What is good about analytical traffic modelling?

Rahmi Akçelik

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Akcelik & Associates Pty Ltd
Trading As "SIDRA SOLUTIONS"
PO Box 1075G, Greythorn, Vic 3104 AUSTRALIA
ABN 79 088 889 687

www.sidrasolutions.com

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Akcelik & Associates Pty Ltd acknowledges the contributions by numerous users from many countries around the world through their valuable comments towards the development of SIDRA SOLUTIONS software products.

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Rahmi Akçelik
SIDRA SOLUTIONS
rahmi.akçelik@sidrasolutions.com

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Summary

This document presents a brief discussion of why traffic modellers use analytical models for traffic and transport planning, management, design and operations purposes. The applications include traffic impact analysis, roundabout geometric design, efficient operation of traffic signal control systems and development of balanced Movement and Place solutions. Analytical models enhance the productivity of transport planners and traffic engineers by allowing them to analyse more scenarios with less effort. They are also used for verification and calibration of various aspects of microsimulation models.

Analytical models are based on a scientific approach and are capable of modelling intersections, interchanges, freeways, rural roads, urban streets and networks with complex traffic conditions. They provide unique value to transport planning and traffic engineering decision-making through balanced solutions that consider the conflicting needs of all transport users including pedestrians, cyclists, buses, tram / light rail, cars and freight vehicles. This provides significant cost savings and environmental benefits.

Some technical issues in the use of microsimulation models are explained as a warning against decision making on the basis of limited viewing of animations generated by microsimulation runs without auditing their analytical soundness.

> ***"The thing about seeking knowledge and understanding through the scientific process, rather than inventing a new product through trial and error, is that it tends to have a cumulative effect: it tends to develop more and more utility over time."***
>
> *Suzie Sheehy, The Matter of Everything, Bloomsbury Publishing, 2022, p.23.*

1 Introduction

The term ***analytical model*** refers to algorithmic models that combine mathematical model elements (based on a combination of traffic theory and empirical derivations) to determine complex system states. The US Highway Capacity Manual Edition 7, Chapter 9 (Glossary and Symbols) ***(1)*** defines an Analytical Model as "*A model based on traffic flow theory, combined with the use of field measures of driver behaviour, resulting in an analytical formulation of the relationship between field measures and performance measures such as capacity and delay."* This is in contrast with a ***simulation model*** which refers to modelling of traffic moving in a network as *individual vehicles* or as *groups of vehicles* (small packs of vehicles or larger platoons).

These traffic modelling techniques produce estimates of traffic performance for use in design, operations and planning work. Because of the complex nature of traffic systems, analytical models use **iterative approximation** methods whereas microsimulation models rely on a large number of simulations.

This brief document presents notes about why analytical modelling techniques are useful for the profession. Earlier documents with more detailed discussion ***(2)***, ***(3)*** are available for download from https://www.sidrasolutions.com/publications.

2 Main Points

1. **An analytical model is**
    - an engineering approach
    - algorithmic
    - combines theoretical and empirical approaches
      e.g. performance estimation based on queuing theory with formulations calibrated using established (well specified) survey techniques
    - auditable (allows in-depth questioning of model assumptions).
2. **An analytical model can**
    - calculate
    - find solutions
    - estimate *capacity* as a basic parameter that determines traffic performance (see *Section 3.1*)
    - optimise traffic performance
    - optimise traffic signal phasings and timings
    - quantify the effect of pedestrians on signal timings and vehicle movement capacity
    - contribute to traffic modelling as part of a Movement and Place approach ***(4)***, ***(5)***, ***(6)***
      (SIDRA with extensive pedestrian modelling and detailed modelling of vehicle movement classes including cyclist, bus, tram / light rail and large truck is ideal in relation to the "Movement" aspect of this, even where "Place" is more important than "Movement")
    - model CO2 emissions for environmental assessments
      (the SIDRA power-based fuel and emissions models can estimate emissions of traffic movements, in particularly CO2, with great accuracy)
    - provide consistent modelling of different intersection types by using algorithms that employ consistent methods
      (SIDRA capacity and performance models provide a unique consistent approach for different types of signalised and unsignalised traffic facilities)

   - predict and assess conditions that cannot be seen in "animation",
     e.g. delay to vehicles departing from the queue after the modelling period under oversaturated conditions (see *Section 3.2*) ***(7)***.

