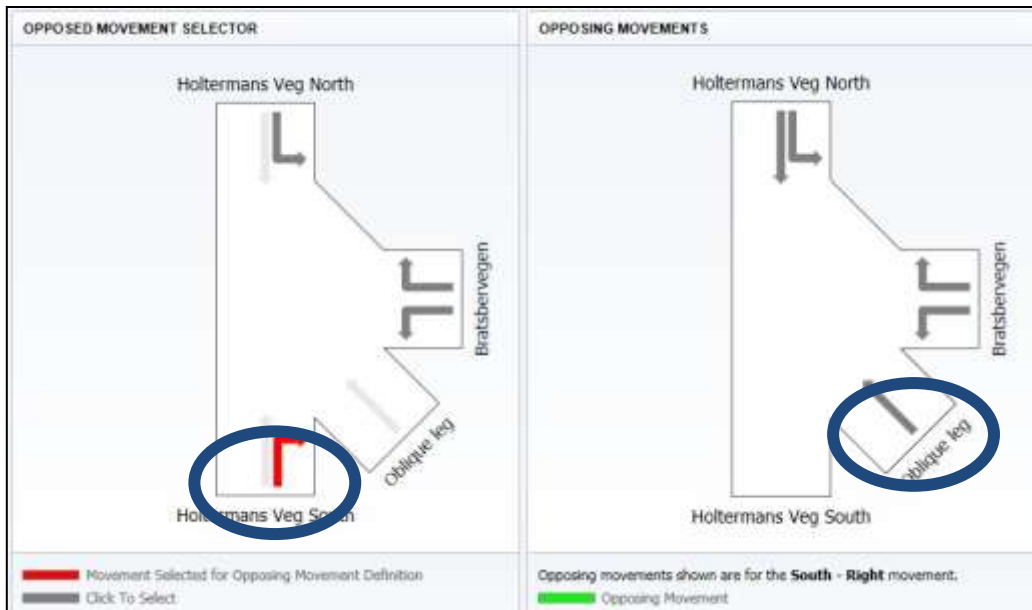


Fig. 4.38

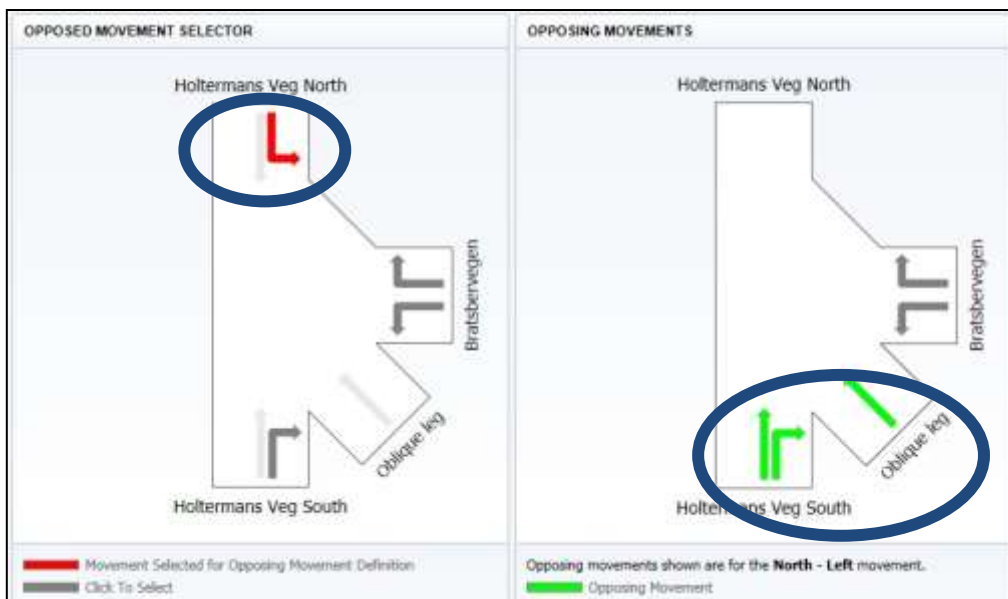


Fig. 4.39

In the Phasing and Timing dialog, phase C has been edited to add the South/East Approach. Once defined the signal sequence, Sidra Intersection can understand that green time for South/East Approach works simultaneously with the green time for South Approach, as it happens in reality.

The blue circlet in Figure 4.10 shows the green arrow corresponding to South/East-North movement in phase C.

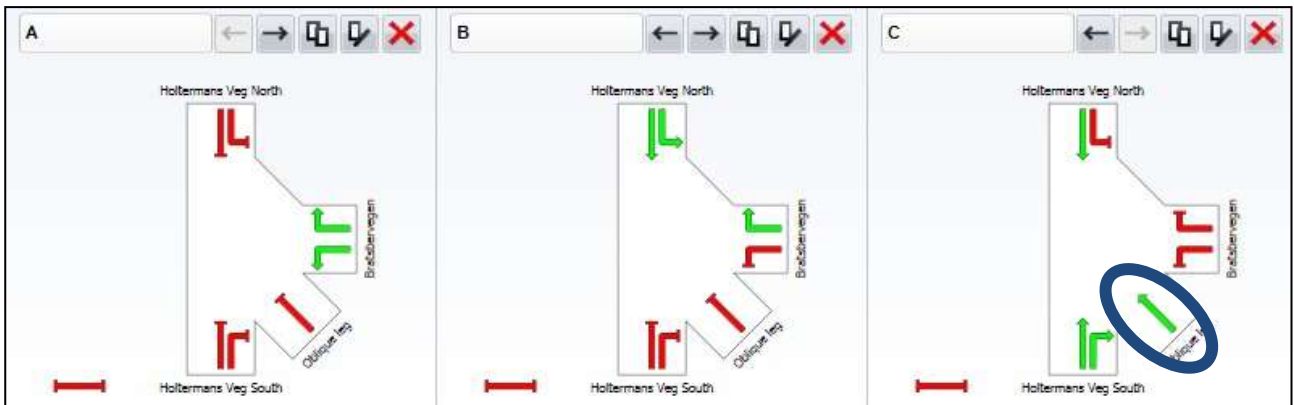


Fig. 4.40

IV. 2. Outputs analysis and comparison

In this section of the thesis the outputs obtained for both the sites modeled with Sidra Intersection will be analyzed and compared to the field observation results. In the first paragraph, the delay parameters for “Trondheim 1” will be compared to delay values calculated from field observations; moreover a connection between the optimum cycle time calculated by Sidra and the real length of the cycle will be matched.

In the second paragraph some parameters used for “Trondheim 2” calibration will be highlighted; further the outputs regarding the bus priority lane (Oblique leg in the modeling) will be compared to the field observations.

In the third and last paragraph the sites modeled in Sidra Intersection will be compared to each other, using Output Comparison utility; in addition some conclusions will be drawn considering a new Sidra output parameter, that conveys delays expressed as seconds per person.

IV. 2. 1. “Trondheim 1” and Field Observations

Table 4.11 shows a recap for the main output parameters concerning the individual lanes that belongs to “Trondheim 1” site. Moreover the table reports the parameters that have been aggregated for each approach, and at the end some information about the whole intersection.

