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CRITICAL REVIEW OF TRANSPORT MODELLING TOOLS (IMPLEMENTATION OPTIONS)

National Transport Modelling Working Group

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Critical Review of Transport Modelling Tools (Implementation Options)

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Sinclair Knight Merz
ABN 37 001 024 095
590 Orrong Road, Armadale 3143
PO Box 2500
Malvern VIC 3144 Australia
Tel: +61 3 9248 3100
Fax: +61 3 9248 3460
Web: www.skmconsulting.com

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SINCLAIR KNIGHT MERZ

Glossary

4 Step Model	Transport demand model incorporating the steps of generation, distribution, mode choice and assignment
Alternative Specific Constant	Term in the utility function that reflects additional (dis)utility associated with a specific choice
Assignment	The process of assigning forecast trips to the transport network, thus modelling the route from trip origin to trip destination
Crowding Function	Mathematical relationship between load factors and the perceived cost of crowding
Distribution	The allocation of generated trips between origin zone and destination zone
Dummy Variable	Dummy variables take the values of 0 or 1 to represent the occurrence or otherwise of a categorical effect. Eg 'Carpool dummy' – 0 if trip is not a carpool, 1 if trip is a carpool
Effective Frequency	Adjusted service frequency to reflect the inability of passenger to board first departing service
Elasticity	The ratio of the percentage change in one variable to the percentage change in another variable
Frank-Wolfe Algorithm	Algorithm for solving certain classes of optimisation, based on the method of "convex combinations". Commonly used in equilibrium traffic assignment.
Generalised Cost	The sum of the monetary and non-monetary component costs of a trip
Generation	Forecast of the number of trips produced in or attracted to a particular transport zone
Headway	Gap between services, generally expressed in minutes
Household Travel Survey	Data collection exercise that often underpin strategic transport models
Incremental Model	A model that predicts the demand resulting from a change in cost, given the base demand
Load Factor	Measure of public transport vehicle loading – usually expressed as 'passengers / seats'
Logit Model	Model form used in discrete choice analysis that calculates the probability of making a particular choice given a set of input variables
LTS	London Transportation Studies. Multi-modal strategic 4-step transport model of London
Mode Choice	Process of allocating modelled trips to a mode of transport
Model Estimation	Process of estimating model parameter values (as opposed to assuming values from models used elsewhere)
Multinomial Logit	Standard logit choice model applied to a number of identified alternatives assumed to have identical and independent error terms
Perceived Cost	Costs (monetary and non-monetary) that are perceived by travellers in the course of making a trip
PLANET	UK strategic nationwide rail forecasting model
RAILPLAN	Capacity constrained assignment model of London public transport operated in EMME/2
Revealed Preference	Technique used to estimate model parameters (typically a value of some attribute) from observing behavioural responses
Stated Preference	Technique used to estimate model parameters (typically a value of some attribute) from stated behavioural responses

Tour	Unit of travel that typically incorporates an outbound and return trip
Trip	Unidirectional journey from origin to destination
Utility	Measure of satisfaction from consuming a good (making a trip)

Executive Summary

Traffic congestion is an ongoing concern in major urban areas around the world and Australian capital cities are facing similar challenges. Most Australian states and territories have developed strategic transport demand modelling (STDM) tools to better understand the influences on rising urban traffic congestion in their capital cities and to help them respond by testing and improving approaches to congestion management.

A range of congestion management interventions can complement road improvements by influencing patterns of demand on our roads. Interventions might include increased provision of public transport services, public behavioural change programs, careful land use planning to reduce travel demand, staggering of work hours, and application of road user charges.

Road pricing is not new. Parking charges are now familiar in most Australian city centres, while toll charges apply on key transport links in Melbourne, Sydney and Brisbane. Many cities also vary public transport fares between peak and off-peak periods. As urban areas and congestion management have become more complex, so has the importance of examining the capabilities of modelling tools to help decision-makers better examine and assess the impacts of demand-side interventions. This is part of the continual evolution of modelling to ensure they reflect good practice.

STDM tools are used for assessing the broad impacts of infrastructure upgrades and policy decisions on road and public transport operation. These tools have some capacity to model mitigation measures to rising urban traffic congestion. STDM may be used in tandem with detailed project models, which consider the smaller-scale impacts of changes to the network.

A critical review of STDM tools in various Australian capital cities was commissioned in February 2009 by the Commonwealth Department of Infrastructure, Transport, Regional Development and Local Government for the inter-jurisdictional National Transport Modelling Working Group. It was a national study, focussing on those cities experiencing significant congestion pressures. The task was to critically review state and territory STDM tools to determine their capacity to model pricing approaches to congestion management, in order to improve decision-making tools.

The critical review found that, while each model can estimate basic responses to road pricing, each model is limited in its ability to:

- differentiate the responses of different population segments;
- calculate the potential transfer of trips between peak and off-peak periods; and
- consider capacity constraints on public transport.

Addressing these limitations would allow more accurate transport modelling of demand management approaches to urban congestion schemes (whether pricing or non-pricing based). This will be particularly so where effective costs or charges vary by time-of-day or road user type. In cities where the public transport system is operating near its capacity during the peak periods, the models may over-represent the shift of trips from car to public transport modes.

The NTMWG subsequently commissioned this further study to research implementation options to overcome these limitations. This report is the result of further investigation into best practice and implementation issues in time-of-day choice and public transport crowding.

Australian Models

Australia's STDM all adopt variants of the classic four-step strategic transport demand modelling structure:

- **Trip generation** determines the number of trips produced from and attracted to each geographic area.
- **Mode choice** determines the proportional split of trips by each transport mode.
- **Trip distribution** (or destination choice) determines the linkages between the origins and destinations of each trip.
- **Trip Assignment** determines the road routes and public transport services used between each origin and destination.

International Good Practice

Time-of-day choice and public transport crowding have only been implemented in a handful of STDMs worldwide. Indeed, as modelling techniques, they represent complex and leading edge methodologies which form the logical evolution of STDMs in order to address today's transport problems. The models of Auckland, Wellington and the West Midlands (UK) are leading examples of where time-of-day choice has been implemented within a strategic modelling framework.

With regards to public transport crowding, the primary examples of implementation are in the various strategic London models. A number of US cities such as San Francisco and Washington have also included crowding.

In the US there has been a recent move towards the inclusion of activity choice and household "lifestyle" patterns in demand models (an adaptation of the traditional four-step structure). While four-step models make use of aggregated household attributes, such as car ownership and household structure, an activity-based model attempts to synthesise the activity patterns of individuals within each household. This potentially provides greater flexibility in modelling the time-of-day activity choices of individuals and their associated travel. While there has been

ongoing research into activity-based methods since the late 1980s, the methods have not been widely applied outside the US.

Models from London, Auckland and Wellington were chosen as case studies for this report as these models have successfully incorporated time-of-day choice or public transport crowding within the 'four step' structure; the same structure that is employed by the Australian strategic models.

Time-of-Day Choice – Key Findings

The relative sensitivity of traveller choices (mode, time-of-day and destination) are reflected by the order in which these steps occur in the strategic model's decision hierarchy. International best practice is to implement time-of-day choice before trip distribution, or destination choice, in the hierarchy. This means that the distribution applied in the time choice of the return leg must be consistent with that of the outward leg, which is achieved by considering the associated trips being made as a single 'tour' (a tour based approach), rather than as a collection of individual trips (a trip based approach). The majority of the existing Australian models operate on a trip based structure.

The effort required to convert existing Australian trip-based models to a tour basis may prove to be only moderate. The required data already exist in the form of household travel surveys. As a point of reference, the Auckland Regional Transport Model, which was originally a trip-based model, was converted to a tour-based model for the purposes of incorporating time period choice modelling. With Auckland's model, there was no need to recalibrate the mode choice and distribution models. If that also proves to be the case for Australia, the effort needed to implement time period modelling in each jurisdiction will be greatly reduced.

Implementing Time-of-Day Choice

Time period choice could be incorporated into the present Australian models in several ways. These range from simplified approaches that could be implemented quickly to more theoretically complete approaches that would be implemented in the longer-term.

- **Short term solutions** – use a simplified time period choice model that can be "bolted on" to existing four-step models without disturbing the current structures. The simplified model can be substituted for the fixed time period factors currently applied in the jurisdictions' models. Although not theoretically ideal, this technique was applied successfully in Wellington to test simple congestion pricing scenarios.
- **Medium term solutions** – recast the models to use tours, rather than trips, and apply a time period choice model prior to distribution. Although requiring significant restructuring of the models, this process can be applied without the need to recalibrate existing mode choice and distribution models (typically a time-consuming and complex task). This process was applied successfully in Auckland and used to test a range of congestion pricing scenarios. At a later

stage, Australia-specific data collection would be undertaken to determine local valuations of time period changes. These values would be used to more accurately calibrate time period models to Australian conditions.