3. **Powerful concepts and model parameters** used by analytical models
   - are well-established
   - are understood by the profession
   - provide a common language for communication
   - are useful in assessing traffic conditions
   - are useful for signal timing analysis including analysis for actuated signal control
   - can be used for verification and calibration of various aspects of microsimulation models (Yoshii 1999).

   These concepts and model parameters include
   - capacity (see *Section 3.1*)
   - degree of saturation (demand flow / capacity ratio)
   - saturation flow (queue discharge flow rate)
   - critical gap and follow-up headway for gap acceptance processes
   - percentile queue length and probability of blockage by downstream queues
   - fundamental relations among flow, speed, density and spacing
   - parameters used by traffic signal control systems such as SCATS MF and detector occupancy
   - bunching (random moving queues in an uninterrupted stream)
   - platoons of vehicles departing from signalised intersections.

   These concepts and parameters have been developed and used in traffic modelling and control for a long time. These include key parameters used in **analytical model calibration**.

4. **"Traffic" vs "individual vehicles"**: The concepts and parameters listed above are for "traffic streams" or "traffic movements" which is a modelling approach that converts "individual vehicle" movement characteristics such as car following, lane change, acceleration and deceleration to more aggregate and measurable "traffic" characteristics. This provides the capabilities listed in Points 1 to 3 above. For information about the level of detail in analytical models, see *Section 3.4*.

5. **Workflow**: Analytical models are less costly than microsimulation to use, providing workflow efficiencies as they
   - are easier to set up (low model specification time due to clarity of concepts)
   - are quicker to run (quicker solutions)
   - reduce modelling times by helping the modeller to spend less time on setting of key parameters
   - help modellers to analyse large number of scenarios (alternative solutions, existing and development conditions, design life analysis for future traffic conditions) and make decisions about recommended solutions with less effort
   - can be reviewed (audited) to assess whether calibration of key model parameters has produced realistic results (as listed above).

6. Analytical models offer **a more stable answer** compared with microsimulation model results which vary due to randomness and depend on the number of simulation runs. Understanding and dealing with **uncertainty** and **sensitivity** of solutions to model parameters is important.

Uncertainty:

- Finding a reliable solution representing **average** and **percentile** values of performance variables would require a large number of simulation runs with long simulation periods for convergent solutions.
- **Analytical models are not "deterministic"** as is claimed sometimes. They use queuing theory for <u>random overflow </u>and <u>persistent oversaturation (congestion)</u> effects.
  See *Section 3.1*.
- **For oversaturated conditions**, simulation cannot be run for longer periods for convergence since queues build up persistently with longer periods because of demand exceeding capacity. An increased number of simulations is needed rather than longer simulations for this reason.
- **For near-saturated conditions** when the average demand is less than but close to capacity, significant **overflow queues** occur due to randomness of arrival flows. Therefore, average results require a large number of simulations. ***Figure 1*** *s*hows the difference between average values of two simulation points for low and high degrees of saturation. This is important since the effect of randomness in arrival flow rates is highest near capacity conditions, and furthermore, the capacity values can also change cycle-by cycle. This shows the difficulty of obtaining performance estimates representing average conditions from microsimulation modelling.
  See the discussions in *Sections 3.1 and 3.2*.
- For convergent solutions, **downstream queue blockage effects** resulting in capacity losses by upstream movements need an increased number of iterations for analytical models and an increased number of simulations by microsimulation models (especially if downstream queue blockage causes oversaturation).

Sensitivity:

The sensitivity of performance variables (delay, queue, stop, etc.) is much higher at high degrees of saturation due to the nonlinearity of the performance function as seen in ***Figure 1***.

