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An overview of dynamic traffic assignment models for practitioners

Saxena N.[1], Irannezhad E.[1], Soet W.[2]

[1]Australian Road Research Board (ARRB), 80a Turner Street, Port Melbourne VIC 3207 Australia

[2]Planning and Technical Services Directorate, Main Roads Western Australia (MRWA), Don Aitken Centre Waterloo Crescent, East Perth WA 6004

Email for correspondence: Neeraj.Saxena@arrb.com.au

Abstract

Dynamic Traffic Assignment (DTA) has received increasing attention in recent years, and there are numerous examples of practical implementations. While the existing strategic planning models in practice are used for long-term travel demand forecasting, they do not quite realistically represent traffic dynamics which are necessary to assess traffic management measures and policies. Thus, DTA modelling has significantly grown into a vast area in transportation engineering in the past two decades. There do exist different types of DTA applications which can largely be classified into analytical and simulation-based DTA. As these are relatively new concepts, practitioners are often posed the challenge of selecting the right DTA tool which is appropriate for the problem context, time and budget constraints.
This paper aims to describe, from practitioner perspective, the key concepts in DTA, previous applications of DTA models nationally and internationally, and a few DTA oriented software tools in practice. The core components of DTA frameworks are discussed including the three Dynamic Network Loading (DNL) modules namely: macro-, meso- and microscopic. The choice of a DNL determines whether the DTA framework is analytical or simulation-based. This paper summarises a few real-world applications of the DTA models across Australia and New Zealand and abroad. Lastly, this paper also lists out a few available software packages in practice and where do they align in the traffic assignment-DNL diagram. Another classification software tools based on analytical and simulation-based DTA is also presented. This paper will extend the knowledge of practitioners in DTA modelling and also provide awareness regarding when DTA models are appropriate and which type and software tool to undertake a DTA project should be selected.

1.Introduction

Dynamic Traffic Assignment (DTA) has been a popular field in recent years in both research and practice. Static transport planning models usually are chosen due to advantages such as assessing land use and infrastructure plans for long-term forecasting, tractability and solution uniqueness rather than for their ability to represent traffic realistically for planning or operational purposes. On the other hand, DTA models can more realistically capture time-dependent phenomena such as queue spillback, as well as the temporal aspects of bottlenecks and congestion (Chiu et al., 2011), and thus may be an appealing alternative to traditional models.

There have been numerous applications of DTA models across the world. In Australia, DTA models have been developed across a few jurisdictions including major metropolitan areas e.g. Sydney, Melbourne, Brisbane, and Auckland across Australia and New Zealand. However, a majority of DTA applications in practice are simulation-based while analytical DTA models have been more or less confined to the research space. Given the merits of analytical DTA models, the key one being the ease of model development, it is useful to investigate the real-world applications and determine if the models have been able to address key policy-level questions at a cheaper personnel cost and time.

The objective of this paper is to introduce and describe several aspects of DTA modelling. This paper also presents a literature survey of DTA implementations in the real-world context. The review illustrates the geography, scale and type of DTA approach used to give a wider overview to the readers. This paper also classifies some software packages that are widely practised across Australia and New Zealand based on the type of traffic assignment solution they provide. This paper will aid practitioners in not only understanding the key components involved in DTA modelling, but also the choice of available software tools to select from depending on the nature of the problem to be solved, time and budget constraints.

The organisation of this paper is as follows: Section 2 discusses transport modelling in general. Section 3 elaborates traffic assignment, which forms the last step of the four-step modelling process. Section 4 explains the components involved in any DTA framework. Section 5 summarises some real-world applications of DTA models to provide a wider overview of its usage to the practitioners. Section 6 maps out the software packages, listed in Austroads guidelines, on the assignment-loading diagram to provide a pictorial depiction of their capabilities. Lastly, Section 7 summarises the report with findings that are in line with the overall project objective.