Lane Summary – “Trondheim 1” Morning Peak (Table 4.41)

Lane Use and Performance																
	Demand Flows				HV	Cap.	Deg. Satn	Lane Util.	Average Delay	Level of Service	95% Back of Queue		Lane Length	SL Type	Cap. Adj.	Prob. Block.
	L	T	R	Total							Vehicles	Distance				
	veh/h	veh/h	veh/h	veh/h	% veh/h	v/c	%	sec			veh	m	m	%	%	
South: Holtermans Veg South																
Lane 1	0	675	0	675	6,1	948	0,712	100	15,9	LOS B	15,0	135,1	500	–	0,0	0,0
Lane 2	0	405	0	405	6,1	948	0,427	60 ⁷	13,2	LOS B	8,8	66,1	500	–	0,0	0,0
Lane 3	0	0	493	493	0,0	914	0,539	100	18,7	LOS B	11,6	81,2	500	–	0,0	0,0
Approach	0	1080	493	1573	4,2		0,712		16,1	LOS B	15,0	135,1				
East: Bratsbervegen																
Lane 1	52	0	0	52	0,0	157	0,332	100	38,5	LOS D	1,8	12,6	500	–	0,0	0,0
Lane 2	0	0	69	69	7,4	570	0,121	100	20,7	LOS C	1,7	12,7	500	–	0,0	0,0
Lane 3	0	0	70	70	7,4	580	0,121	100	20,7	LOS C	1,7	12,9	500	–	0,0	0,0
Lane 4	0	0	23	23	7,4	186 ¹	0,121	100	19,9	LOS B	0,5	4,0	22	Turn Bay	0,0	0,0
Approach	52	0	162	214	5,6		0,332		24,9	LOS C	1,8	12,9				
North: Holtermans Veg North																
Lane 1	197	0	0	197	0,0	290	0,680	100	37,2	LOS D	6,9	48,0	140	Turn Bay	0,0	0,0
Lane 2	0	261	0	261	8,4	1363	0,192	100	2,9	LOS A	2,6	20,3	500	–	0,0	0,0
Lane 3	0	261	0	261	8,4	1363	0,192	100	2,9	LOS A	2,6	20,3	500	–	0,0	0,0
Approach	197	522	0	719	6,1		0,680		12,3	LOS B	6,9	48,0				
Intersection				2506	4,9		0,712		15,8	LOS B	15,0	135,1				

The highlighted parameters, as in the previous chapters, will be used for comparison and analysis.

Lane 1 South Approach:

- **15,9** seconds (with **0,712** as degree of saturation) is the average delay calculated by Sidra and **15,54** seconds the value from field observation. The percentage difference between the delays is 2,26%;
- Back of Queue parameter (95-th percentile) is **15** vehicles and it is similar to the worst value of queue length registered during the field observation, **13** vehicles queued. To remember that the 95th percentile queue length is the value below which 95 per cent of all observed cycle queue lengths fall, as in the case under analysis.

Lane 2 South Approach:

- **13,2** seconds (with **0,427** as degree of saturation) is the average delay calculated by Sidra and **12,07** seconds the value from field observation. The percentage difference between the delays is 8,66%;
- **8,8** vehicles is the output parameter of Sidra for Back of Queue, and it is close to the worst value registered during the field observations (**8** vehicles queued during the 18th cycle analyzed).

Lane 3 South Approach:

- as for the previous lanes, the average delay for lane 3 is also a bit bigger than the field observation output; **18,7** seconds is parameter for Sidra, and

16,84 seconds results from the field observations, while the percentage difference is 9,95%;

- **11,6** vehicles is Back of Queue Sidra value and it doesn't include the worst length of queue for field observation (**14** vehicles). This length, probably caused by an exceptional event, belongs to the 5 per cent of all modeled queue lengths that exceed the Sidra value. Moreover all the other values registered during the field observation (see Figure 3.16) remain below 11,6 vehicles.

The Back of Queue expressed as a distance for North Approach lane 1 (short lane for left turning) is 48 meters. This value is significantly lower than the length of the short bay (140 m), meaning that the queue never reaches the adjacent lane. This circumstance calculated by Sidra was confirmed by the field observations; however Trondheim's drivers report that during bad weather days, especially in winter for the evening peak, the queue in the short bay can reach the adjacent lane.

Figure 4.12 is the recap table obtained from Detailed Output of Sidra and it provides all the information about phase and cycle time. The purpose is to compare the phase time calculated to obtain an optimum cycle and a typical cycle and phase time from field observations.

Intersection ID: 1								
Fixed-Time Signals, Cycle Time = 70 sec (Optimum Cycle Time)								
Phase	Change Time	Starting Intgrn	Green Start	Displayed Green	Green End	Terminating Intgrn	Phase Time	Phase Split
A	0	6	6	6	12	6	12	17%
B	12	6	18	11	29	6	17	24%
C	29	6	35	35	70	6	41	59%
Current Phase Sequence: Split Phasing								
Input phase sequence: A B C								
Output phase sequence: A B C								

Fig. 4.12

The cycle chosen from the field observations is the second analyzed in Table 3.10, and it represents a typical cycle during the morning peak. Indeed these phase

times, with minimal changes, are frequent during the analyzed period, from 7:15 to 8:00 a.m. (45 cycles).

Table 4.13, that highlights the comparison between Sidra and field outputs, shows how the values for green time and phase time are really similar.

This remark allows to consider the optimum cycle time calculated by Sidra to minimize the delay, as a good approximation of the real cycle length.

Table 4.13 – Comparison between Sidra Output and Field Observations

	Phase A		Phase B		Phase C	
	Sidra	Field	Sidra	Field	Sidra	Field
Green+Yellow Time	10	10	15	15	39	35
All Red Time	2	3	2	3	2	4
Phase Time	12	13	17	18	41	39

IV. 2. 2. “Trondheim 2” and Field Observations

Table 4.14, that shows the lane summary for “Trondheim 2” site, represents part of Sidra outputs.

Degree of Saturation and Average Delay for South Approach lane 1 have been highlighted in order to show the output parameters used to calibrate the site. Indeed, as explained in the previous paragraphs (see IV.1.2.), the basic saturation flow has been changed (from 1950 tcu/h to 2800 tcu/h) with the purpose of reaching comparable values of degree of saturation and average delay for both the sites. The calibration works since 0,717 and 15,8 seconds are values similar to those of “Trondheim 2” (0,712 and 15,9 seconds).

South/East Approach information have been highlighted as well, because they represent the new leg outputs of the site (i.e. bus priority lane).

As expected the Degree of Saturation and the Average Delay are low values, meaning that the lane works well in order to favor the public transport: 11,6 seconds of average delay is the lowest value in the intersection if straight direction for North Approach is not considered (delay for this movement is almost zero). Values representing Back of Queue, expressed as usual in vehicles and distance, are low as well (1,2 veh and 18,1 meters).

Lane Summary – “Trondheim 2” Morning Peak (Table 4.14)

Lane Use and Performance																
	Demand Flows				HV	Cap.	Deg. Satn	Lane Util.	Average Delay	Level of Service	95% Back of Queue		Lane Length	SL Type	Cap. Adj.	Prob. Block.
	L	T	R	Total							Vehicles	Distance				
	veh/h	veh/h	veh/h	veh/h	% veh/h	v/c	%	sec			veh	m	m		%	%
South: Holtermans Veg South																
Lane 1	0	1014	0	1014	0,0	1516	0,717	100	15,8	LOS B	25,8	180,4	500	–	0,0	0,0
Lane 2	0	0	493	493	0,0	914	0,539	100	19,3	LOS B	11,6	81,2	500	–	0,0	0,0
Approach	0	1014	493	1507	0,0		0,669		16,5	LOS B	25,8	180,4				
South East: Oblique leg																
Lane 1	0	66	0	66	100,0	591	0,112	100	11,6	LOS B	1,2	18,1	500	–	0,0	0,0
Approach	0	66	0	66	100,0		0,112		11,6	LOS B	1,2	18,1				
East: Bratsbervegen																
Lane 1	52	0	0	52	0,0	157	0,332	100	38,6	LOS D	1,8	12,6	500	–	0,0	0,0
Lane 2	0	0	69	69	7,4	570	0,121	100	20,7	LOS C	1,7	12,7	500	–	0,0	0,0
Lane 3	0	0	70	70	7,4	580	0,121	100	20,7	LOS C	1,7	12,9	500	–	0,0	0,0
Lane 4	0	0	23	23	7,4	186	0,121	100	19,9	LOS B	0,5	4,0	22 Turn Bay		0,0	0,0
Approach	52	0	162	214	5,6		0,332		25,0	LOS C	1,8	12,9				
North: Holtermans Veg North																
Lane 1	197	0	0	197	0,0	290	0,680	100	37,2	LOS D	6,9	48,0	140 Turn Bay		0,0	0,0
Lane 2	0	261	0	261	8,4	1363	0,192	100	2,9	LOS A	2,6	20,3	500	–	0,0	0,0
Lane 3	0	261	0	261	8,4	1363	0,192	100	2,9	LOS A	2,6	20,3	500	–	0,0	0,0
Approach	197	522	0	719	6,1		0,680		12,3	LOS B	6,9	48,0				
Intersection				2506	4,9		0,680		15,9	LOS B	25,8	180,4				

As explained in the previous chapter (see III.3.4), the buses delay has been calculated even from the field observations in order to understand if this data could have been comparable to the buses delay obtained by Sidra. The difference between these values (11,6 and 14,52 seconds) is 20,1%, and it represents what was expected: the numbers are comparable but not so close. This depends on how the real intersection works, indeed the buses don't have a real priority lane but just something similar. Nevertheless the modeling with Sidra Intersection works well, it's just a matter of knowing how to read and interpret the results.