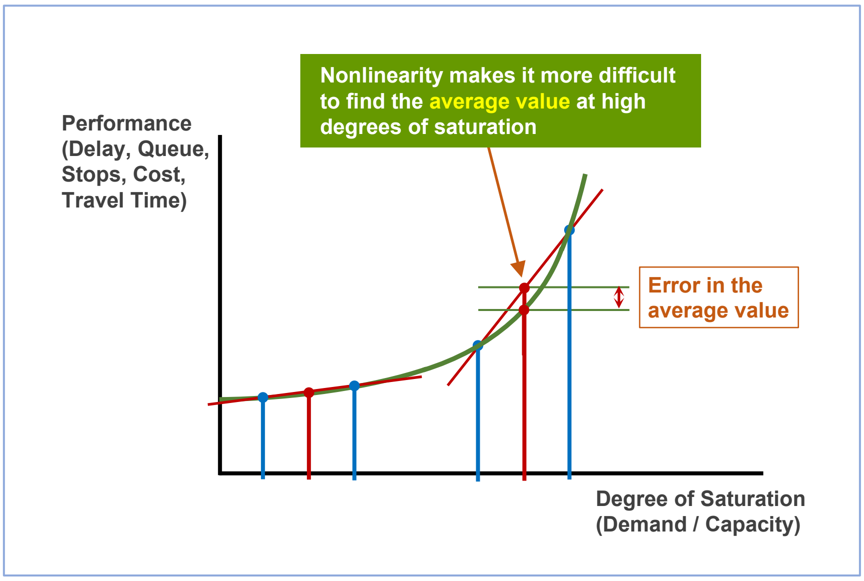


Figure 1 - Non-linear characteristic of traffic performance

7. Existing analytical models get improved and models are developed for new areas of transport practice as traffic science discovers laws applicable to traffic movements.

In Conclusion

8. Analytical models for traffic design, operations and planning practice facilitate **better knowledge and understanding of the laws that rule traffic movements** (as distinct from, but based on, the behaviour of individual vehicles and their relationships) and the interactions of those movements in a complex traffic system. Watching an animation, even if it is a perfect replication of the real-life conditions, does not reveal those laws to a modeller who does not have adequate knowledge based on concepts developed by decades of **traffic science**.

   It is also uncertain whether an animation based on a single simulation run would represent the traffic conditions of a scenario given the variations among many simulation runs necessary for oversaturated and near-saturated traffic conditions (refer to ***Figure 1***).

9. **No model is perfect.** It is important to understand the model and know its limitations. An analytical model user with **knowledge and expertise** can question the model assumptions and address areas of concern more readily because of the conceptual strength of the model.

   Expert use of traffic models with high levels of knowledge and understanding will be even more important as **Artificial Intelligence (AI)** threatens to take over the decision-making process in the traffic planning, design and operations processes as in other professions.

3 Discussion

Various points noted in *Section 2* are discussed in some more detail in this section.

3.1 Capacity as a dynamic concept

Capacity is the highest sustainable flow rate that can be achieved during a specified time period under given (prevailing) road, geometric, traffic, environmental and control conditions. This means that the capacity of a traffic facility varies by time period.

In addition to geometric conditions, *demand flow levels* cause significant capacity variations for movements subject to gap acceptance (opposed / permitted turns at signals, minor road movements at stop and give-way / yield sign controlled intersections, entry movements at roundabouts, merging at freeway entry ramps and at exit short lanes at intersections). For example, in design life analysis for roundabouts, increased demand flows over the years mean increased circulating flow rates resulting in reduced capacities. See ***Figure 2*** for the SIDRA design life analysis results for the Roundabout Example 2 given in Highway Capacity Manual, Chapter 33 ***(1)***.