2. Traffic Assignment

Traffic assignment corresponds to the last step in the four-step model (The Geography of Transport Systems, 2021). Traffic assignment involves distributing individual trips onto available routes/paths between an Origin-Destination (OD) pair such that it satisfies Wardrop's equilibrium conditions (Sheffi, 1985). One of the early yet commonly used traffic assignment approaches is the Static Traffic Assignment (STA) technique. An STA follows User Equilibrium (UE), which is defined as follows: *at UE, all used paths between an OD pair have the minimum and equal generalised travel cost (can be a function of travel time). In other words, no user can derive additional travel cost savings by unilaterally switching routes.* The mathematical formulation of UE conditions can be solved analytically (or numerically), which provides a closed-form unique solution using a regular personal computer. This particular property gives STA the ability to model large networks, and thus continues to be used as a primary strategic transport planning tool by agencies across the world.

Table 1: Strategic transport model applications in Australia

Model Name	Abbreviation	State	Area
24-hour Regional Operation Model	ROM24	WA	Perth
Strategic Transport Evaluation Model	STEM	WA	Perth
Sydney Strategic Travel Model	STM	NSW	Sydney
Melbourne Integrated Transport Model	MITM	VIC	Melbourne
Canberra Strategic Transport Model	CSTM	ACT	Canberra
Brisbane Strategic Transport Model – Multi-Modal	BSTM-MM	QLD	Brisbane
Metropolitan Adelaide Strategic Transport Evaluation Model	MASTEM	SA	Adelaide

(Source: adaptation from Bliemer et al., 2013)

For example, some applications of strategic transport planning tools (based on STA) in Australia are summarised in Table 1. However, STA models are also known to suffer from two limitations:

- STA models can forecast a volume-by-capacity (V/C) > 1, which is counterintuitive as the observed flow on a link can never exceed its capacity
- They lack a temporal component and thus cannot represent phenomena such as evolution and dissipation of congestion, bottleneck formation, queue spillback, etc.

A DTA approach introduces the temporal dimension to the traditional STA approach, thus giving it the name *dynamic*. Figure 1 shows how the two approaches (STA and DTA) compare against the actual recurrent congestion level observed in-field at an aggregate-level (e.g. the entire road network). STA having no time dependency is denoted by a straight line which is not an accurate representation of the real-world recurrent congestion. On the other hand, DTA closely follows the actual recurrent congestion pattern (e.g., higher congestion during peak than off-peak) and thus is a better choice to study the effects of congestion, queue spillback, etc.

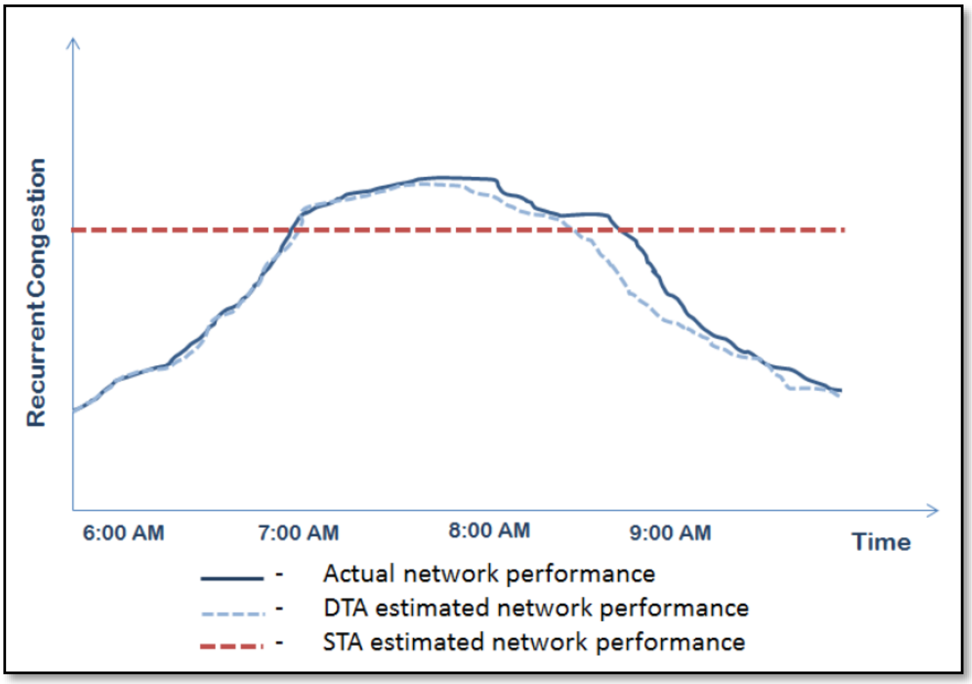


Figure 1: Comparison of STA and DTA against observed congestion
(Source: Saxena (2018))