- **Long term solutions** – In the longer term, other model structures, such as activity-based approaches might be considered when the methods for applying these approaches have been effectively applied and verified in a range of international contexts and can therefore be adjudged to be international best practice.

Public Transport Crowding – Key Findings

International best practice is to apply crowding penalties based on the assigned passenger loadings of public transport vehicles. These penalties add a perceived cost to a trip to represent the discomfort of travelling in crowded conditions. Because these costs are dependent on load factor, multiple iterations of the public transport assignment are required in order to reach a converged position.

Multiple iterations of the public transport assignment cause model run times to be extended. For some models this will be significant. It is therefore recommended that analysis be undertaken by each jurisdiction to understand the level of crowding now and in the future. A crowded public transport assignment should only be run where crowding is found to be an issue.

Implementing Public Transport Crowding Models

Public transport crowding models typically take into account the discomfort experienced by passengers in crowded conditions and the reduced level of service when passengers cannot board overcrowded vehicles. These "inconvenience attributes" are incorporated into the assignment step of the four-step model which allocates passengers to public transport services.

The two mainstream STDM software platforms used in Australia (Cube and EMME) both support public transport crowding. Implementation is relatively simple; modellers need to supply suitable crowding parameters and then activate the crowding functionality within the software. Public transport capacities must be accurately represented in the model and crowding costs fed back to the mode choice and distribution steps. Valuation of crowding attributes is fairly well documented (see, for example, Douglas Economics 2006).

Public transport crowding models are iterative – in other words, they need to be run multiple times to achieve convergence of the outputs. Because a large number of iterations (say, 10-30) may be needed, this process will extend model running times. While this is not expected to be a significant issue for the Perth, Adelaide and Canberra models, the Sydney, Melbourne and Brisbane models may be disadvantaged, with run times possibly exceeding 1-2 days.

Public transport crowding models could be implemented in several stages:

- **Short term** – assess the need for crowding models and ensure public transport lines and capacities are accurately coded into the model.
- **Medium term** – implement crowding models with attributes based on published values.
- **Long term** - obtain jurisdiction-specific crowding valuations through primary research and investigate ways to streamline model processes in order to reduce model run times.

Recommendations

As the critical review found, all of the Australian models include the basic functionality needed to model road-pricing schemes successfully. Each model can estimate basic responses to road pricing and other non-price demand management approaches. However, the models are presently limited in their ability to reflect road users' time-of-day choice and the impacts of public transport capacity constraints. These limitations mean that it will be difficult to model more sophisticated approaches to congestion management such as time-specific road-user charging.

This further study into the implementation options has found that Australia's major urban STDMs can be enhanced to assess more complex congestion management interventions. The study has identified viable short and medium-term enhancements to the models, based on good international practice.

While time-of-day choice may be considered in all jurisdictions where time-dependent charging is to be tested, public transport capacity constraints may only be needed in those cities that are expected to experience significant public transport crowding within their desired planning horizons. The practical impacts in terms of software run-times can be significant.

In the longer term, national STDM development may wish to consider a different basis for modelling that could lend itself to even greater sophistication and integration with other infrastructure planning. Jurisdictions should keep abreast of emerging STDM approaches. An example is activity based modelling, which has been theoretically developed and applied in limited circumstances in the US, offers promise for consideration in Australia if it proves to be of international best practice in the future.

The following table summarises the recommendations for each jurisdiction's model. Whilst the recommendations below are jurisdiction specific, there is considerable commonality between the various models. The collaborative approach demonstrated by the NTMWG should therefore be continued so that the jurisdiction groups can share research and information, and ensure a consistent approach wherever possible.

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- **Table 1 Jurisdiction Recommendations**

Jurisdiction	Recommendations
Sydney	▪ Because the STM already uses a tour-based approach, the addition of a time period choice component should, in theory, involve little restructuring. However, because the model is differently structured to those of the other jurisdictions, a more detailed assessment of the model will be required before an Auckland-style approach can be implemented. ▪ With current crowding levels in Sydney, it is likely that some form of crowding model will be required. Given the long model run times, investigations should be carried out by the jurisdiction to see whether crowding can be omitted from some iterations of the model in order to speed up run times.
Melbourne	▪ Model structure is suitable for employing the Auckland methodology. Recent household travel survey is expected to contain sufficient sample size for developing tour time groups. ▪ Crowding is an acknowledged issue in Melbourne. A method for minimising the impact of crowding on model run times is required.
Brisbane	▪ Model structure is compatible with the Auckland methodology. The jurisdiction needs to check that sufficient local household travel data is available to estimate tour time groups and related time period factors. ▪ Components of public transport crowding have already been implemented. Given the long model run times, investigations should be carried out by the jurisdiction to see whether crowding can be omitted from some iterations of the model in order to speed up run times.
Perth	▪ Existing model is well suited to Auckland methodology. The jurisdiction needs to ascertain whether suitable data already exists. ▪ It is recommended that analysis on capacities and demand volumes be undertaken to enable the jurisdiction to form a view as to whether crowding is an issue.
Adelaide	▪ The Auckland methodology appears to be a good fit for this model. Peak hour factors provide the opportunity to model time period choice at a finer (more microscopic) level of time segmentation. ▪ Analysis is required to decide whether capacity constraints are an issue for all public transport modes. Appropriate crowding functions applicable to light rail should to be identified.
Canberra	▪ Implement an incremental choice model that factors the peak period car matrices prior to assignment based on the change in the peak/off-peak cost differential. ▪ Achieve good public transport validation in the recalibrated 2006 model. Conduct analysis of current and future volume to capacity ratios to determine whether crowding should be modelled.

1. Introduction

1.1. Background

On 7 November 2008, the Australian Transport Council (ATC) agreed to review the transport modelling of congestion pricing scenarios. Ministers agreed that jurisdictions will cooperate in the transport modelling of congestion, transport network performance, socio-economic and emissions outcomes of various targeted theoretical congestion pricing scenarios (with the scenarios to be determined within the project). The transport modelling work is being undertaken by a National Transport Modelling Working Group (NTMWG), comprising experts from jurisdictions, the Bureau of Infrastructure, Transport and Regional Economics (BITRE), the Commonwealth Department of Infrastructure, Transport, Regional Development and Local Government (DITRDLG) and chaired by Victoria.

In implementing ATC's request, the NTMWG undertook a critical review of the capability of existing state and territory capital city strategic transport models to model pricing approaches to congestion management, in order to improve decision-making tools. The review was informed by a consultancy ('Critical Review of Transport Modelling Tools', March 2009) completed for the NTMWG by Sinclair Knight Merz. The review found that the existing Australian models had limitations in forecasting time period choice (peak spreading) and public transport capacity constraints (crowding), and indicated that these improvements may enhance the ability of Australia's strategic transport demand models to evaluate congestion pricing scenarios.

The Standing Committee on Transport (SCOT), comprising transport and roads agency heads, has agreed to the need for further work to investigate what would be needed to implement time period choice and public transport capacity constraints in the jurisdiction models.

This report is the outcome of that further work, providing a review of best practice and implementation issues in time period choice and public transport crowding. The purpose of the report is to assist transport agencies to plan and implement these improvements so that congestion pricing scenarios can be modelled satisfactorily in each jurisdiction.

1.2. A Transport Modelling Primer

Australia's capital city models all adopt variants of the classical four-step transport demand modelling structure whereby:

- **Trip generation** determines the number of trips produced or attracted to each geographic unit (zone). Trip rates are typically expressed as a function of land use and household demographics, and are categorised by purpose (for example, work, education, shopping).

- **Trip distribution** determines the linkages between trip productions and attractions, and represents travellers' choice of destination from all of the alternatives available. Most trip distribution models assume that travellers will be more attracted to closer opportunities and larger trip generators. So shopping trips, for example, might tend to be attracted to nearby shopping precincts or to larger, more distant shopping centres.
- **Mode choice** determines the proportional split of trips by each transport mode. At the strategic modelling level, the main mode split is between private car and public transport. The choice of public transport service (eg. bus, train, ferry) is usually handled by the assignment model.
- **Assignment** allocates trips to the available routes linking each origin and destination. Usually separate assignments are undertaken for private vehicles (highway assignment) and public transport. The highway assignment is based on optimising the route choice of private vehicles and the public transport assignment apportions travellers to public transport services based on travel times, waiting times and interchange penalties.