IV. 2. 3. “Trondheim 1” and “Trondheim 2”

In this section of the thesis the sites modeled in Sidra Intersection will be compared analyzing different parameters, like Intersection Capacity, Average Control Delay, Performance Index, Fuel Consumption and Emission values, and last but not least the Delay expressed as seconds per person, useful indicator to understand the effectiveness of the priority lane.

For this comparison, it is necessary to remark that “Trondheim 2” has been modified before the analysis: Basic Saturation Flow of South Approach lane 1 (straight direction) has been set again to the default value, 1950 tcu/h.

This change has been made for the following reasons:

- 2800 tcu/h, set as basic saturation flow, is the right value in order to compare “Trondheim 2” and field observations, but it causes a decrease of the degree of saturation for South Approach and as a consequence for the whole intersection;
- over and above that, other parameters dependent on the degree of saturation and concerning the intersection (Intersection Capacity, Control Delay and so on) would have been incorrect;
- therefore the default value of Basic Saturation Flow (1950 tcu/h) allows a more accurate evaluation of the intersection performance.

Intersection Performance Comparison (vehicles only) - Hourly Values (Table 4.25)

Vehicle Performance Measure	Units	Site 1	Site 2	Difference Site2 - Site1	%Difference Diff / Site1
Demand Flows (Total)	veh/h	2506	2506	0	0,0
Percent Heavy Vehicles	%	4,9	4,9	0,0	0,0
Degree of Saturation		0,712	0,822	0,110	15,4
Practical Spare Capacity	%	26,3	9,4	-16,9	-64,2
Effective Intersection Capacity	veh/h	3518	3047	-470	-13,4
Control Delay (Total)	veh-h/h	10,97	12,82	1,85	16,8
Control Delay (Average)	sec	15,8	18,4	2,7	16,8
Control Delay (Worst Lane)	sec	38,5	57,0	18,5	48,2
Control Delay (Worst Movement)	sec	38,5	57,0	18,5	48,2
Geometric Delay (Total)	veh-h/h	1,58	1,66	0,08	5,3
Geometric Delay (Average)	sec	2,26	2,38	0,12	5,3
Stop-Line Delay (Total)	veh-h/h	9,39	11,16	1,76	18,8
Stop-Line Delay (Average)	sec	13,49	16,03	2,53	18,8
95% Back of Queue - Vehicles (Worst Lane)	veh	18,0	37,6	19,5	108,3
95% Back of Queue - Distance (Worst Lane)	m	135,1	263,0	128,0	94,7
Total Effective Stops	veh/h	1616	1633	17	1,0
Effective Stop Rate	per veh	0,65	0,65	0,01	1,0
Proportion Queued		0,69	0,65	-0,04	-5,7
Performance Index,1		81,8	95,6	13,9	17,0
Travel Distance (Total)	veh-km/h	1427,8	1443,9	16,1	1,1
Travel Distance (Average)	m	570	576	6	1,1
Travel Time (Total)	veh-h/h	38,5	40,8	2,3	6,0
Travel Time (Average)	sec	55,3	58,6	3,3	6,0
Travel Speed	km/h	37,1	35,4	-1,7	-4,6
Cost (Total)	\$/h	4760,90	5337,34	576,44	12,1
Fuel (Total)	L/h	168,6	167,8	-0,8	-0,5
Carbon Dioxide (Total)	kg/h	422,4	421,3	-1,1	-0,3
Hydrocarbons (Total)	kg/h	0,653	0,653	0,000	0,0
Carbon Monoxide (Total)	kg/h	27,30	25,66	-1,64	-6,0
NOx (Total)	kg/h	0,911	0,864	-0,047	-5,1

The highlighted outputs in Table 4.15, as written before, constitute the parameters thanks to which the comparison has been done and the following list explains why “Trondheim 2” could be considered worse in terms of performance than “Trondheim 1”:

- Effective Intersection Capacity for “Trondheim 1” (**3518** veh/h) is **13,4%** bigger than “Trondheim 2” value (**3047** veh/h);
- as a consequence the Practical Spare Capacity for site 1 is bigger as well (**26,3%** and **9,4%**);
- Average Control Delay is higher for “Trondheim 2”, indeed **18,4** sec is **16,8%** bigger than **15,8** sec (“Trondheim 1” value). Control delay was chosen as representative example, but all the delay parameters increase moving from site 1 to site 2;
- Back of Queue values for the worst lane, expressed in vehicles and distance, are both worse for site 2 (from **18,0** to **37,6** vehicles and from **135,1** to **263,0** meters);
- Total Cost shows an increase of **12,1%** from site 1 to site 2 (**4760,90** \$/h and **5337,34** \$/h);
- and the Performance Index, that represents a summary of several performance parameters, is bigger for “Trondheim 2” (**95,6** is **17%** bigger than **81,8**).

The only parameters that remain more or less constant in both sites, are values regarding fuel consumption and pollutant emissions:

- fuel consumption stays almost constant, around **168** L/h;
- emission values stay constant or even decrease for “Trondheim 2” (**-6%** for Total Carbon Monoxide and **-5,11%** for Total NO_x).

Analyzing these performance parameters, as written before, “Trondheim 1” seems to be better than “Trondheim 2”, however Sidra Intersection provides other elements to estimate the quality of the sites.

Table 4.16, built thanks to the Intersection Summary (one of the output tabs), shows delay parameters related to persons and some other parameters that appear in previous Table 4.15.

As shown by the highlighted parameters, Total and Average Control Delays of “Trondheim 2” are both lower than for “Trondheim 1”, meaning that individuals experience more delay in the site without the priority lane. The Average Control Delay for example is **15,8** sec per person for “Trondheim 1” and **14,2** sec per person for “Trondheim 2”, showing a decrease of 10,2%.

This type of reasoning gives to the decision maker a justified motive to insert a bus priority lane into a normal signalized junction. Moreover a bus lane can be added to an intersection in order to encourage modal shift from private to public transport.

Intersection performance measure comparison - (Table 4.16)

Intersection Performance Measure	"Trondheim 1"		"Trondheim 2"	
	Vehicles	Persons	Vehicles	Persons
Demand Flows (Total)	2506 veh/h	5568 pers/h	2506 veh/h	5568 pers/h
Percent Heavy Vehicles	4,9%		4,9%	
Degree of Saturation	0,712		0,822	
Practical Spare Capacity	26,3%		9,4%	
Effective Capacity	3518 veh/h		3047 veh/h	
Control Delay(Total)	10,97 veh-h/h	24,13 pers-h/h	12,82 veh-h/h	21,96 pers-h/h
Control Delay (Average)	15,8 sec	15,8 sec/pers	18,4 sec	14,2 sec/pers
Control Delay (Worst Lane)	38,5 sec		57,0 sec	
Control Delay (Worst Movement)	38,5 sec	38,5 sec	57,0 sec	57,0 sec
Geometric Delay (Average)	2,3 sec		2,4 sec	
Stop-Line Delay (Average)	13,5 sec		16,0 sec	
Level of Service (LOS)	LOS B		LOS B	

CHAPTER V

LINSIG 3.1 MODELING

In this chapter, the intersection modeling with LinSig (version 3.1) will be described. This modeling is based on the field observations described in Chapter 3, and can be considered as an alternative to the modeling with Sidra 5.1.

This additional software, that promises to model carefully bus priority lanes, has been used in order to achieve more significant comparisons and deductions.

In the first part, as done in Chapter IV, all the main inputs will be listed and described, highlighting the parameters that differ from the Sidra modeling. Also in LinSig, the modeling of the intersection will be performed through two different sites, following the same criteria used for Sidra.