A DTA model uses smaller time-slices of the OD matrix, also called the ODT, instead of using a single OD matrix for the analysis period. The time-slices, which are generally 15-minutes, signify the time period during which the network characteristics and traveller behaviour (e.g. route choice) are assumed to be unchanged. Each time-slice is again meant to follow Wardrop conditions which is referred to as Dynamic User Equilibrium (DUE) in the context of DTA. DUE is defined as follows: *at DUE, all used paths between an OD pair for a given time-slice have the minimum and equal generalised travel cost. In other words, all trips between an OD pair commencing within the same time interval have the minimum and equal generalised travel cost.* Thus, a DTA model is able to represent the evolution of traffic congestion both spatially and temporally, queue spillback and bottleneck formation (Chiu et al., 2011). There has been an increasing number of DTA model applications in Australia and New Zealand which are summarised in Table 2.

Table 2: DTA model applications in Australia and New Zealand

Model Name	Area	Reference
Metropolitan Area Dynamic Assignment Model (MADAM)	Sydney	Duell et al. (2016)
DTA model for Melbourne	Melbourne	Shafiei et al. (2018)
DTA model for Gold Coast	Gold Coast	Bliemer et al. (2014)
DTA model for Auckland (ADTA)	Auckland	AFC (2018)

Figure 2 compares the STA and DTA on the basis of demand. As shown in the visualisation row, while STA uses just an OD matrix (for the analysis period), DTA combines it with a departure time profile, which can be derived from household travel surveys, to form multiple ODTs (which are represented in the form of a cube) corresponding to a time-slice (generally 15-minutes). One can argue that DTA is nothing but conducting STA with a shorter OD matrix, i.e. instead of a single 3-hour OD matrix, using three 1-hour OD matrices. While it makes sense semantically, conceptually this equivalence can only be valid if the maximum trip duration is less than the time-slice. For example, if there exists a significant proportion of trips which last more than 60 minutes in duration, then STA on a 3-hour matrix is not the same as DTA on three 1-hour matrices. It is so because the trips spanning across two or more time-slices require a more involved path travel time determination logic (e.g. considering travel times in previous time periods), which is discussed next.

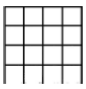
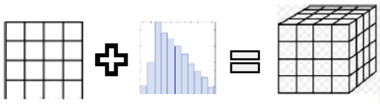
	STA	DTA
Inputs Required	OD Matrix	OD Matrix Departure time profile
How demand is processed?	As a single matrix for the entire analysis period. E.g. 1 matrix of N hours **OD (2-d)**	OD matrix is fragmented into multiple matrices of smaller duration. E.g. 4 matrices of N/4 hours **ODT (3-d)**
Visualisation		

Figure 2: STA vs DTA based on demand
(Source: Saxena (2018))

Figure 3 shows how the path generalised travel costs (measured in terms of travel time only in this instance) are obtained in STA and DTA models which are then used in shortest path computations. STA utilises *Instantaneous link travel times* which is defined as the total route travel time at the time of starting the trip. For example, the top figure shows that if a trip, traversing the path 1-2-3-4, commences within the time-slice t=0 then the path travel time is 3 units. The DTA model, on the other hand, utilises *Experienced link travel times* which is defined as the prevailing link travel time upon arrival at that link. For example, the bottom figure shows the same trip starting at t=0 will have a path travel time of 9 units. With regard to realism, Experienced travel time scores over Instantaneous travel time as the latter does not take into consideration the dynamics of traffic congestion as the journey unfolds (Chiu et al., 2011).