While these four steps form the backbone of the modelling process, there are several other important considerations in the four-step process:

- **Land use forecasts** provide the essential inputs for the trip generation step. Typically, the region is divided into zones, each with relatively homogeneous land use, and forecasts of population, employment and educational enrolments made for each zone.
- An accurate representation of the **road and public transport networks** are important to calculate the costs of travel between each origin and destination. In the case of public transport, service frequencies and routes (lines) are generally used by strategic models to represent the available level of service.
- The **order of the trip distribution and mode choice** steps may be different for each trip purpose. In the classical model, trip distribution often preceded mode choice, but current best practice is to evaluate the relative sensitivity of the mode and destination choices, and order the steps so that the least sensitive choice occurs earlier in the process. This ordering is important to maintain the mathematical rules of the choice models[1] used for mode and destination choice.
- The trip generation, distribution and mode choice steps are commonly (but not always) implemented on a **24-hour basis**. In most of the Australian models[2], fixed factors are used to allocate travel to each period of the day.

[1] These models are commonly implemented using a nested multinomial logit formulation.
[2] The Canberra model includes only the AM peak period and therefore does not allocate trips to multiple time periods. The current Melbourne model applies time period factors between distribution and mode choice, with separate mode choice models being implemented for each time period.

The Sydney model differs from the other jurisdiction models in the way that travel is represented. While the other jurisdictions use **trips** as the basic unit of travel, the Sydney model uses **tours**. A trip is defined as a single journey between an origin and destination, whereas a tour encapsulates the outward and return journeys that make up a person's travel across the day.

The tour-based structure introduces extra complexity to the modelling process, but provides benefits when implementing time-of-day choice models. The linkage between the outbound and return trip is important in the consideration of the duration of an activity (such as work or education), which is not explicitly taken into account by trip-based approaches.

The remainder of this chapter provides an overview of time-of-day choice and public transport crowding modelling.

1.3. Time-of-Day Choice

Time-of-day choice models become important when considering differential charging for peak and off-peak periods.

The literature in time period choice modelling usually distinguishes between "micro" and "macro" time period shifts:

- **Micro shifts** occur when drivers change their departure time within the same time period. For example, a micro shift might occur when a commuter decides to leave home half an hour earlier to avoid the most congested part of the morning peak.
- **Macro shifts** refer to the transfer of trips between time periods. A macro shift could occur when, for instance, a driver decides to go shopping in the middle of the day (off-peak) to avoid congested roads in the evening peak. Typically, discretionary trips, such as shopping trips, have more propensity for re-timing than non-discretionary trips such as the commute to and from work.

In some respects, this distinction is not really relevant from the driver's point of view; a micro shift is simply a smaller change in departure time than a macro shift. However, from a modeller's point of view, the distinction is important, as each time period is typically modelled with different network conditions and travel costs.

This report focuses on macro time shifts, as strategic transport models are generally not designed to model micro shifts within a peak period. Most strategic models consider averaged trip demands and network costs within each time period. In addition, macro shifts are likely to be the principal impact of differential peak and off-peak congestion pricing, so a focus on macro shifts seems appropriate.

Most time period choice models incorporate a multinomial logit (MNL) model[3] to allocate travel proportionally between each time period. The MNL model uses the relative costs between time periods to determine the probability of travel within each period. Much of the debate on these models has centred around the correct placement of the time period choice within the four-step hierarchy. Although time period choice models are still somewhat rare, current consensus (in the UK at least) is for the macro time period choice decision to occur early in the four-step process, commonly before the distribution step[4]. These considerations are discussed in further detail in the next chapter.

1.4. Public Transport Crowding

Congestion pricing schemes will potentially contribute to a mode shift from private car to public transport. The increased demand for public transport may contribute to crowding on public transport services. If passenger volumes approach the network's capacity, the take-up of public transport may be suppressed to some extent.

In Australia it is standard practice for public transport assignment procedures to be unconstrained. In other words, the capacity of the public transport network is not taken into account when determining demand on public transport services. This has historically been considered a reasonable approach as, compared to cities like London, high levels of crowding have not been experienced in Australian cities and the networks have available capacity. However, factors such as continuing population growth, fluctuations in fuel prices and improvements to public transport networks have contributed to recent sharp increases in public transport patronage in some Australian cities. In some areas, this has led to persistent crowding on public transport services during peak periods.

To account for crowding, models need to incorporate the perceived inconvenience of travelling on crowded services. Typically this is done by applying a cost penalty to the parts of a passenger's journey that occur in crowded conditions. The cost penalty is effectively a valuation of the passenger's discomfort and the reduced likelihood of being able to board the passenger's preferred service.

Crowding procedures are incorporated into the main transport modelling software packages used in Australia (Cube and EMME), though these features are not currently used in the jurisdictions' strategic models. Although implementation is relatively straightforward, the crowding process needs to be iterated in order to achieve convergence. This will have an adverse effect on model

[3] See for example, Ortúzar, JD and LG Willumsen (2001), *Modelling Transport*, John Wiley & Sons Inc.
[4] See WebTAG.

running times, potentially extending analysis times beyond 1-2 days for the larger jurisdiction models. Implementation and run-time considerations are discussed in more detail in Chapter 3.

1.5. Study Methodology

In order to form recommendations on time period choice and public transport crowding for the Australian models, the following steps were undertaken (see Figure 1).

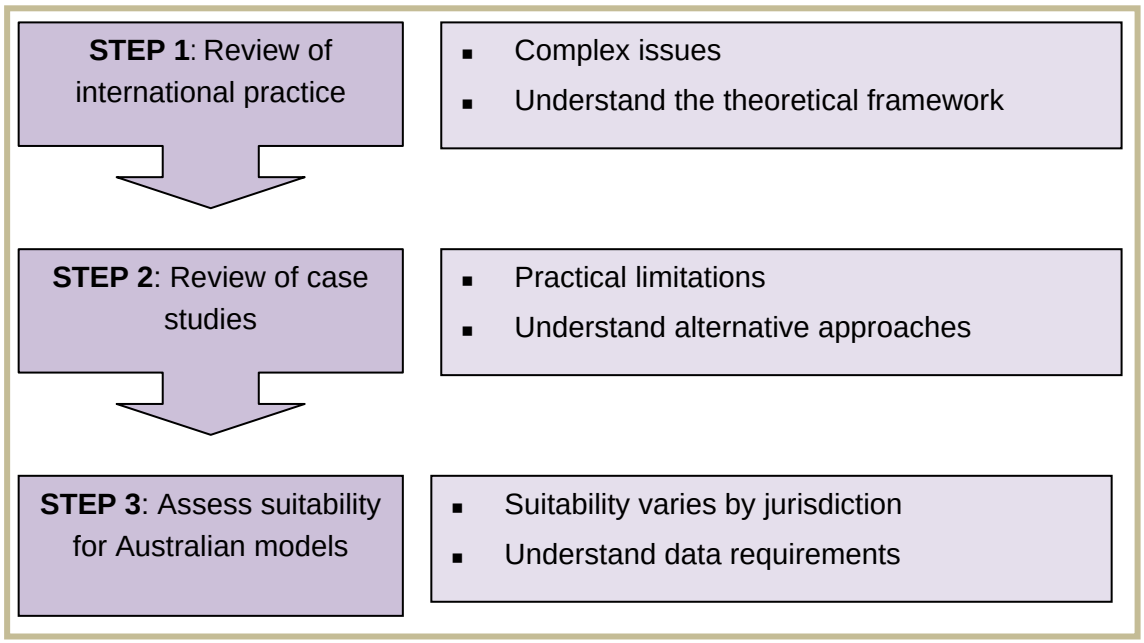


Figure 1 Methodology Flow Chart

The review of international practice was largely based on the published literature, but also included correspondence with John Bates, a leading researcher and practitioner in the field of time-of-day choice modelling and crowding. The review primarily covered UK, European, US and New Zealand research and practice, although the study team noted that the bulk of the published literature originated from the UK and Europe.

The review included case-studies where time period choice and/or public transport crowding have been successfully implemented in urban transport models. Because an understanding of implementation issues required considerable technical detail, the study team mainly drew on SKM's experience of implementing the Auckland Regional Transport Model, Wellington Transport Strategy Model and London Docklands Light Rail Model where technical documentation was readily available.

Chapter 2 and Chapter 3 of this report cover the review of international practice and case studies. Chapter 4 provides a preliminary discussion of how the modelling enhancements could be applied to the Australian capital city models.