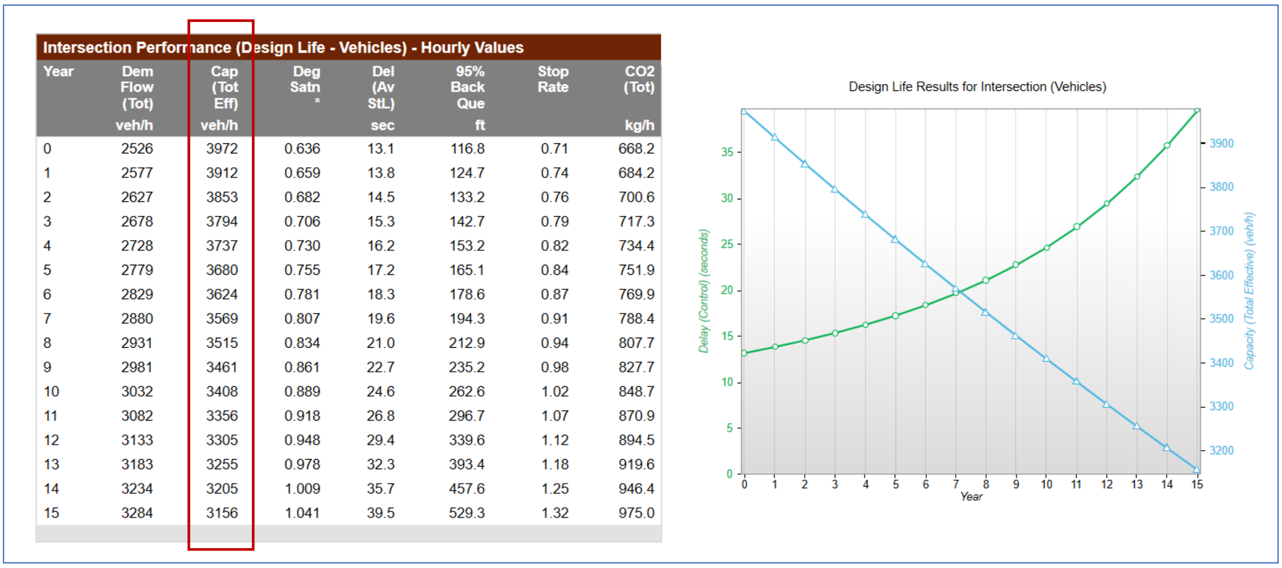
Short lane capacities and lane blockages by downstream queues are also subject to large variations due to demand flow levels in addition to queue storage lengths of approach short lanes at intersections and downstream lanes in networks.

In analytical models based on queuing theory foundations, capacity is the main parameter in equations estimating performance measures such as delay, queue length, stops, and travel time. For performance estimation, analytical models use *capacity* as the *service rate* under prevailing conditions. This applies even when the demand flows are below capacity levels (undersaturated conditions).

Microscopic simulation models do not estimate capacity. The capacity of a lane is achieved under high demand (fully saturated, or oversaturated) conditions when queued vehicles use all opportunities provided by green periods and gaps in opposing streams. The method of increasing the demand flow rate for the subject approach (or lane) to create oversaturated conditions in order to measure capacity has been suggested in the literature as a way of obtaining capacity estimates from microsimulation models.

This method has several problems. Firstly, signal timings would be affected, i.e. cycle time would increase and green splits would be biased. This problem could be solved by performing such an analysis using the signal timings obtained with current demand flows. However, a further problem arises when the increased demand flow method is applied to a *closed (interactive) system* such as closely-spaced intersections or roundabouts. In the case of closely-spaced intersections, the possibility of queue blockage is increased as a higher demand flow is fed into the downstream approach. This would give a reduced capacity for the upstream intersection. Another example of a closed system is a roundabout where the amount and queuing characteristics of the entering flow will affect each leg in turn, eventually affecting the circulating stream characteristics for the subject approach.

Thus, creation of oversaturated conditions by increasing demand flow levels would be useful only as a capacity calibration process since this method would mean changed prevailing traffic conditions, and therefore performance estimates would not be applicable. This method would have a very limited application since the increased demand flow levels would also affect capacities of short lanes, opposed lanes, and so on.



Intersection Performance (Design Life - Vehicles) - Hourly Values

Year	Dem Flow (Tot) veh/h	Cap (Tot Eff) veh/h	Deg Satn *	Del (Av StL) sec	95% Back Que ft	Stop Rate	CO2 (Tot) kg/h
0	2526	3972	0.636	13.1	116.8	0.71	668.2
1	2577	3912	0.659	13.8	124.7	0.74	684.2
2	2627	3853	0.682	14.5	133.2	0.76	700.6
3	2678	3794	0.706	15.3	142.7	0.79	717.3
4	2728	3737	0.730	16.2	153.2	0.82	734.4
5	2779	3680	0.755	17.2	165.1	0.84	751.9
6	2829	3624	0.781	18.3	178.6	0.87	769.9
7	2880	3569	0.807	19.6	194.3	0.91	788.4
8	2931	3515	0.834	21.0	212.9	0.94	807.7
9	2981	3461	0.861	22.7	235.2	0.98	827.7
10	3032	3408	0.889	24.6	262.6	1.02	848.7
11	3082	3356	0.918	26.8	296.7	1.07	870.9
12	3133	3305	0.948	29.4	339.6	1.12	894.5
13	3183	3255	0.978	32.3	393.4	1.18	919.6
14	3234	3205	1.009	35.7	457.6	1.25	946.4
15	3284	3156	1.041	39.5	529.3	1.32	975.0