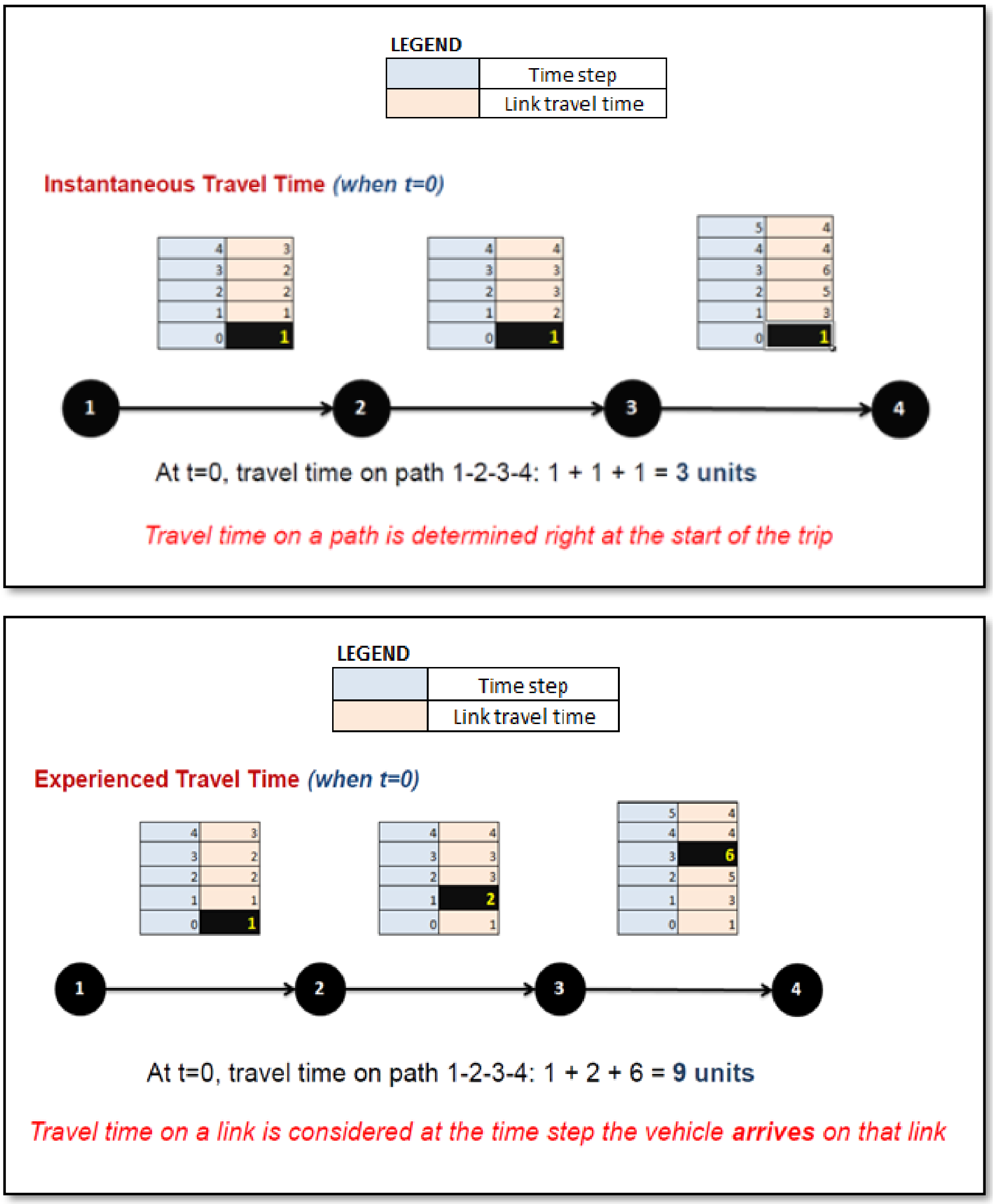


Figure 3: Path travel time computation in STA vs DTA
(Source: Saxena (2018))

3. Components in DTA

A DTA framework, in general, comprises four components which form an iterative process (refer to Duthie and Carrizales (2011) for the flowchart of the iterative process). The first component is the Dynamic Network Loading (DNL) module which is responsible for: 1) propagating traffic onto the network and accounting for intersections, roundabouts etc., and 2) determining the link travel time inclusive of any form of delays e.g. turning delays. Thus, a DNL module produces a vector of time-dependent travel times for a link. The next module, the Time-Dependent Shortest Path (TDSP), computes the shortest path/route between an OD pair using the link travel time (or the link generalised cost) information computed earlier. Once the shortest path has been identified, the third module, Path Assignment (PA), distributes traffic demand among the set of available paths by moving a proportion of traffic from other routes onto the identified shortest path. Lastly, relative gap checks for convergence of the iterative process.