2. Time-of-Day Choice

2.1. The Theory

In considering time-of-day choice modelling techniques, it is useful to first define common terms used in the literature. These terms are explained in Table 2.

- **Table 2 Time-of-Day Choice – Key Terms**

Term	Meaning
Micro Time Choice	The choice of departure time interval within a peak period (e.g. choosing to travel 15 minutes earlier to avoid the busiest part of the peak).
Macro Time Choice	The choice of time period in which to travel (e.g. choosing to travel in the interpeak to avoid road-charging in the AM peak).
Peak Spreading	In the modelling literature, peak spreading usually refers to the re-timing of trips from the busiest part of the peak to the shoulder of the peak.

Two aspects of time period choice modelling theory are commonly addressed in the literature. These are:

a) **The form of the choice model**, i.e the model structure, explanatory variables and sensitivity parameters; and

b) **The hierarchical placement of the model** within the four-step strategic model, e.g. before or after mode choice.

The first aspect is very much an academic question and it may be that the optimal form is impractical for incorporating into strategic transport models. Nonetheless it is appropriate that this report briefly discusses the various models used in the literature to forecast time-of-day choice.

2.1.1. Choice Models

Almost without exception, the modelling of discrete time of departure choices in the literature is undertaken through the application of a multinomial logit (MNL) model. In essence, a logit model determines the probability that a certain choice will be made from a set of available alternatives. The probability is based on the "utility" of each alternative, where the utility is a measure of the perceived attractiveness of the alternative. In transport models, utility is usually expressed in terms

of a cost, which incorporates travel times, distance, out-of-pocket costs and other attributes of a traveller's journey.

In a time period logit model, the available alternatives are the time periods defined in the model. In simple models, this may be a simple choice between individual time periods (e.g. AM peak, PM peak, off-peak). In more refined models, the choices may be between combinations of time periods (e.g. outbound journey in the AM peak, return journey in the PM peak). Note that this involves a tour-based approach to modelling.

The model assumes that travellers associate a certain utility with travelling at a particular time; travellers choose departure times that optimise their utility. Typical variables that are included within the utility measure are:

- preferred departure/arrival time;
- "schedule delay" (i.e. the difference between the preferred and actual times of departure/arrival);
- duration of activity;
- travel duration;
- travel cost; and
- socio-demographic indicators such as income group, household size, age etc.

The general conclusions from this work indicate, perhaps unsurprisingly, that a traveller's sensitivity to changes in departure time is significantly related to the size of the time shift, with smaller (micro) time shifts more likely than larger (macro) time shifts.

The model as described above would not be directly implemented in a strategic model, as information about preferred departure times, schedule delay and activity durations are generally not readily available. With its high level of data requirements, this form of model is more suited to project level analysis of micro time choice. A key issue when modelling micro time choices is the requirement for travellers' preferred departure (or arrival) times; these are not available within strategic models.

However, the concept has been adapted to suit large scale transport models (Hess, Rohr, Daly & Hyman, 2007). In this study, four groups of parameters were included in the utility functions:

- marginal utilities of travel time and travel cost;
- socio-demographic dummy variables (education, age and sex);
- time period constants (necessary in the absence of schedule delay information); and
- mode-specific constants (applied to public transport when the model is of simultaneous mode and time choice).

The results of this analysis suggested that there is more substitution between alternative time periods than between alternative modes, showing that travellers are more sensitive to departure time than their choice of mode. The results also indicated that the sensitivity is greater for switches between shorter than between longer time periods. A model for switching to shoulders of the peak (i.e. a smaller shift in departure time) would therefore have greater sensitivity than a model for switching between peak and off-peak periods. These findings were consistent with earlier models estimated with time period data.

Other studies have reported further attributes that may affect departure time choice. In a 2004 study, Ettema, Ashiru and Polak (2004) state that departure time models should take account of the following:

- attributes of journeys (such as travel time and costs) undertaken at various times of the day,
- changes in the duration of activities, and
- changes in the timing of activities.

Here, the implication is that the timing and duration of activities affect a traveller's ability to change their departure time, and will affect their sensitivity to congestion charging. For example, an office-based employee who works in a full-time day job may be constrained to travel in the AM and PM peaks, even though the cost of travel is higher during these time periods.

The flexibility of travelling times was addressed in a study looking at departure time choice in response to the Stockholm congestion charge. Kristoffersson (2007) found that it was beneficial to segment the population into three groups based on schedule flexibility and value of time:

- commuter with flexible schedule and other trips;
- commuters with fixed schedule and school trips; and
- business trips.

Using both stated and revealed preference data, a departure time and mode choice model was estimated in a mixed logit framework and later connected to a dynamic assignment model.

There are useful lessons, in terms of segmentation, to be learnt from published studies that can be applied to strategic models, however this sort of approach is more appropriate for project-specific or customised models. In Section 2.1.3, we look at some practical applications of how time-of-day choice modelling has been incorporated into strategic transport models in New Zealand.

2.1.2. Model Structure

The traditional four stage transport model is structured as depicted in Figure 2. The thin arrows represent the feedback of travel costs to earlier steps in the model. Note that that the order of the

distribution and mode choice modules varies (or may be simultaneous) and the cost feedback loop does not always feed back into trip generation.

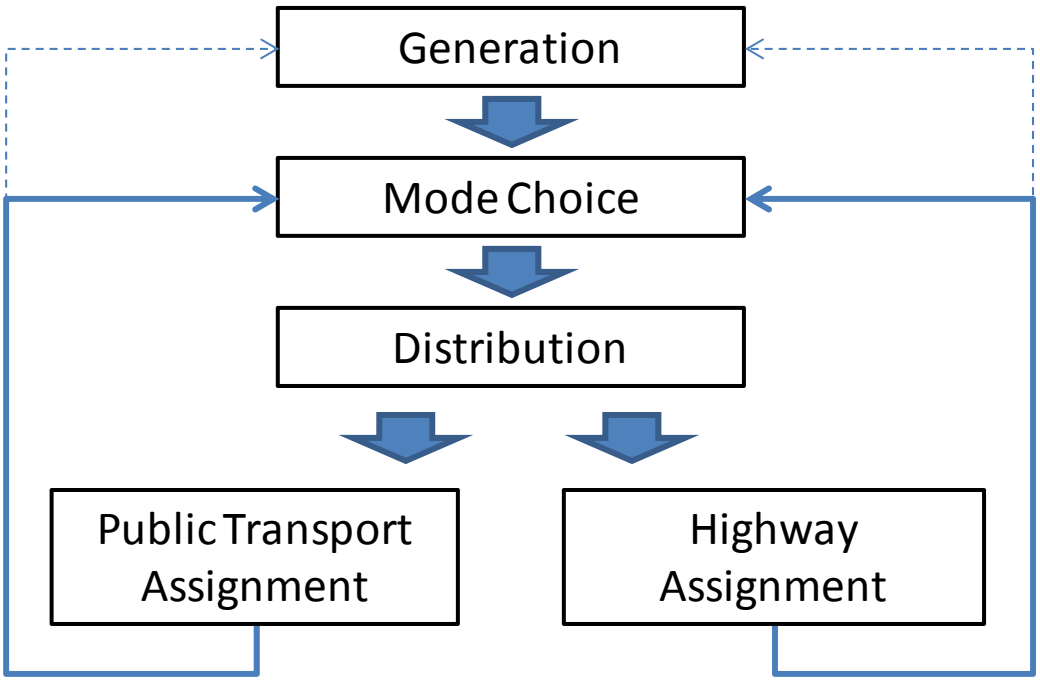


Figure 2 Traditional Four-Step Transport Model Structure

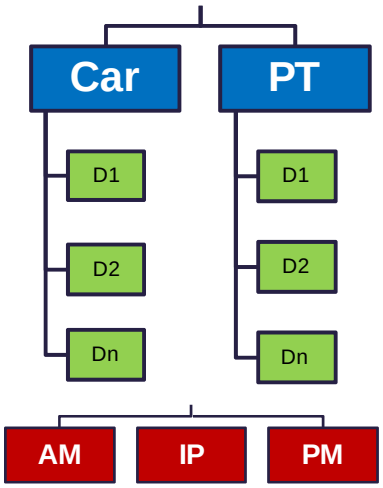
Typically, generation, mode choice and distribution are calculated on a 24 hour basis with fixed time period factors applied before assignment. In some cases (such as the current Melbourne MITM), time period factors are applied earlier in the process.