After describing all the phases for the modeling of both sites, the outputs will be analyzed and used for the comparison. Unfortunately LinSig does not provide any utility software for the comparison, thus a table reporting the main indicators will be created in order to obtain clearer results.

V. 1. Inputs

In this section of the thesis the field observations (Ch. 3 data) will be modeled into a software package for the assessment and design of traffic signal junctions called LinSig 3.1 (JCT Consultancy Ltd.); moreover, as in the previous chapter, all the inputs will be listed and described.

This software is used by traffic engineers to construct a model of the junction or network which can then be used to assess different designs and methods of operation. The last version, LinSig 3.1, introduces new modeling improvements that will be really useful for the thesis purpose:

- lane by lane modeling, that allows the user to specify several details for each lane (in Sidra Intersection this was not always possible);
- improvement of bus modeling, and consequently improvement of bus priority lane modeling (main purpose of the thesis).

The field surveys will be modeled in LinSig 3.1 with two sites, following the same criteria of Sidra modeling in Ch. 4 (see IV.1.):

- “Trondheim I”, the first site, will be modeled without the bus priority lane;
- “Trondheim II”, the second site, will be modeled with the bus priority lane, but in this case it will not be necessary to use the “oblique leg” trick.

In addition, it should be reminded that, as in Chapter 4, buses (ordinary city buses and intercity buses) will be considered as LinSig Buses, while the commercial heavy vehicles, like high (above 2 meters) 3-axis vehicles and so on, will be converted to LinSig Light Vehicles using the corresponding equivalence coefficient (2,5). Moreover all the motorcycles, low (below 2 meters) 2-axis vehicles, low 3-axis vehicles and high (above 2 meters) 2-axis vehicles, will be considered as LinSig Light Vehicles.

V. 1. 1. “Trondheim I” (no bus priority lane)

Figure 5.1 is a screenshot of the “Trondheim I” junction. This type of layout shows some new elements that will be listed below:

- Each Arm represents a one-way section of road forming part of the Network. Each Arm contains a number of Lanes which are used to

- represent how traffic uses the Arm. Arms are not themselves involved in traffic model calculations but are used purely to group and organize Lanes;
- Lane Connectors join each Lane to Lanes on other Arms that can provide or receive traffic to or from the Lane. The Lane Connectors represent how road markings dictate the way traffic should flow between Lanes.
- The circlets in front of the lanes specify if it is a signal-controlled (yellow) or not (green) lane;
- Upon each Lane and Lane Connector the flows, crossing the element, are shown (different colors mean different layers, in this case “black” = LinSig Light Vehicles and “red” = Buses). LinSig allows to manage simultaneously different layers specifying if the layer models or not buses.

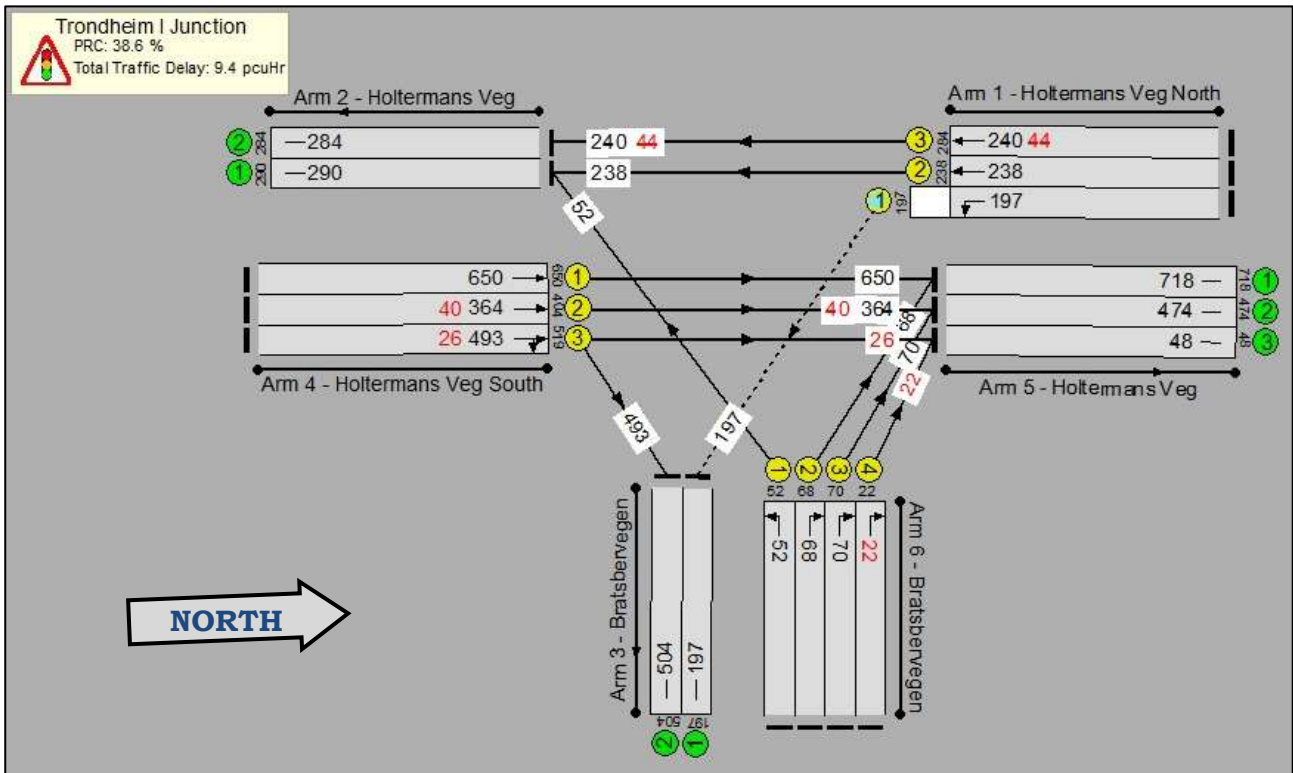


Fig. 5.42

In the Graphical tab within the Network Settings dialog, the drive side has been changed to right-hand side. Since LinSig is one of the most widely used traffic signal design software in the UK, left drive side is the default value.

In the Layout View, that displays the overall layout of the Network's Junctions, all the lanes, grouped into arms, and the lane connectors were added, reproducing the real intersection design (3-legs signalized intersection).

After all the junction elements were added, it was necessary to edit them. First of all in the Edit dialog the lanes characteristics were set:

- If the lane is signal-controlled, in the General tab the appropriate switch is to be selected; if the lane is not a signal-controlled lane or it is an exit lane, the default value can be maintained. Moreover, if the lane is signal-controlled;
- In Lane Details tab the lane length was specified, pointing up that Lane 1 of Arm 1 is a short turning lane (140 meters) while Lane 4 Arm 6 is a short continuous lane (22 meters);
- In the Saturation Flow Data tab the lanes widths were specified, and as a consequence the Geometric Lane Saturation Flow was set. Moreover LinSig 3.1 allows the user to specify the Turning Radius for each movement on the lane;
- In the Flows tab, the total incoming and outgoing flows on the selected lane were specified. Moreover, as mentioned above, LinSig allows the user to create different layers on the same lane, so that different categories of vehicles can be handled one by one (in the case under analysis two different layers were used, the black one for LinSig light vehicles and the red one for buses). This feature is really useful to model bus lanes.

It should be reminded that volumes are exactly the same used in Chapter 4;

- In the Movement tab once selected Lane 1 Arm 1, opposing movements (Arm 4, Lanes 1,2,3) were specified. This is necessary because North-East movement runs in the same phase as South-North movement (in Sidra Intersection this setting was not necessary since it was an automatic process).

In the Edit dialog for lane connector, the cruise speed (or the time) through the selected lane connector was specified, using the same data of Chapter 4; in addition the Platoon dispersion, adjustable at the bottom of the tab, was

maintained at its default value (35), meaning that the arrival patterns are not influenced by either signal control or other factors (isolated intersection).

Figure 5.2 is a screenshot of the Flows tab, in the Edit dialog for lane. The blue arrow points to the layers.