3.1. Analytical vs Simulation-based DTA Approaches

Table 3 shows the algorithms involved with regards to each of the four modules forming the iterative DTA process. The table shows that a majority of the modules, except the DNL (in some instances), can be solved using analytical (e.g. solving simultaneous equations) and numerical (e.g. iterative process). In other words, the other three modules provide a closed-form solution, which is the auxiliary flows and travel times on links. The DNL, which determines link travel times, offers a variety of solution methods which can be broadly classified into analytical and simulation-based. In fact, it is the type of DNL being used in any software application which classifies a DTA model as an analytical DTA or a simulation-based DTA model. The following discussion mainly focusses on the DNL while the other components have not been covered in the scope of this paper.

Table 3: Methodologies adopted within DTA framework

Module	Algorithm used	Solution Mechanism
DNL	Congestion Functions (e.g. Bureau of Public Road (BPR)) equations, delay functions	Analytical
	Cell Transmission Model (CTM), Cellular Automata, car following, gap acceptance, lane changing models	Simulation
TDSP	Dijkstra's algorithm, label setting, label correction, heuristic methods	Numerical
PA	Method of Successive Averages (MSA), Frank-Wolfe (FW), TAPAS, etc.	Numerical
Relative Gap	$1 - \frac{SPTT}{TSTT} \leq \alpha$ where SPTT is shortest path travel time, TSTT is total system travel time and α is stopping threshold for the iterative procedure	Analytical

A key methodological difference between the analytical and simulation-based methods is that while the former requires solving an optimization problem involving a system of simultaneous equations, the latter utilizes numerical or simulation-based techniques to solve the complex traffic flow problem. The analytical approach is thus able to provide a closed-form solution, i.e. a fixed solution to the optimization problem. While this method is computationally quick to solve, it in general fails to consider the impacts of other traffic phenomena such as lane changing, bottleneck formation and formation, propagation and dissipation of queues which often take place within the link. On the other hand, the simulation-based method computes a stochastic and approximate solution to the complex real-world problem, including lane change, bottlenecks, queue spillback, using numerical and simulation techniques. As this method often requires greater input information, the computational effort required is usually large. Table 4 summarizes the merits and shortcomings of both the methods.

An appropriate solution method should be selected with considerations to the following aspects:

- Model purpose: Strategic versus operational
- Scale of the problem (i.e. study area)
- Time horizon for modelling
- Roadway facilities and modes to be studied
- Project time and budget constraints.

Table 4: Comparison of Analytical and Simulation-based DTA models

Analytical DTA	Simulation-based DTA
Method	
Involves simultaneously solving Congestion Functions (e.g. BPR equations: $\boldsymbol{t = t_0\left(1 + \alpha\left[\frac{V}{C}\right]^{\beta}\right)}$), junction delay functions etc.	Involves simulation techniques such as the Cell Transmission Model (CTM), cellular automata, microsimulation, etc. to represent traffic conditions
Pros	
• Closed-form solution • Computationally less intensive • Faster processing time even for larger networks	• Avoids oversaturated conditions of V/C > 1 • Models physical queue formation
Cons	
• Often leads to situations where V/C > 1 • Models a point queue, i.e. a vertical stack of queued vehicles which does not reflect queue spillback onto upstream links in real-world	• More computationally intense due to lack of a closed-form solution • Calibration is more onerous

3.2. Comparing DNLs based on Granularity

Based on the level of resolution/granularity, i.e. the unit of analysis of traffic flow, DNLs can be classified into three categories namely: macroscopic, mesoscopic and microscopic.