There are thus three choices of where a time period choice model should be included in the above model structure:

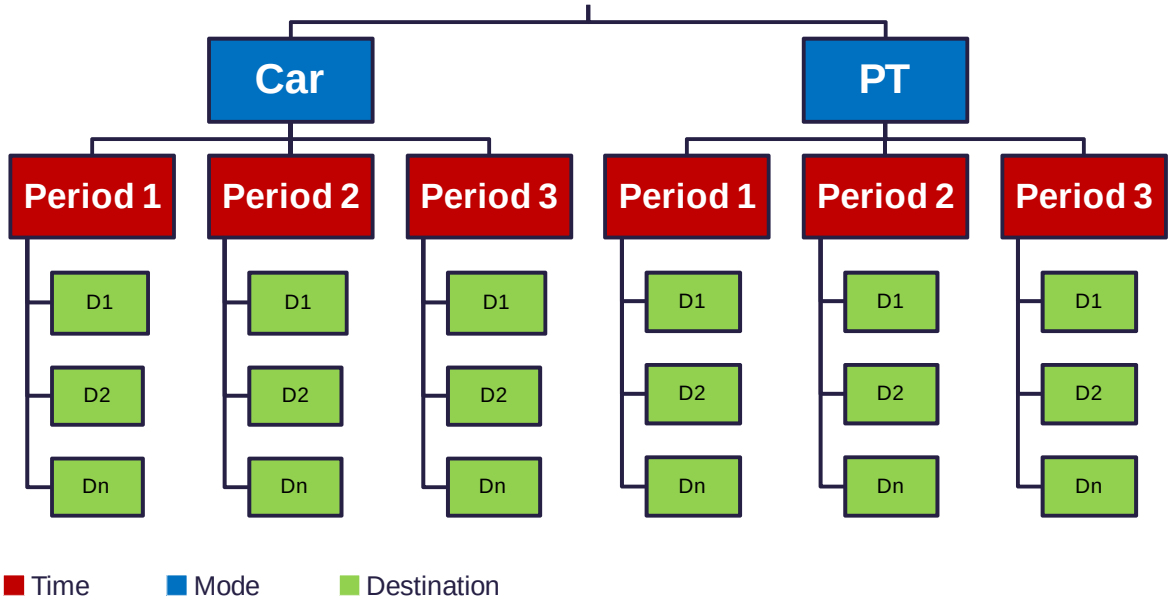
a) Before assignment (generally where fixed factors are currently applied – see Figure 3);

b) Between mode choice and distribution (see Figure 4); or

c) Before mode choice and distribution (see Figure 5).



- **Figure 3 Time Period Choice Before Assignment**



- **Figure 4 Time Period Choice Between Mode Choice and Distribution**

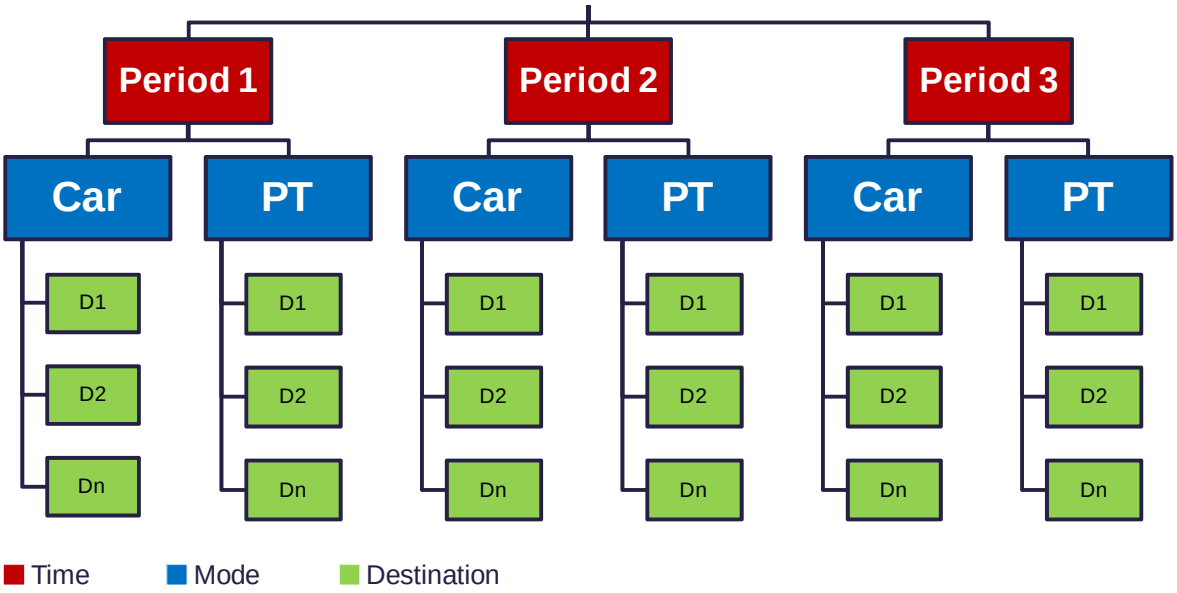


Figure 5 Time Period Choice Before Mode Choice and Distribution

Current UK WebTAG guidance (UK Department for Transport 2009) recommends that time period choice be placed high in the hierarchy – normally **before** the distribution step:

- In models where distribution *precedes* mode choice, time period choice would be positioned immediately after the trip generation step, resulting in period-specific distribution and mode choice models.
- In models where distribution is *after* mode choice, time period choice would fall between mode choice and distribution, resulting in a 24-hour mode choice model and period-specific distribution models.
- In models with simultaneous distribution and mode choice, time period choice would precede the combined step, resulting in a period-specific distribution/mode choice model.

While this guidance is available, time-of-day modelling is not yet common practice, and there are very few reported examples of implementation at a city-wide scale. Strategic modelling best practice is to evaluate the relative sensitivity of the mode and destination choices, and order the steps so that the least sensitive choice occurs earlier in the process. The same principles apply when incorporating time of day choice into an existing model structure: the positioning of the time of day choice model should reflect the relative sensitivity of time of day choice, mode choice and destination choice. Each jurisdiction modelling group should check the relative sensitivity of the model choice components before implementing the methodology.

In order to meet general requirements for symmetry between outward and return trips, it is necessary to consider tour-based approaches when modelling time-of-day choice before trip distribution[5] (Gordon, Daly, Bates, Oladeinde, 2007). Section 2.2.2 discusses an alternative **tour time group** approach embedded within a trip based model.

2.1.3. Alternative Structures

In the US there has been a recent move towards the inclusion of activity choice and household "lifestyle" patterns in demand models (an adaptation of the traditional four-step structure). Cities that have adopted this approach include[6]:

- Portland (METRO);
- San Francisco (SFCTA);
- New York (NYMTC); and
- Columbus (MORPC).

While four-step models make use of aggregated household attributes, such as car ownership and household structure, an activity-based model attempts to synthesise the activity patterns of individuals within each household. This potentially provides greater flexibility in modelling the time-of-day activity choices of individuals and their associated travel. However, while there has been ongoing research into activity-based methods since the late 1980s and 1990s, the methods have not been widely applied outside of the US.

Activity-based analyses have been broadly defined by the US Transportation Research Board (2007) as follows:

[5] A tour represents the linked outward and return journeys by a traveller, for example travel to work in the morning and the commute home in the evening. Note that when modelling demand on a 24 hour basis, some consideration should be given to tours (if only informally) to ensure symmetry of outward and return journeys.

[6] See 'Transportation Research Board (2006) Innovations in Travel Demand Modelling, Conference Proceedings 42, Volume 2: Papers' for details.

> *Activity-based models differ from previous travel forecasting methods in concept and structure. The approach recognises the complex interactions between activity and travel behaviour. The conceptual appeal is that the need and desire to participate in activities form the basis of the model.*
>
> *The difference between activity-based models and the current four-step approach include a consistent and continuous representation of time, a detailed representation of persons and household time-dependant routing, and micro-simulation of person travel and traffic. (Transportation Research Board, 2007)*

The immediate future of activity-based approaches is, perhaps, exemplified by the TRANSIMS project developed by the Los Alamos National Laboratory in the US (US Department of Transportation 2009). The TRANSIMS model differs from conventional four-step approaches in that it synthesises the activities of individuals within households in order to derive trip-making behaviour. Each individual's trip-making behaviour is simulated on the network to build a picture of overall travel activity.