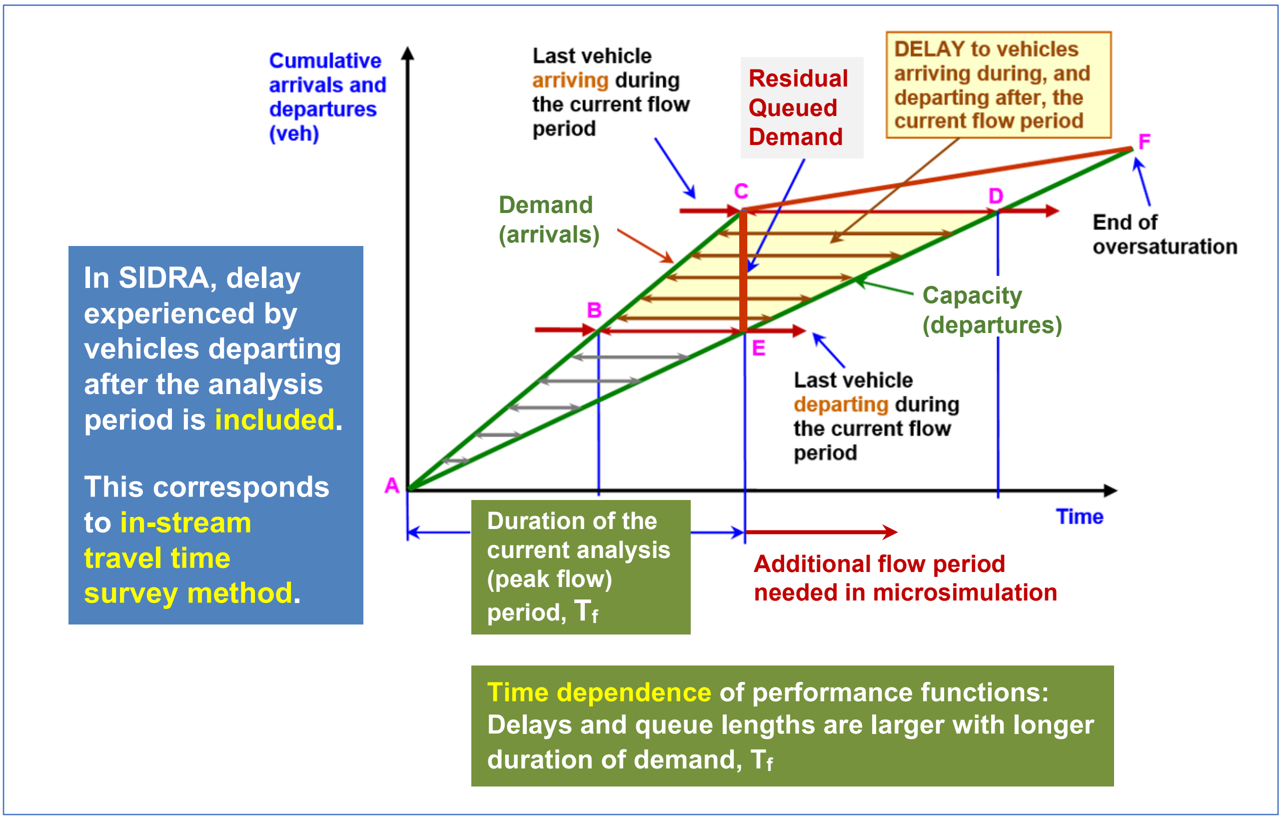
Figure 2 - SIDRA design life analysis results for the Roundabout Example 2 given in Highway Capacity Manual, Chapter 33

3.2 Delay in oversaturated conditions

Delay to vehicles departing from the queue after the modelling period under *oversaturated conditions* is an important example of predicting the conditions beyond the analysis period that cannot be seen in "animation" *(7)*.

As shown in the deterministic queueing model shown in ***Figure 3***, the SIDRA delay for oversaturated conditions includes the delay experienced after the end of the flow period until the departure of the last vehicle arriving during the flow period. This corresponds to the *path-trace (instrumented car) survey method* of measuring delays. There is a significant difference between this method and the method which measures the delay experienced by vehicles in the queue during the analysis period only.