A *macroscopic DNL* generally represents traffic conditions at an entire link-level using Congestion Functions (e.g. BPR equations). As a result, a macroscopic DNL is unable to model lower-level traffic phenomena such as lane changing, bottleneck formation which takes place within a link during traffic congestion. However, this DNL being the least computationally intensive, as it can be solved analytically, is widely used in large-scale strategic transport modelling. On the other end of the spectrum is a *microscopic DNL* which models inter-vehicle interactions (e.g. car following, gap acceptance, etc.) within a link. Thus, a microscopic DNL provides the highest level of traffic resolution. This DNL utilises techniques such as Cellular Automata which model individual vehicle propagation within a link and network. However, as this DNL models individual vehicle interactions, it requires greater input parameters (e.g. driver reaction time, route choice parameters, etc.) which makes it an onerous exercise during model development and calibration. Lastly, a *mesoscopic DNL* lies within these two realms (macroscopic and microscopic) as it models a bunch (platoon or packets) of vehicles at a time. The Cell Transmission Model (CTM) and Link Transmission Model (LTM) are commonly used techniques in a mesoscopic DNL. These models are not excessively resource intensive and are able to represent queue spillback, bottleneck formation, etc. at an aggregated level (by platoon or packet).

Table 5 summarises the differences among the three DNL categories, based on the level of resolution. Furthermore, readers can refer to Bliemer et al. (2013) which provides an excellent discussion and comparison among the three.

Table 5: Comparison among macro, meso and microscopic DNLs

Item	Macroscopic	Mesoscopic	Microscopic
Modelling resolution	Link as a whole	Packets of vehicles	Individual vehicles
Technique used	Congestion Functions	CTM, LTM	Cellular automata, car following, gap acceptance, lane changing models

Solution mechanism	Analytical	Analytical or Simulation	Simulation
Complexity (model development and calibration)	Low	Medium	High
Processing time for large-scale networks	Minutes to a few hours	Few hours to few days	Several days
Data needs	Low	Medium	High
Vehicle trajectories	Approximated from link flows	Output from model	Input to model
Intersections	Approximated with delay functions	Modelled	Modelled
V/C	>1 possible	≤ 1	≤ 1
Queues and shockwaves	No	Yes, on each roadway segment	Yes, lane-by-lane
Time step	24 hour or peak period	6-second simulation intervals	1-second simulation interval
Transit	Yes	Yes	Yes
ITS (e.g. ramp metering, VMS)	No	Yes	Yes

[adapted from Duthie and Carrizales (2011)

4. Case Studies in DTA

Table 6 summarises a few practical DTA applications that have been undertaken within Australia and New Zealand and internationally. It is worth acknowledging the existence of a vast literature on DTA frameworks which have been formulated and used in the research space (see Peeta and Ziliaskopoulos (2001) for an excellent review of the academic DTA works). However, these works have not been included in this summary report to keep the discussion more relevant to practitioners. Furthermore, the applications summarised in this table correspond to trip-based models only, and a review of other modelling paradigms such as tour-based, activity-based models is not in the scope of this paper.

Table 6: DTA trip-based applications at a glance

Study	Objective of Study	Study Area	DTA Platform	PA and DNL Type
		Australia and New Zealand		
Duell et al. (2016)	Simulation-based DTA model to serve as proof of concept for the Australian cities	Sydney, AU *(42628 links, 18454 nodes, 1131 travel zones)*	Vista	Simulation-based DTA with Mesoscopic DNL
Shafiei et al. (2018)	Propose a machine learning technique to classify and calibrate the traffic flow fundamental diagrams against empirical data obtained from a large number of freeway loop detectors across the network.	Melbourne, AU *(55719 links, 24502 nodes, 2974 travel zones)*	Aimsun	Simulation-based DTA with Mesoscopic DNL
Bliemer et al. (2013) *[Research study]*	A research study aimed at a modelling framework where the traffic assignment model exhibits a good balance between traffic flow realism, robustness, consistency, accountability, and ease of use.	Gold Coast, AU *(9565 links, 2987 nodes)*	OmniTrans	Analytical DTA with Macroscopic DNL
AFC (2018)	Develop, calibrate and validate a DTA model for the large-scale Auckland network.	Auckland, NZ	Aimsun	Simulation-based DTA with Mesoscopic DNL