Conceptually, the continuous representation of time in activity models would suggest that they are well placed to model time-of-day choice as a behavioural response to congestion pricing. In practice, however, this assertion has not been tested. For example the New York Best Practice Model (NYBPM), which is an activity-based model, includes a time-of-day choice module. However, the current version of the NYBPM uses fixed factors to allocate trips to time periods. While there is a desire to incorporate more flexible timing considerations, this is yet to be implemented.

Activity models are still in their infancy although they have been applied in several major US cities as noted above. However "there is no consensus yet that they should be widely adopted" (Transportation Research Board, 2007). These models therefore represent 'leading edge research' rather than 'international best practice'.

The cost of these approaches is large and, until evidence shows that they provide significant value over and above the traditional four-stage approach, they are not recommended for Australian application in the short to medium term. When activity-based techniques have been verified in a wide range of international contexts (and there is appropriate software, data and computing power to support these approaches), it may be appropriate that the jurisdiction modelling groups consider these as an option to supplement the present four-step approaches.

2.2. In Practice

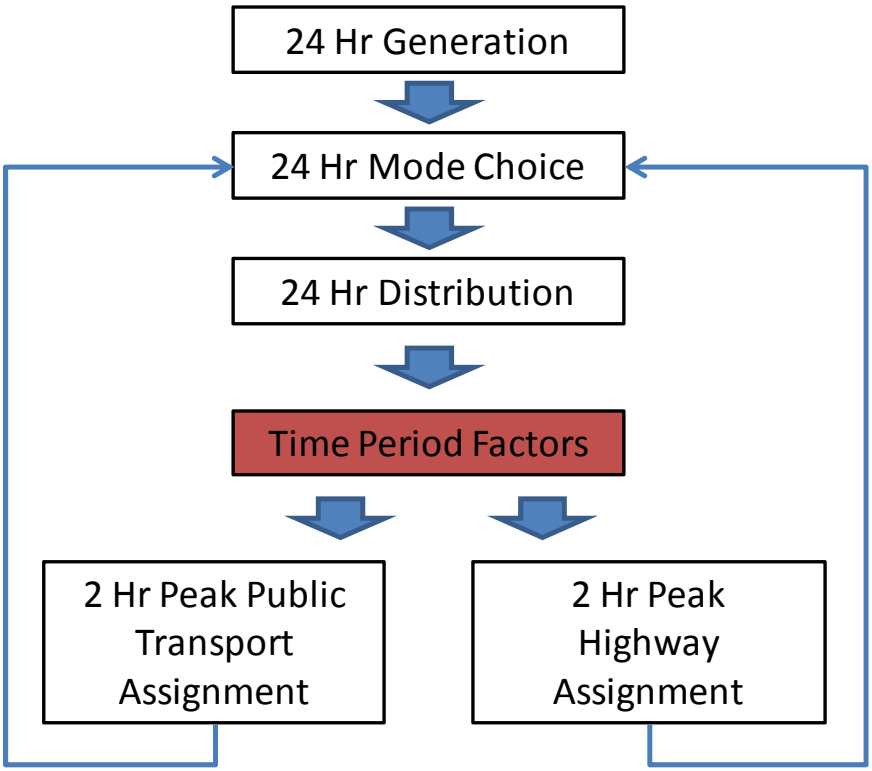
Modelling time-of-day choice is not common practice within strategic transport models and there are only a limited number of international examples to draw upon.

This section considers actual examples of where time period choice has been successfully implemented into strategic transport models. The report focuses on Wellington and Auckland models for the following reasons:

- they provide two alternative approaches compatible with Australian models;
- in both cases the time-of-day choice functionality was implemented in the context of modelling the impact of congestion pricing policies;
- both methods have been implemented within the last six years; and
- full technical documentation was available to the study team.

2.2.1. Wellington (NZ)

The Wellington Transport Strategy Model (WTSM) generates 24 hour trips by purpose and mode in production/attraction form (trips are 'produced' at home and 'attracted' to workplaces, schools, shops etc) Time period factors allocate the trips in these matrices to three time periods (AM peak, interpeak and PM peak) and converts them into origin and destination form prior to assignment. This structure of the Wellington model is illustrated schematically in Figure 6 below.



- **Figure 6 Structure of Wellington Transport Strategy Model**

Time period factors represent the proportion of total trips which are allocated to each modelled time period. These are derived from household travel survey data and therefore represent base year trip patterns. With the knowledge that the model would likely be used to test the impact of congestion pricing strategies, an incremental choice model was developed that allows the car time period factors for each purpose to change in the future.

The incremental model estimates the change in the peak proportion of trips as a function of the change in the peak/interpeak cost differential between the base and policy scenarios. Essentially, this is a standard incremental model in which choice probabilities change from the base position in line with cost changes for individual alternatives. If both peak and off-peak change by the same amount, then there will be no change in the choice probability. This is defined mathematically below.

$$MF^1(d)^t_{pij} = \frac{MF^0(d)^t_{pIJ} \times \exp \lambda_p (GC^1(d)^t_{pij} - GC^0(d)^t_{pij})}{\sum_k [MF^0(d)^k_{pIJ} \times \exp \lambda_p (GC^1(d)^k_{pij} - GC^0(d)^k_{pij}]}$$

Where

- MF = Matrix Factor, proportion of demand (d) in each of the peak periods;
- GC = Generalised Cost
- the superscripts 0 and 1 describe base and policy;
- λ_ρ = peak spreading parameter and is implicitly negative; and
- the choices (k in the denominator) are the am peak and pm peak and rest of day (the other 20 hours, using costs for the interpeak to represent all off-peak travel).

In principle λ_ρ should be larger than the distribution model parameter for car trips for each trip purpose; this parameter was set to give reasonable results and be consistent with the Sydney Harbour Tunnel experience and other international evidence.

In the Wellington model, the above formula is applied to the AM and PM peaks with the assumption that the impact on the interpeak is

a) in the reverse direction; and

b) half the sum of these two effects (in that some of the change will be to the pre AM peak and post PM peak).

In other words, if the number of trips in the AM peak is forecast to reduce by 10 trips, five additional trips are assumed to take place in the pre AM peak (shift to earlier travel time) and five trips in the interpeak (shift to later travel time). Likewise, if the number of trips in the PM peak is forecast to reduce by 10 trips, five additional trips are assumed to take place in the interpeak (shift to earlier travel time) and five trips in the post PM peak (shift to later travel time).

The adopted value of the peak spreading parameter was –0.015. This value has been based on the international experience suggesting an elasticity of the peak period proportion to change in generalised cost of -0.2 to -0.5. This value for the parameter yields an elasticity of the peak period proportion of trips with respect to costs of –0.32 in the AM peak for those sectors of the matrix travelling in the peak direction.

To further aid understanding of this methodology, a worked example is provided below. For simplicity this example considers two modelled periods: peak and off-peak, and only includes travel between one origin and one destination zone. The example illustrates the impact of a significant increase in peak period travel costs, off-peak costs are assumed to remain constant. The inputs to this example are given in Table 3. The table shows that the base proportion of trips

that take place in the peak is 60%. The base case cost of travel in the peak is 5 minutes, increasing to 10 minutes in the policy scenario (E.g. as a result of a peak period congestion charge). Off-peak travel costs are 5 minutes in both base and policy scenarios.

Wellington Worked Example

- **Table 3 Inputs to Wellington Worked Example**

	Peak	Off-peak
Base Proportion - $MF^0(d)^k_{pIJ}$	0.6	0.4
Base Cost - $GC^0(d)^k_{pij}$	5 min	5 min
Policy Cost - $GC^1(d)^k_{pij}$	10 min	5 min
Spread Parameter - λ_p	-0.015	

STEP 1: Evaluate top line (numerator) of the equation

$$MF^0(d)^t_{pIJ} \times \exp \lambda_p (GC^1(d)^t_{pij} - GC^0(d)^t_{pij})$$

= [Base Proportion of Peak Travel] x exp[spread parameter * (policy peak cost – base peak cost)]

= 0.6 * exp[-0.015 * (10-5)]
= 0.6 * 0.927743
= 0.56

STEP 2: Evaluate bottom line (denominator) of the equation

$$\sum_k [MF^0(d)^k_{pIJ} \times \exp \lambda_p (GC^1(d)^k_{pij} - GC^0(d)^k_{pij}]$$

In this example, two periods (k) are considered. The peak has already been evaluated in the numerator (STEP 1 above) and shown to be equal to 0.56. Below we evaluate the off-peak.