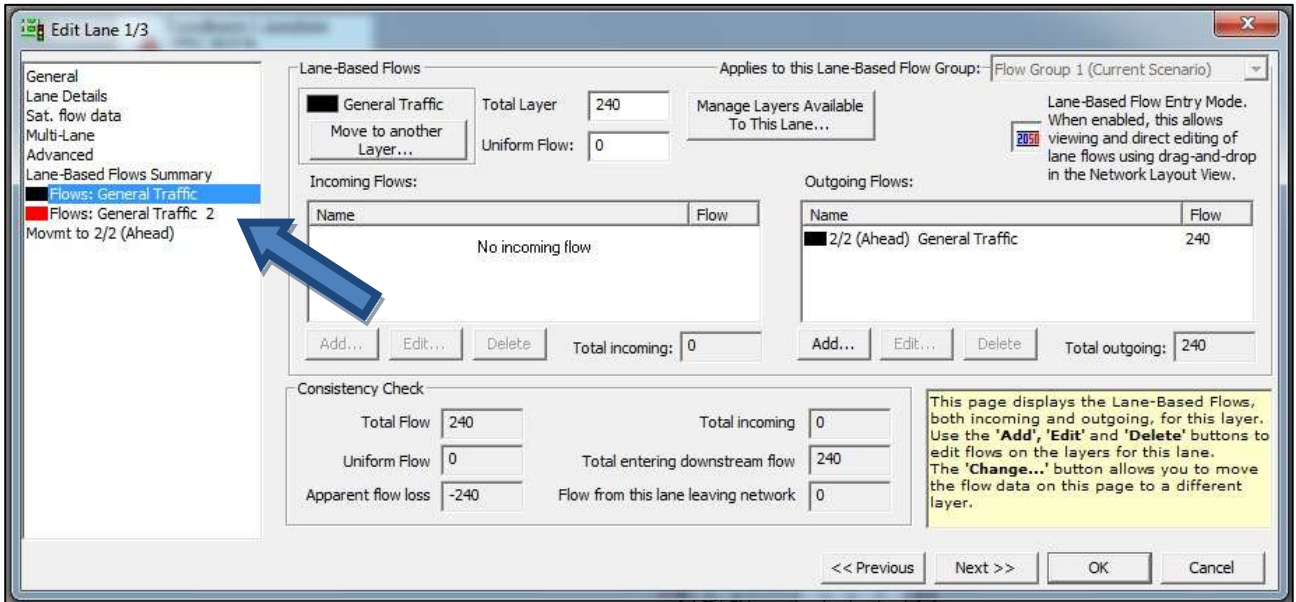


Fig. 5.43

In the Phases dialog, shown in Figure 5.3, all the phases were added in order to match them to the corresponding movement. This procedure is necessary to build the right design according to the field observations.

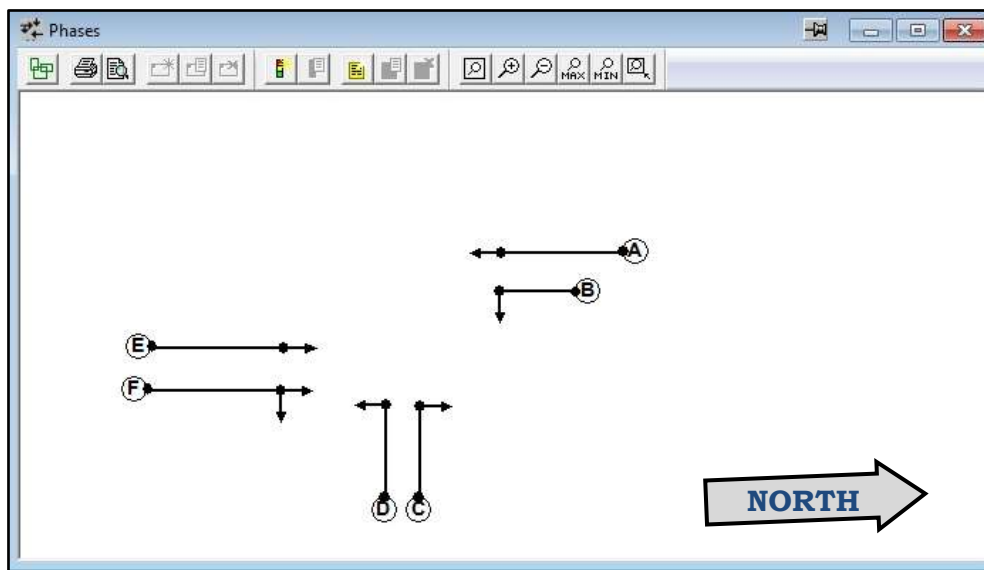


Fig. 5.44

The Intergreen view is used to enter and edit the Phase Intergreen matrix for each Controller, while the Stage Sequence View is used to create and edit stage sequences for each controller. It should be noted that LinSig indicates as “stage” what in the previous chapter Sidra Intersection indicated as “phase”.

As shown in Figure 5.4, the stages sequence (the same used in Sidra Intersection) reproduces what surveyed in the field observations.

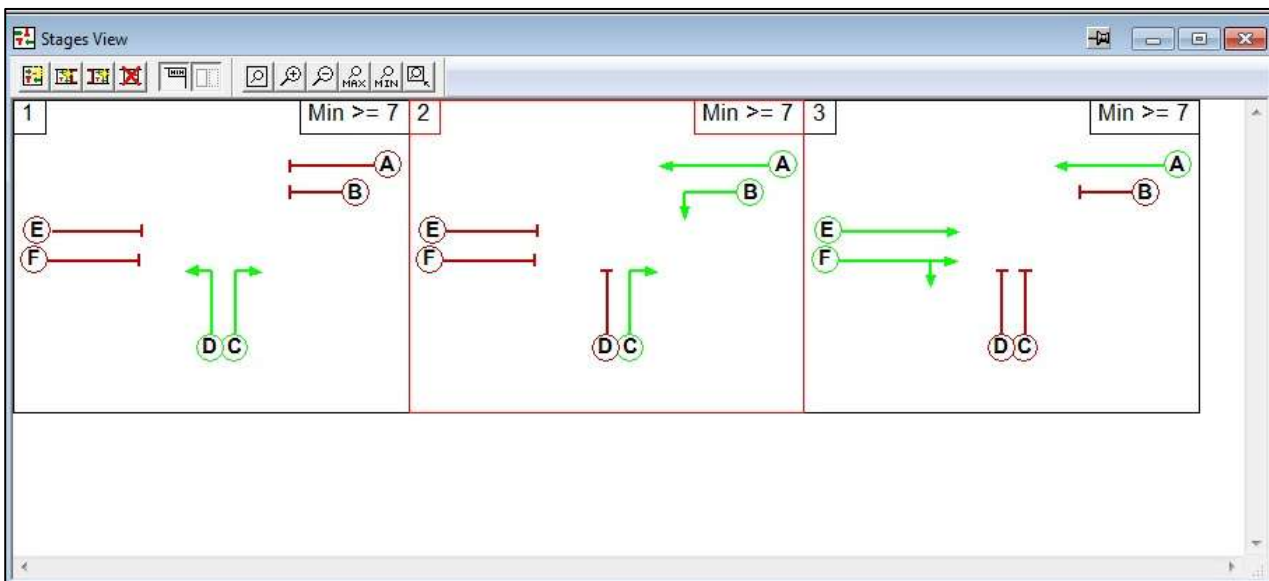


Fig. 5.45

In the Signal Timings view the stage and phase timings for the current scenario were adjusted in order to have the same phase and cycle time obtained in Sidra Intersection (see Figure 4.12).

Stage Change Points and Stage Lengths (what in Sidra Intersection is called Phase time) can all be changed graphically by dragging the blue stage change point cursors, highlighted by the blue arrow in Figure 5.5.