Study	Objective of Study	Study Area	DTA Platform	PA and DNL Type
		International		
Sadabadi et al. (2015)	Model impact of travel time reliability for both private vehicles and transit.	Portland, Oregon, US	DynusT	Simulation-based DTA with Mesoscopic DNL
Zockaie et al. (2015)	Forecast impact of congestion pricing schemes on different user classes.	Chicago, Illinois, US	Dynasmart-P	Simulation-based DTA with Mesoscopic DNL
Erdoğan et al. (2015)	Use simulation-based DTA to build statewide dynamic model.	Maryland, US *(189,000 links, 67,000 nodes)*	Transims	Simulation-based DTA with Microscopic DNL
Binkowski and Hicks (2014)	Dynamic model to aid decision-making process during staged construction of major freeway	I-96 freeway, Detroit, Michigan, US	DynusT	Simulation-based DTA with Mesoscopic DNL
Wellander et al. (2013)	Evaluate dynamic road tolling strategies.	Alaskan Way Viaduct, Seattle, Washington, US	Dynameq	Simulation-based DTA with Mesoscopic DNL
Wismans et al. (2013)	Comparing STA and DTA in the evaluation of fuel emissions and noise levels.	A12 highway, Amsterdam, Netherlands	OmniTrans	Analytical DTA with Macroscopic DNL
Duthie and Carrizales (2011b)	Bottleneck analysis at regional level	Downtown and regional areas, Austin, Texas; Seattle, US	Vista	Simulation-based DTA with Mesoscopic DNL
Parsons Brinckerhoff (2012)	Regional model for policy assessment	San Francisco, California, US *(7000 links, 3000 nodes)*	Dynameq	Simulation-based DTA with Microscopic DNL
Boyles et al. (2006)	Developed simulation-based and analytical DTA models to test congestion pricing policies	Dallas–Fort Worth, Texas, US *(56574 links, 15987 nodes)*	Vista	Simulation-based DTA with Mesoscopic DNL
Chang and Ziliaskopoulos, (2003)	Simulation-based model to evaluate transit signal priority	Chicago, US	Vista	Simulation-based DTA with Mesoscopic DNL

[adapted from Duell et al. (2016)]

5. Relevant Software Tools

Figure 4 shows a few popular software packages, mentioned in Appendix M of the Austroads Guide to Traffic Management Part-III (Austroads, 2020), on PA-DNL diagram. While the rows in this diagram represent the two types of path assignment: STA and DTA, the columns correspond to the three types of DNLs namely: macroscopic, mesoscopic and microscopic. This diagram extends the existing knowledge of the available software tools, given in AGTM Part-III, to even include their traffic assignment capabilities. A brief description of each of the software tools presented can be viewed/downloaded as a separate document in an online repository available here.