= 0.56 + [Base Proportion of Off-Peak Travel] x exp[spread parameter * (policy off-peak cost – base off-peak cost)]

= 0.56 + 0.4 * exp[-0.015 * (5-5)]
= 0.56 + 0.4 * 1
=0.96

STEP 3: Divide the numerator by the denominator to give policy case peak proportion

= 0.56/0.96
= 0.58

The impact of the policy in the above example has been to reduce the proportion of travel in the peak period from 60% to 58% for this origin-destination pair (consequently the off-peak proportion has increased from 40% to 42%). It should be noted that the model performs this calculation for each origin-destination pair, separately by journey purpose.

In the model, these proportions are applied to total daily trips (24hr) to derive period specific matrices for assignment. If we assume that in the base daily trip matrix there are 100 trips between zone i and j, 60 will be assigned in the peak and 40 in the off-peak. In the policy scenario, 58 trips will be assigned in the peak and 42 trips in the off-peak.

It should be noted that the level of impact from the change in peak period travel costs is directly attributed to the spread parameter. For example if, in the above example, the spread parameter was -0.03 (i.e. double the -0.015 assumed in the example) the peak period factor would reduce to 0.56 in the policy scenario.

2.2.2. Auckland (NZ)

The Auckland Regional Transport Model (ART) includes five time periods: AM and PM peaks, school peak, interpeak and off peak. The original intention was to construct an incremental time-of-day model similar to that described above for Wellington. However, recognising the increasing body of research that suggests time period choice should be higher up the four-step decision-making hierarchy, an alternative approach was considered.

As noted above, in order to meet general requirements for symmetry between outward and return trips, it is necessary to consider tour based approaches if the time-of-day model is above trip distribution in the four-step hierarchy (Gordon et al, 2007). This is to ensure the distribution implied in the time choice of the return leg is consistent with that of the outward leg.

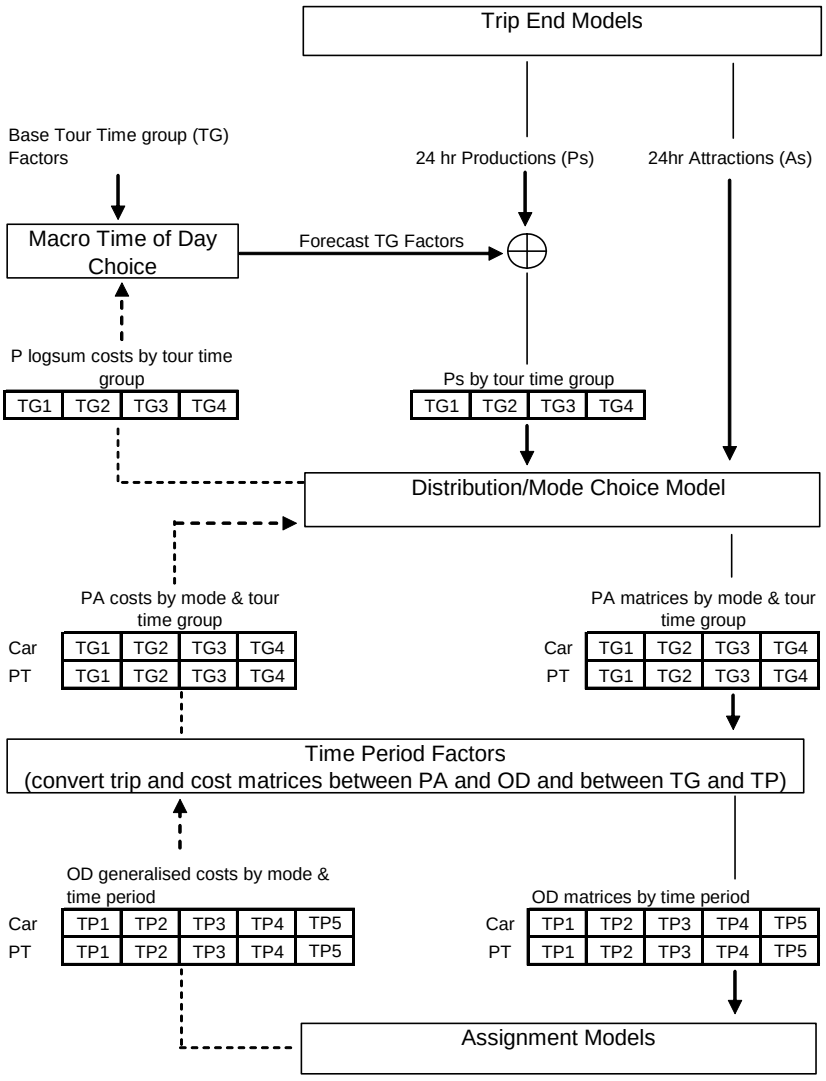
A tour-based approach has the added advantage that both the inbound and outbound trip charges can be taken into account. For example, consider a congestion charging scheme where charges apply in the AM and PM peaks. A commuter who travels through the charging zone in the AM peak and PM peak will be charged in both directions. A second commuter who travels in the AM peak and off-peak will only be charged in one direction. In this case, the second commuter may be more willing to pay a charge in the AM peak because there is no charge for the off-peak return trip.

In the Auckland model (which is a trip-based, rather than tour-based model) this was achieved through the implementation of '**tour time groups**'. The groups are defined according to the outward (from home) and return legs of the tour of which a given trip is a component, namely:

- TG1: out in the am peak, back in the pm peak,
- TG2: out in the am peak, return not in the pm peak,

- TG3: out not in the am peak, return in the pm peak,
- TG4: all other trips.

Figure 7 illustrates the ART model structure. For the majority of model segments in the ART, mode choice and distribution are modelled simultaneously. Appendix B details the case where mode split precedes distribution, and time-of-day choice is located between the two.



- **Figure 7 The Structure of the ART Time-of-Day Modelling**

In the above structure, distribution and mode choice models are applied separately by tour time group. It is important to stress that it is the same model being applied each time and it is not necessary to calibrate separate models for each tour time group. In the course of the Auckland

study, a simplified spreadsheet model was developed to test this assumption. The analysis showed that a distribution model applied with 24-hour demand yielded similar results to separate models for four tour time groups. In this test, all models used the same sensitivity parameters.

In order to better understand the processes of the above model structure, a worked example is provided below. For ease of understanding, this example presents a two zone, single purpose model. The example considers home based work (commuting) trips with productions representing the home end of the trip, attractions representing the work end of the trip.

The worked example below is included in order to provide a broad illustration of the process of macro time period choice using the tour time group approach. It should be stressed that the example does not provide full detail and explanation of some key (but complex) aspects of the methodology including:

- how the 24-hour attraction constraint is maintained over the four tour time groups;
- how the period-specific origin-destination matrices are derived from tour time group production-attraction matrices; and
- how the composite costs (and therefore the incremental composite costs) are calculated.

This information, including full mathematical description, is included as Appendix B to this report.

Step 1: Trip Generation

The Trip Generation model produces estimates of trip ends (productions and attractions) for a 24 hour period as given in Table 4.

- **Table 4 24 Hour Trip Ends**

Trip Ends	Zone 1	Zone 2	Total
Productions (P)	100	80	180
Attractions (A)	75	105	180

Step 2: Allocation of Trip Ends to Tour Time Groups

Base case Tour Time Group (TTG) allocations are derived from household travel survey data and are applied to trip productions. In this example they are the same in each zone abut this will not necessarily be the case. Trip attractions are entered into the distribution model on a 24 hour basis. Table 5 presents example TTG proportions.

- **Table 5 Tour Time Group Proportions**

Tour Time Group	Out/Return	Base Proportion	Productions Zone 1	Productions Zone 2
TG1	AM/PM	30%	30	24
TG2	AM/other	30%	30	24
TG3	other/PM	16%	16	13
TG4	other/other	24%	24	19

Step 3: Distribution and Mode Split

Figure 7 illustrates a simultaneous distribution and mode choice model. In order to keep this example simple, a single mode model is assumed and therefore only the distribution stage is illustrated.

There is one distribution model for each TTG (each with the same sensitivity parameter). The inputs to the model are the productions and attractions by zone (from Trip Generation) and generalised costs specific to each TTG. The generalised costs are calculated for each modelled time period (AM peak, PM peak and other – where other represents the interpeak, school peak and off-peak periods), the relevant combination is then applied to derive the TTG cost. Note than in order to apply the same model parameters from the existing 24 hr distribution model (to avoid recalibration), the TTG costs must be halved.

The calculation of TTG generalised cost is illustrated for a single cell in the production – attraction matrix (E.g. zone 1 to zone 2 trips) in Table 6.