Traffic performance is ***time dependent***. This means that delay, queue length, and so on are larger if the demand persists for longer periods (longer analysis period, T_f in ***Figure 3***). This applies to oversaturated (demand larger than capacity) as well as near-saturated conditions (demand below but close to capacity). Under this condition, running simulations for long periods for convergent solutions would bias the results. It is therefore important to run a large number of simulations to allow for randomness effects with each simulation run for the given analysis period (after the warm-up period).



In SIDRA, delay experienced by vehicles departing after the analysis period is included.

This corresponds to in-stream travel time survey method.

Time dependence of performance functions: Delays and queue lengths are larger with longer duration of demand, T_f

Figure 3 - Measuring delays experienced by vehicles in oversaturated conditions

3.3 Is an analytical model a "deterministic model"?

It is often stated that an analytical model is a *deterministic* model (it gives the same answer always). While analytical models give more stable results, there are conditions, especially in network modelling with lane blockages causing oversaturated conditions, when SIDRA results will differ according to the number of iterations when the iterative process has not converged yet.

The statement that an analytical model is a *deterministic* model is not correct since analytical models deal with *randomness* and *oversaturation* in traffic flows through the use of traffic theory. This is reflected by the estimation of overflow queues, and the effect of randomness on average values of delay, queue length and stop rate. Other important calculations in analytical models such as percentile queue lengths, probabilities of short lane overflow and probabilities of blockage by downstream queues in networks are also based on randomness in traffic flows.

Usually, the statements that analytical models are *deterministic* do not consider how many microsimulation runs are needed, and/or how long the simulation runs should be processed for convergence, to be able to match the analytical models in allowing for randomness effects.

3.4 Analytical model level of detail

Different analytical models differ in level of detail (or level of aggregation of traffic characteristics). For example, in increasing levels of aggregation as seen in ***Figure 4***:

- **SIDRA INTERSECTION** uses *lane-based* intersection and network models
- **US Highway Capacity Manual** and software packages based on it use *lane groups and movement groups*
- **UK ARCADY** software for roundabouts uses *approach movements.*