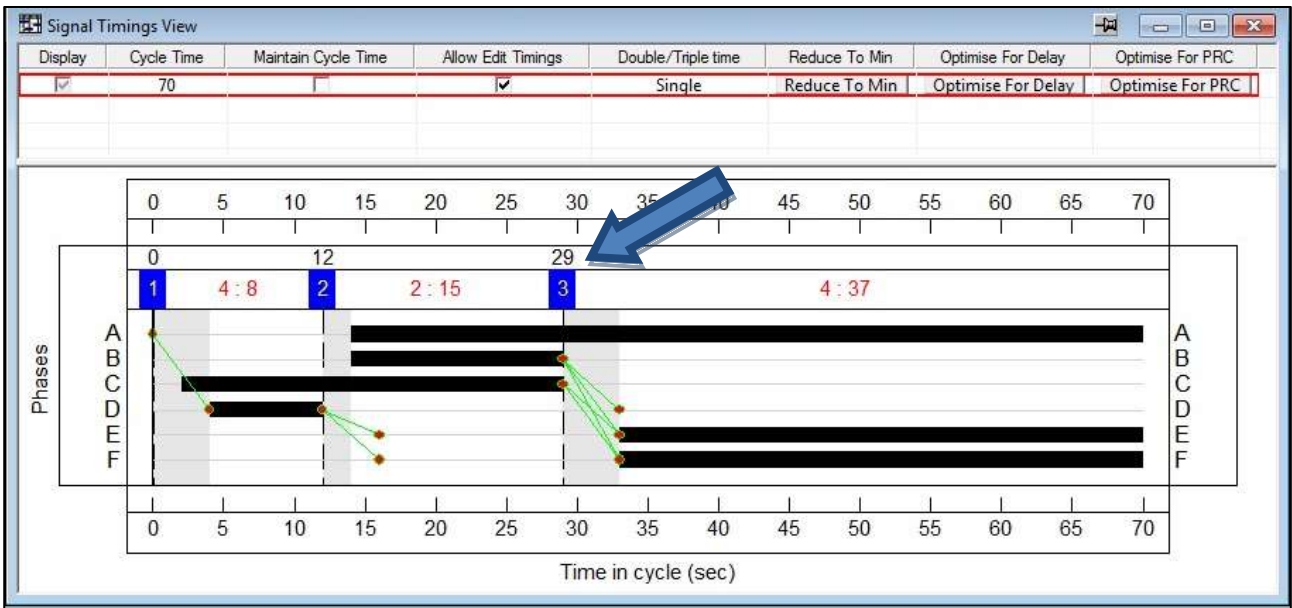


Fig. 5.46

V. 1. 2. "Trondheim II" (bus priority lane modeled)

Figure 5.6 shows a layout screenshot of the "Trondheim II" site. As highlighted by the blue arrow, this site has a bus priority lane in Lane 2 of Arm 4 (South Approach).

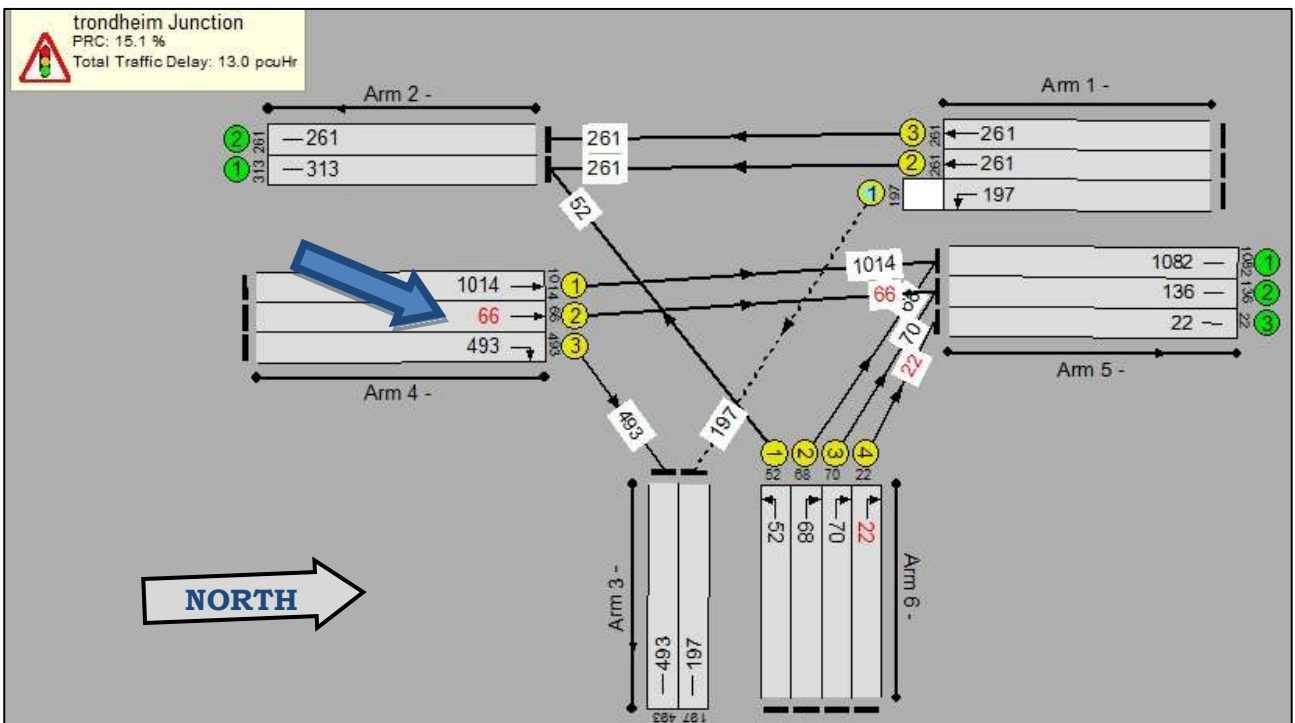


Fig. 5.47

In order to create this second site, “Trondheim I” has been cloned and the following elements were changed:

- As explained above this site is modeled with a priority lane for buses, therefore the volume on Arm 4 has been modified. In lane 1 the flow is **1014** LinSig Light Vehicles (straight direction to lane 1 arm 5), in lane 2 the flow is **66** buses (bus priority lane) and in lane 3 the flow is **493** LinSig Light Vehicles;
- As a follow-on from the point above, the volumes were changed both on the lane connectors coming from Arm 4 and on the relative exit lanes in Arms 3 and 5;
- As for “Trondheim 2” in Sidra modeling, the basic saturation flow for lane 1 in arm 4 was directly changed in order to adjust the degree of saturation for lane 1. The modified value is 2800 pcu/h (blue arrow in figure 5.7).

The rest of the inputs remain the same specified in “Trondheim I”.

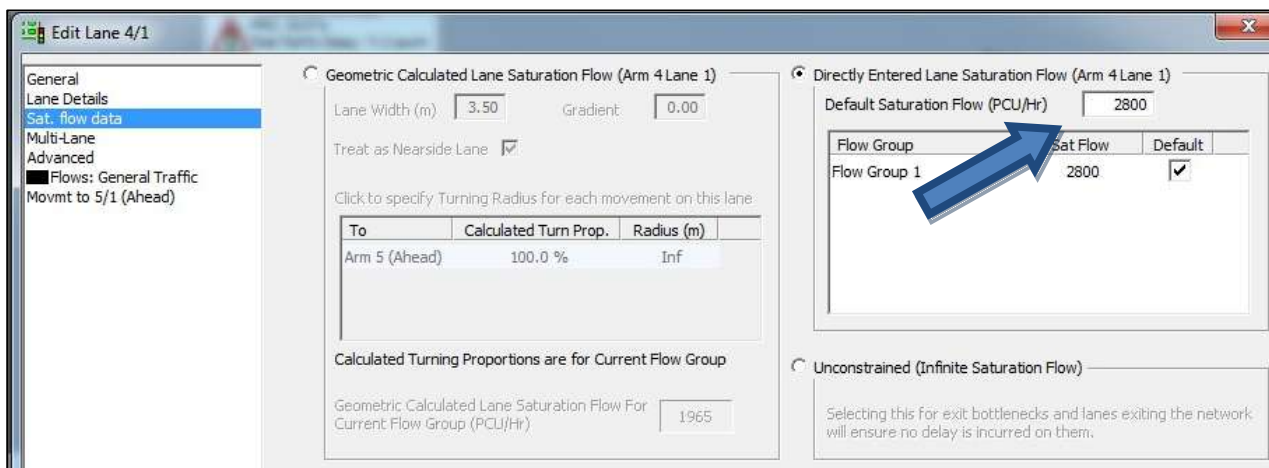


Fig. 5.7

V. 2. Output analysis and Comparison

Like in the previous chapter, the outputs obtained by LinSig modeling will be compared with the results of Sidra modeling and field surveys.