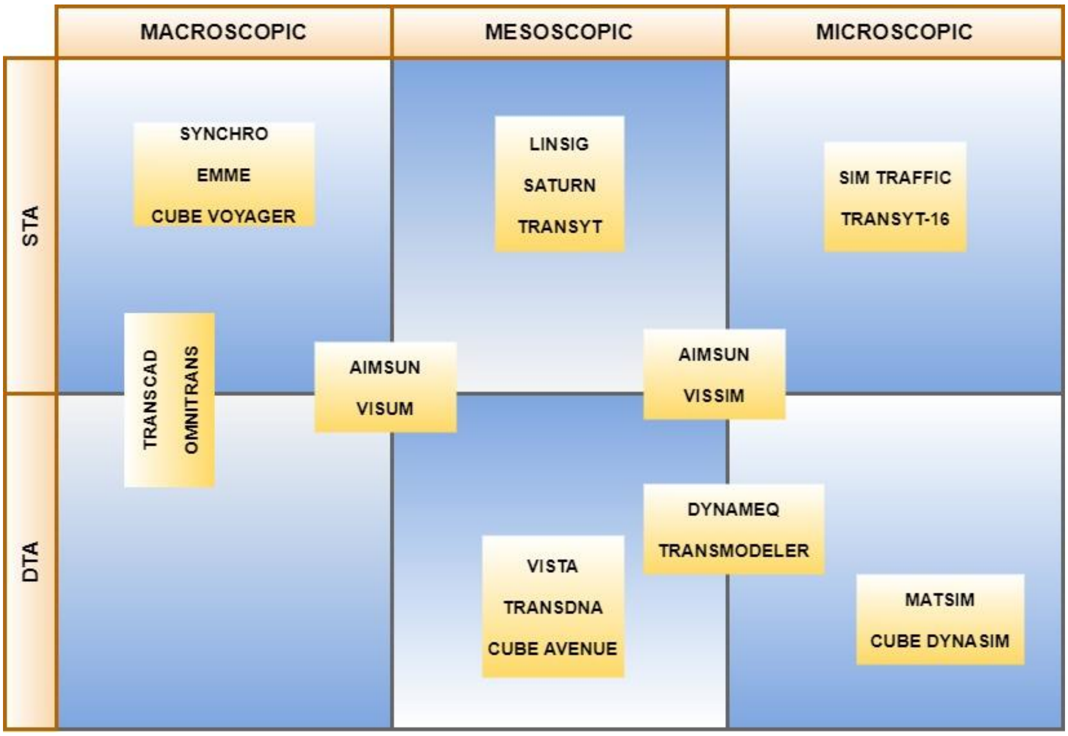


Figure 4: Classification of a few popular software packages

Figure 5 extends Figure 4 by focusing primarily on DTA oriented software tools and classifying them into analytical and simulation-based. As discussed earlier, analytical DTA usually corresponds to macroscopic DNL where travel times and delays can be computed by solving set of equations. On the other hand, simulation-based DTA refers to mesoscopic and microscopic DNLs which require simulation techniques to generate vehicle flow and the resulting travel times and delays. As shown in Figure 5, a limited number of software packages offer the analytical DTA capability, when compared to the simulation-based counterparts.

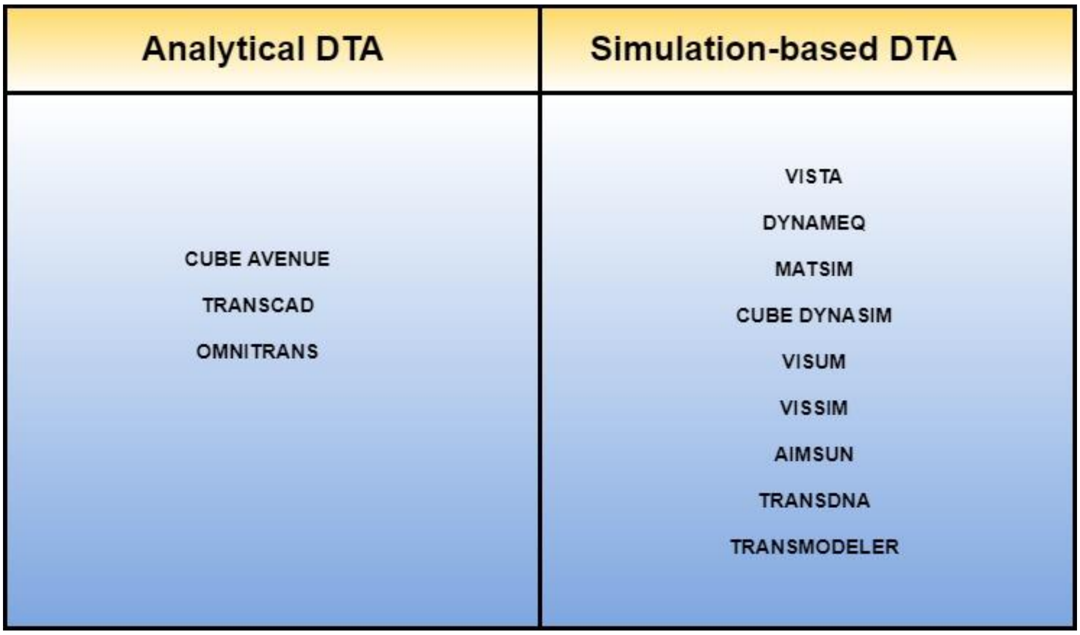


Figure 5: Classification of DTA software packages

6. Discussion

In summary, the above sections highlight the following aspects:

- STA and DTA are two widely used traffic assignment methods each having its own merits and demerits
- DNLs can be classified into macroscopic, mesoscopic and microscopic based on the level of resolution
- The choice of DNL leads to the entire DTA framework being addressed as analytical and simulation-based. In other words, macroscopic DNL in a DTA is termed analytical DTA and mesoscopic and microscopic DNLs in DTA are referred to as simulation-based
- The choice of DTA framework depends on the nature of the problem to be solved, time and budget constraints
- There exist a limited number of software packages and applications of analytical DTA when compared to their simulation-based counterparts.

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