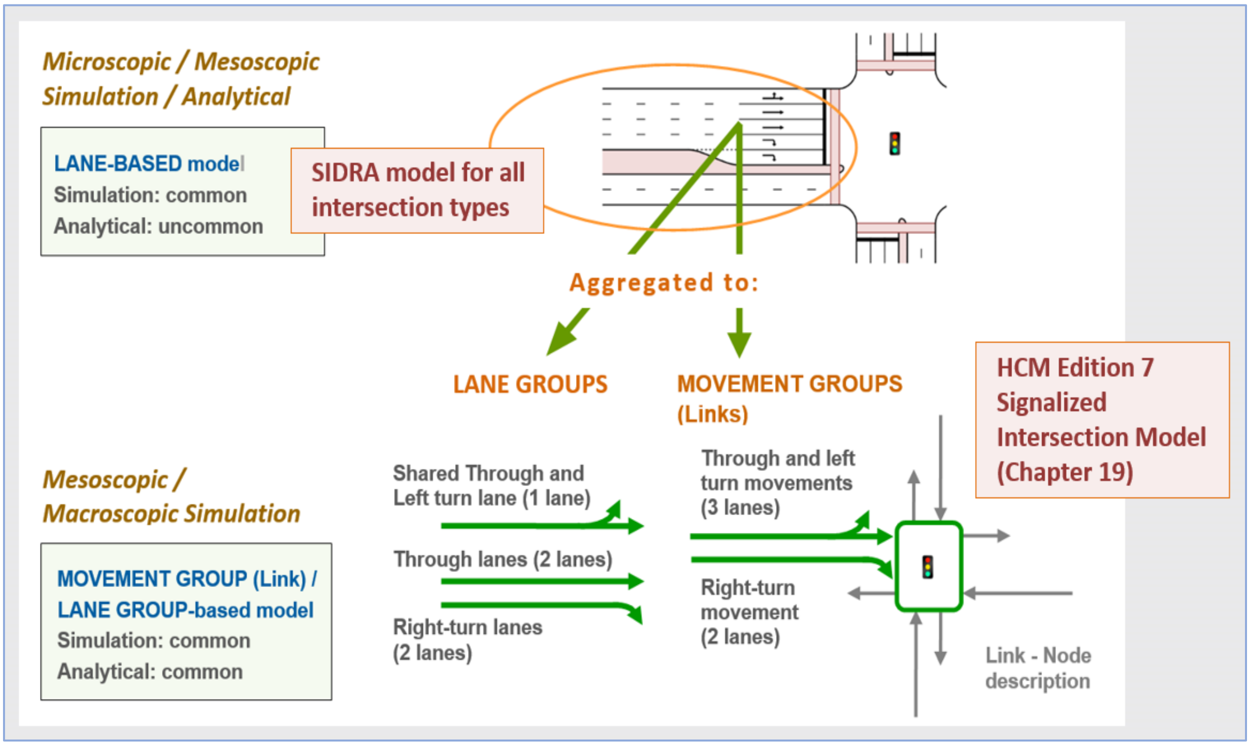


Figure 4 - Lane-based and Movement Group (Link) / Lane Group-based models

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Author

Dr Rahmi Akçelik is a leading scientist and software developer with 50 years of practical, research and training experience in the area of road traffic operations, traffic engineering, management and control. He is Director of Akcelik and Associates Pty Ltd (trading as SIDRA SOLUTIONS). He has 350 technical publications in his area of expertise. He is the author of the SIDRA INTERSECTION and SIDRA TRIP software packages. Rahmi served as member of various US Transportation Research Board Committees. He has trained several thousand professionals in over 300 workshops, courses and seminars.

Awards received by Rahmi include the *2014 Roads Australia Award for Technical Excellence* in recognition of the exceptional achievement of an individual in a technical or scientific area relevant to transport, the *2008 ITE ANZ Contribution to the Transportation Profession Award, the 1999 Clunies Ross National Science and Technology Award* for outstanding contribution to the application of science and technology, *and the 1986 ITE US Transportation Energy Conservation Award.*

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➭ Available for download from **https://www.sidrasolutions.com/publications**.

(1) TRB (2022). *Highway Capacity Manual Edition 7*. Transportation Research Board, National Research Council, Washington, DC, USA, 2022.

(2) ➭ AKÇELIK, R. and BESLEY, M. *Microsimulation and Analytical Methods for Modelling Urban Traffic*. Paper presented at the Conference on Advance Modelling Techniques and Quality of Service in Highway Capacity Analysis, Truckee, California, USA, 2001.

Microsimulation models can help with the analysis of complex traffic problems in urban areas, alongside the analytical techniques that are in use. However, concerns are often expressed regarding misuse of microsimulation. This paper focuses on compatibility between microsimulation methods and established analytical techniques that are used in traffic engineering. Several key components of traffic models are discussed including (i) the use of simulation for capacity analysis, (ii) modelling of queue discharge (saturation) flow at signalised intersections; (iii) modelling of gap-acceptance situations at all types of traffic facilities, and (iv) estimation of lane flows at intersection approaches. The consistency of definitions and measurement methods for traffic performance variables such as delay and queue length is also discussed.

(3) ➭ AKÇELIK, R. *Microsimulation and Analytical Models for Traffic Engineering*. Presentation at the ARRB - AUSTROADS Microsimulation Forum 19-20 Sep 2007.

This presentation discusses relationships between microsimulation and analytical models. The above paper ***(2)*** is recommended in relation to this presentation.

(4) DoT Victoria. *Movement and Place in Victoria*. Department of Transport, Melbourne, Victoria, 2019.

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(7) AKÇELIK, R., BESLEY, M., ESPADA, I. and NASH, D. *Management of traffic modelling - a critique of Austroads Report AP-R621-20 (Transport modelling for project managers)*, 2nd Edition. Technical Note. Akcelik & Associates Pty Ltd, Melbourne, Australia, 2021.

This second edition of the critique report is prepared in response to the Austroads Report AP-R647-21. It should be of interest to transport and traffic modelling project managers, guide developers and software users. There have been significant improvements in report AP-R647-21 in removing and clarifying technical aspects of the previous report AP-R621-20 which were criticised. However, the criticised Model Categorisation scheme remains unchanged in the new report. The traffic and transport model categorisation system recommended by the authors of this critique report (based on the geographic extent of the area to be modelled and the purpose of model use) remains current. The criticism of lumping together different software packages into forced model categories also remains. A method is proposed for the assessment of model categories and key model features that apply to individual software packages.

(8) YOSHII, T. (1999). *Standard Verification Process for Traffic Simulation Model - Verification Manual*. Draft Report. Kochi University of Technology, Kochi, Japan.