It should be noted before starting the analysis that frequently LinSig 3.1 provides output delay parameters expressed in pcu×h (Total Delay in Sidra). For this reason the following Formula 5.7 has been used to convert delay parameters into parameters expressed in seconds, in order to have understandable comparisons.

(Formula 5.7)

where:

- is an average delay parameter expressed in seconds;
- is a general delay parameter expressed in pcu×h (LinSig 3.1);
- is the number of equivalent vehicles that crosses the considered elements (a single lane or the entire intersection according to the case under analysis) in one hour.

In this chapter the delay outputs produced by LinSig will be indicated with both units of measurement.

V. 2. 1. “Trondheim I” vs. “Trondheim 1” and Field Observations

Before starting the analysis of the LinSig outputs, it is necessary to explain a new parameter that will be used in the comparison: Back of Uniform Queue at the end of Red. This value is the extent of the uniform queue on a lane at the end of the lane’s controlling phase’s red period. This value will be compared to the mean back of the queue observed during the field surveys (average of the peaks in Graphics 3.14, 3.15, and 3.16).

Lane 1 Arm 4 (lane 1 on South Approach in Sidra):

- **15,2** seconds (2,8 pcu×h) is the average delay calculated by LinSig while **15,54** seconds the value from field observation (**15,9** seconds by Sidra). The percentage difference between LinSig and field observations is -2,24%;
- **0,609** is the degree of saturation coming from LinSig, while **0,712** from Sidra. This difference explains why the LinSig delay value is lower than the Sidra one;
- The Back of Uniform Queue is **5,4** vehicles while the average of the peaks in Figure 3.14, showing the mean length of the back of the queue, is **5,77** vehicles.

Lane 2 Arm 4 (lane 2 on South Approach):

- **11,9** seconds (1,3 pcu×h) is the average delay calculated by LinSig while **12,07** seconds is the value from field observations (**13,2** seconds from Sidra). The percentage difference between the delays is -1,4%;
- **0,379** is the degree of saturation coming from LinSig, while **0,427** from Sidra. This difference explains once again why the LinSig delay value is lower than the Sidra one;
- even for lane 2, the Back of Uniform Queue (**3,4** vehicles) is close to the average of the peaks in Figure 3.15 (**3,48** vehicles).

Lane 3 Arm 4 (lane 3 on South Approach):

- as for the previous lanes, the average delay for lane 3 is also lower than the field observation output; **15,2** seconds is the value obtained by LinSig while **16,84** seconds the result from field observations (**18,7** seconds for Sidra). The percentage difference is -9,84%;
- counter to what happened in the previous two lanes, the degree of saturation for LinSig (**0,570**) is higher than the one calculated by Sidra (**0,539**). Probably it is caused by the geometric delay overestimation in Sidra;
- the Back of Uniform Queue is **4,3** vehicles while the average of the peaks in Figure 3.16 is **5,32** vehicles. The difference of these two values is a bit bigger than for the previous lanes, probably it is caused by the exceptional event presumed in the comparison in Chapter 4 (see IV. 2. 1.).

Item	Tot Gm	Start Gm	End Gm	Flw pcu	Sat Flow pcu/Hr	Max Sat pcu/Hr	Cap pcu	Deg Sat	Arr pcu	UDly pcuh	TDly pcuh	Dly s/pcu	UStops stops	UStops stps/pcu	UQ End Red pcu	Bar
- Network	-	-	-	-	-	-	-	60.9%	-	7.0	10.4	-	1542.4	-	-	-
- Trondheim I Jui	-	-	-	-	-	-	-	60.9%	-	7.0	10.4	-	1542.4	-	-	-
1/1	15	14	29	197	1930	1930	441	44.7%	197	1.3	1.7	30.6	168.9	0.9	2.8	-
1/2	56	14	0	238	2070	2070	1686	14.1%	238	0.1	0.2	2.6	47.6	0.2	0.7	-
1/3	56	14	0	284	2070	2070	1686	16.8%	284	0.1	0.2	2.7	60.9	0.2	0.9	-
2/1	-	-	-	290	1930	1930	1930	15.0%	290	0.0	0.1	1.1	0.0	0.0	-	-
2/2	-	-	-	284	1930	1930	1930	14.7%	284	0.0	0.1	1.1	0.0	0.0	-	-
3/1	-	-	-	197	1965	1965	1965	10.0%	197	0.0	0.1	1.0	0.0	0.0	-	-
3/2	-	-	-	504	1965	1965	1965	25.6%	504	0.0	0.2	1.1	0.0	0.0	-	-
4/1	37	33	0	650	1965	1965	1065	60.9%	650	2.0	2.8	15.2	436.4	0.7	5.4	-
4/2	37	33	0	404	1965	1965	1065	37.9%	404	1.0	1.3	11.9	230.9	0.6	3.4	-
4/3	37	33	0	519	1676	1676	911	57.0%	519	1.5	2.2	15.2	341.1	0.7	4.3	-
5/1	-	-	-	718	1965	1965	1965	36.5%	718	0.0	0.3	1.1	0.0	0.0	-	-
5/2	-	-	-	474	1965	1965	1965	24.1%	474	0.0	0.2	1.2	112.7	0.2	-	-
5/3	-	-	-	48	1965	1965	1965	2.4%	48	0.0	0.0	0.9	0.0	0.0	-	-
6/1	8	4	12	52	1915	1915	246	21.1%	52	0.4	0.5	36.6	46.1	0.9	0.9	-
6/2	27	2	29	68	1915	1915	766	8.9%	68	0.2	0.3	15.7	41.8	0.6	0.8	-
6/3	27	2	29	70	1965	1965	786	8.9%	70	0.3	0.3	15.6	43.0	0.6	0.8	-
6/4	27	2	29	22	2015	2015	806	2.7%	22	0.1	0.1	15.2	13.2	0.6	0.2	-

Fig. 5.8

Figure 5.8 shows the LinSig Network Results view while the blue circlets highlight the data used for the above comparisons.

As shown by the delay output parameters reported above, LinSig tends to underestimate the value compared to field observation delays. However, the percentage difference between LinSig 3.1 and field observations is a bit lower than what determined in Chapter 4 (percentage difference between Sidra 5.1 and field observations), thus it is possible to maintain that LinSig, in the case under analysis, provides more accurate outputs.

Moreover, it should be noted that the queue parameter of LinSig chosen for the comparison is reliable if it is compared to the mean length of the queue at the end of the red light in the field observations.

V. 2. 2. “Trondheim II” vs. “Trondheim 2” and Field Observations

In this section of the thesis, the priority lane delay calculated by LinSig 3.1, in the second site (“Trondheim II”), will be compared to what observed during the field surveys for buses. Moreover this delay obtained with LinSig will be analyzed in order to understand if it is consistent with bus delays in Sidra 5.1.

The average delay obtained by LinSig in the bus priority lane, as shown in Figure 5.9 (Lane 2 Arm 4 highlighted in the red box), is 9,4 seconds. This value, once again, is lower than what calculated from field surveys in Chapter 3 (14,52 seconds), but this was expected: indeed, as explained in the previous chapters, the buses don’t have a real priority lane.

↑ Item	Tot Gm	Start Gm	End Gm	Flw pcu	Sat Flow pcu/Hr	Max Sat pcu/Hr	Cap pcu	Deg Sat	Arr pcu	UDly pcuh	TDly pcuh	Dly s/pcu	UStops stops	UStops stps/pcu	UQ End Red pcu
1/3	56	14	0	261	2070	2070	1686	15.5%	261	0.1	0.2	2.7	52.2	0.2	0.8
2/1	-	-	-	313	1930	1930	1930	16.2%	313	0.0	0.1	1.1	0.0	0.0	-
2/2	-	-	-	261	1930	1930	1930	13.5%	261	0.0	0.1	1.1	0.0	0.0	-
3/1	-	-	-	197	1965	1965	1965	10.0%	197	0.0	0.1	1.0	0.0	0.0	-
3/2	-	-	-	504	1965	1965	1965	25.6%	504	0.0	0.2	1.2	0.0	0.0	-
4/1	37	33	0	1014	2800	2800	1520	66.7%	1014	3.2	4.2	15.0	724.3	0.7	8.5
4/2	37	33	0	66	1915	1915	1040	6.3%	66	0.1	0.2	9.4	31.1	0.5	0.5
4/3	37	33	0	493	1577	1577	856	57.6%	493	1.5	2.1	15.6	324.0	0.7	4.1
5/1	-	-	-	1082	1965	1965	1965	55.1%	1082	0.3	0.9	3.0	707.5	0.7	-
5/2	-	-	-	136	1965	1965	1965	6.9%	136	0.0	0.0	1.0	0.0	0.0	-
5/3	-	-	-	22	1965	1965	1965	1.1%	22	0.0	0.0	0.9	0.0	0.0	-
6/1	8	4	12	52	1915	1915	246	21.1%	52	0.4	0.5	36.6	46.1	0.9	0.9

Fig. 5.9

Despite the delay calculated by LinSig 3.1 is 35,3% lower than the corresponding field observation , it is possible to maintain that the value is consistent with Sidra output (11,6 seconds of average delay). Indeed, as occurred in the comparison between “Trondheim I” and “Trondheim 1”, LinSig provides delays always underestimated compared to Sidra, thus the results are reasonable.

Even for the other lanes in Arm 4 (lane 1 straight direction and lane 3 for right turning), this general result is confirmed:

- **15,0** seconds is the delay for lane 1 in LinSig, lower than **15,8** that is the Sidra result (see Table 4.14, South Approach lane 1);
- **15,6** seconds is the delay for lane 3 in LinSig, while **19,3** is the value for Sidra (see Table 4.14, South Approach lane 2).

V. 2. 3. “Trondheim I” vs. “Trondheim II”

In this section, output parameters regarding the entire intersection, like total and average delay and intersection degree of saturation, will be used to compare “Trondheim I” and “Trondheim II”. Furthermore, for the sake of completeness, the same output parameters for “Trondheim 1” and “Trondheim 2” (Sidra) will be reported.

Before the comparison, it should be noticed that, for the same reasons reported in IV.2.3, even “Trondheim II” has been modified: the basic saturation flow for lane 1 in arm 4 has been brought again to its default value, according to the lane width (1935 pcu/h).

Unfortunately, LinSig 3.1 doesn’t allow the user to change the vehicle occupancy within the inputs, thus it is not possible to know the average delay experienced by individuals, which is a valuable parameter that can support the introduction of a bus priority lane.

Table 5.10 shows a recap of the intersection parameters reported above. As expected, “Trondheim I” works better than the intersection with the bus priority lane (“Trondheim II”):

- The Degree of Saturation is **0,609** for the 3-legs junction without bus lane, while **0,782** with the bus lane. This parameter documents how “Trondheim I” shows more spare capacity than “Trondheim II”;

- The Average Delay is **10,4** seconds for “Trondheim I” while **13,0** seconds for “Trondheim II”. Even this parameter confirms that an intersection without a bus lane can perform better in terms of delay per vehicle, but, as explained in the previous chapter, this is not always true if the delay per person is considered.

Intersection performance measure comparison - (Table 5.10)

Intersection Performance Measure	“Trondheim I”	“Trondheim 1”	“Trondheim II”	“Trondheim 2”
Demand Flows (Total)	2506 veh/h	2506 veh/h	2506 veh/h	2506 veh/h
Percent Heavy Vehicles	4,9%	4,9%	4,9%	4,9%
Degree of Saturation	0,609	0,712	0,782	0,822
Total Delay	7,0 veh-h/h	10,97 veh-h/h	8,7 veh-h/h	12,82 veh-h/h
Average Delay	10,4 sec	15,8 sec	13,00 sec	18,4 sec
Delay (Worst Lane)	36,6 sec	38,5 sec	57,5 sec	57,0 sec

The parameters reported for “Trondheim 1” and “Trondheim 2” in table 5.10 show, once again, how Sidra Intersection 5.1 tends to overestimate the outputs while LinSig 3.1 does the opposite. Despite this general tendency, the delays for the worst lane, left turning on East Approach, are really close (36,6 sec and 38,5 sec for the intersection without bus lane, while 57,5 and 57,0 sec for the priority lane junction).

CHAPTER VI

CONCLUSIONS

The main purpose of this thesis was to analyze the modeling of a bus priority lane through the traffic engineering software Sidra Intersection 5.1. This software, used in 92 countries including U.S.A. & Canada, Australia, South Africa and others (like Norway), does not include, in version 5.1, a specific tool that can model a priority lane. For this reason a method called the oblique leg technique, has been used to represent this special type of lane.

Furthermore, in order to judge the modeling results, a real intersection in Trondheim was chosen as basis for the comparison of the outputs.

The following list shows a recap of the main conclusions, valid only for the case under analysis, based on different parameters that constitute the terms of comparison:

- The percentage difference between Sidra Delay parameters (like average delay per lane) and lane delay obtained with the field observations is never higher than 10%, remarking that Sidra always tends to overestimate the outputs, especially for right and left turning.

Only the percentage difference between the delay in the bus priority lane (in “Trondheim 2”) and the delay for buses determined in field observations exceeds this 10%, but this is because the real intersection doesn’t have a full bus priority lane, but just something similar;

- The Back of the Queue in Sidra (95Th percentile) contains the peaks of the queue length at the end of the red registered during the field observations. Just once, the real queue length has exceeded the Back of the Queue, and it was caused by an unexpected event.

These results show that Sidra Intersection, with a careful calibration, can be used as a software for general intersection modeling, and in particular for intersections with priority lanes.

In order to confirm the above conclusions, it was decided to model the same intersection using a software, that promises to model bus priority lanes, called LinSig (Version 3.1). Thus the outputs of LinSig were analyzed and compared to those achieved with Sidra and during the field observations.

Overall, it seems that LinSig provides on average more accurate results compared to Sidra, although it tends to underestimate the output parameters, in terms of delay and queue length. This tendency is also evident in the comparison between parameters representative of the whole intersection, like Intersection Total Delay, where LinSig provides always values lower than Sidra (up to 35% less). This is probably caused by the software calculation method for delays in right and left turning (highest difference in terms of percentage).

Unfortunately LinSig 3.1 doesn't allow the user to set vehicle occupancy values, unlike Sidra that can manage this data. So, in Chapter 4 the average vehicle occupancy for the buses was added in order to determine the delay experienced by an individual. According to the results, it can be stated that the intersection with the priority lane works better compared to the normal 3-legs junction, in terms of delay per person. Moreover the vehicle occupancy that has been used in Sidra (40 persons per vehicle), is an underestimated value compared to a typical morning peak. This means that if a common value for the average occupancy during a morning peak (like 60 or 70 persons per vehicle) had been used, the delay per person would have been even lower, justifying even more the conversion of a normal lane into a priority lane.

In summary, it can be stated that Sidra Intersection 5.1 is an intuitive and complete traffic modeling software, furthermore it makes really easy to manage several typical types of traffic situations, as shown in Chapter 2.

In the same way LinSig 3.1 is a solid traffic engineering software, which also allows bus lane modeling, thanks to the capacity of handling different layers in volume flows. However, as a personal opinion, LinSig 3.1 is less user friendly than Sidra 5.1 and it takes more time to learn to use it.

For the next version of Sidra (Sidra Intersection 6), "Akcelik & Associates" software house has promised to introduce "movement classes", which will include buses and bicycles. This will allow treating movements belonging to different classes individually in terms of lane disciplines, lane flow calculations, signal phases and signal timing.

Also JCT Consultancy Ltd (LinSig software house) will introduce a new version (LinSig 3.2) which will include new features designed to make LinSig easier to use

for users in Australia and New Zealand, as well as some improvements applicable to all LinSig users in the world.

The most important limitation of this thesis lies in the fact that field observations have been collected in an intersection that works like a priority lane intersection, but where it is not possible to identify a real bus priority lane. This characteristic has caused the need to handle the results with care, especially during the comparison with Sidra and LinSig models.

For this reason, a future study investigating a real bus priority lane junction would be very interesting, in order to achieve even clearer results and conclusions.

Furthermore, it would be interesting to assess the effects of variations of some parameters (like vehicle occupancy, volume flows and so on) using a sensitivity analysis.

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