- **Table 6 Calculation of TTG Generalised Cost (min)**

	Period Costs	
A	AM Peak	30
B	Other	20
C	PM Peak	30

TTG	**TTG Costs**	
TG1	(A+C)/2	30
TG2	(A+B)/2	25
TG3	(B+C)/2	25
TG4	(B+B)/2	30

The distribution model uses the production-attraction matrix of costs to distribute zone productions to zone attractions, creating a production-attraction matrix of tours. Note that balancing factors are used to ensure that the attraction constraint is maintained over the four tour time groups. One matrix is produced for each TTG as shown below. The four TTG matrices combined equates to a 24 hour production-attraction matrix.

TG 1	Zone 1	Zone 2	**TOTAL**
Zone 1	17	13	**30**
Zone 2	9	15	**24**
TOTAL	**26**	**28**	**54**

TG 2	Zone 1	Zone 2	**TOTAL**
Zone 1	16	14	**30**
Zone 2	7	17	**24**
TOTAL	**23**	**31**	**54**

TG 3	Zone 1	Zone 2	**TOTAL**
Zone 1	8	8	**16**
Zone 2	3	9	**12**
TOTAL	**11**	**17**	**28**

TG 4	Zone 1	Zone 2	**TOTAL**
Zone 1	11	13	**16**
Zone 2	4	15	**12**
TOTAL	**15**	**28**	**28**

24 Hr	Zone 1	Zone 2	**TOTAL**
Zone 1	52	48	**100**
Zone 2	23	57	**80**
TOTAL	**75**	**105**	**180**

STEP 4: Application of Time Period Factors and Assignment

Fixed factors convert the tour group production-attraction matrices into origin-destination format by time period. Note that the fixed factors applied here simply convert from tour time groups to time periods. For instance, a tour that encapsulates outbound travel in the AM peak and return in the PM peak would produce a single trip in the AM peak and another trip in the PM peak.

Once the origin-destination matrices have been determined, they are assigned to the network separately for each time period. For brevity this process is not illustrated in this example.

The outputs of the assignment are a revised set of generalised costs in origin-destination format by mode and time period. These costs are then transformed into production and attraction format and grouped to represent TTG generalised costs. The costs are fed back into the distribution and mode-choice model.

STEP 5: Macro Time of Day Choice

For this example it is assumed a congestion charge has been applied in the assignment whereby all peak period trips to or from Zone 2 face an increase in cost that is equivalent to 10 minutes. With reference to Table 6 above, the revised zone 1 production to zone 2 attraction costs are represented in Table 7.

- **Table 7 TTG Generalised Cost with Congestion Pricing (min)**

	Period Costs	
A	AM Peak	40
B	Other	20
C	PM Peak	40

TTG	TTG Costs	
TG1	(A+C)/2	40
TG2	(A+B)/2	30
TG3	(B+C)/2	30
TG4	(B+B)/2	40

The change in TTG costs will have an impact on travellers' time of day choice. The macro time of day choice model is therefore run to generate new TTG factors that will reapportion the 24 hour productions to tour time groups, separately for individual zones.

As the time of day choice model is an incremental model, the cost inputs to the model are incremental costs; that is the change in costs between the with and without congestion charging scenarios.

$$T_i^{TG1} = \frac{TG1_B \times \exp(\lambda \times \Delta CC_i^{TG1})}{(TG1_B \times \exp(\lambda \times \Delta CC_i^{TG1}) + TG2_B \times \exp(\lambda \times CC_i^{TG2})}$$

Where

T_i^{TG1} = Revised Proportion of zone i productions in Time Tour Group 1

$TG1_B$ = Base proportion of trips in Time Tour Group 1

λ = Time-of-Day Choice Model Spread (sensitivity) parameter

ΔCC_i^{TG1} = Change in Tour Time Group 1 zone i composite cost (logsum)

Table 8 shows the impact of the time of day choice model with respect to our two zone example (assuming λ = -0.03). The largest impact is on zone 2 productions, this is to be expected as all peak period trips with a zone 2 production are affected by the congestion charge. Conversely only zone 1 productions which have a zone 2 attraction are affected, therefore the overall impact on zone 1 productions is less.

- **Table 8 Output of Time-of-Day Choice Model**

Tour Time Group	Base Proportion	Scenario Proportion – Zone 1	Scenario Proportion – Zone 2
TG1	30.0%	28.7%	25.9%
TG2	30.0%	29.8%	30.1%
TG3	16.0%	15.9%	16.0%
TG4	24.0%	25.6%	28.0%

The revised set of TTG factors are applied to the 24 hour trip productions to generate productions by TTG.

STEP 6: Distribution and Mode Split (Iteration 2)

The distribution and mode split model is re-run taking account of both:

1. The revised tour time groups generated by the time of day choice model; and
2. The revised generalised costs from the assignment.

The model continues through this iterative process until the convergence criteria has been met.

It should be noted that for non-home based trip purposes, the Auckland model applies the Wellington approach. The Auckland model report notes that the inclusion of the time-of-day model 'did not significantly add to model run times'.

2.2.3. Other studies

PRISM – West Midlands (UK), Rand Europe (2007)

> The PRISM model system is a (tour based) variable demand multi-modal transport model developed for the West Midlands region by RAND Europe and Mott MacDonald. It consists of detailed network models covering the highway and public transport (PT) systems, which are linked to a disaggregate model of travel demand. The demand model reflects a number of traveller responses in a number of interacting modules, including car ownership, public transport travel pass ownership, tour frequency, destination choice, mode choice and time-of-day choice.

In conducting tests to discover the effect of various model structures it was found that for both commuting and other journey purposes, the recommended model structure was to have mode and time-of-day choice "at the same level". However in testing the order of mode choice and destination choice (distribution) for non-commuting purposes it was found that a better model fit could be achieved with destination choice below mode choice in the model hierarchy. This would mean modelling time-of-day choice before distribution.

The above outcome would have had undesirable impacts on model run times as well as budgetary implications of altering the existing model structure. It was therefore decided that the loss of fit from modelling time-of-day choice at the same level as destination choice (and therefore not modelling mode and time choice simultaneously) would be acceptable.

The purpose of presenting this example is to illustrate the trade-off that needs to be considered between theoretical good practice and budget/resource realities. This is an important consideration in developing time-of-day choice modelling procedures for implementation in Australian models.

Washington State

The focus of the analysis in this report has been on macro time period choice. For completeness, however, it is worth including an example from Washington State (Cambridge Systematics, 2005) where micro time period choice has been implemented within the EMME/2 framework.

The existing model contained five coarse time periods, namely:

1) AM Peak – 5:00 a.m. to 10:00 a.m.
2) Midday – 10:00 a.m. to 3:00 p.m.

3) PM Peak – 3:00 p.m. to 8:00 p.m.
4) Evening –8:00 p.m. to 11:00 p.m.
5) Night – 11:00 p.m. to 5:00 a.m.

In order to model time period choice, the three time periods where congestion is in evidence (AM peak, Midday and PM peak) were divided into 30 minute time slices thus, in total, the model included 32 time periods. A multinomial logit model was applied to forecast the probabilities of a trip arriving (from home) and departing (to home and to non-home based purposes) in each of the 32 time periods.

The utility function incorporated in the time period model included variables listed in Table 9.

Table 9 Variables included in Washington Micro Time Period Choice Model

Variable	Description
Household Size	Commuters residing in larger households were shown to be less likely to travel to and from work in peak times.
Income Group	Commuters residing in high income households were shown to be more likely to travel to and from work in peak times.
Congestion Level	Congestion is measured as the difference in generalised cost between the night time period (free flow) and the applicable modelled period (eg AM peak). Congestion was shown to have a negative effect on travel decisions.
Carpool Dummy	Carpool trips were shown to be more likely to occur for home to work trips but less likely to occur for work to home trips.
Bridge Dummy	The significance of this variable (crossing one of three bridges in the region) varies by purpose and time of day. For example, in the AM peak there was shown to be a higher likelihood that trips across the bridge would be solely for work related purposes.

The main purpose in highlighting this example is to demonstrate the range of additional variables included in micro time period choice models, plus the ability to introduce micro time choice within the EMME structure. This approach is not recommended for Australia's strategic models.

2.3. Application in Australia

The issues relating to the application of time-of-day choice modelling in Australia are slightly different for each jurisdiction's model. Chapter 4 provides further discussion of the specific considerations for each model.

One of the principal considerations will be to assess what can be implemented in the short term (simple, quick-to-implement techniques) versus longer term objectives (restructuring and recalibrating models) in the context of time and resource constraints.

The Australian capital city models fall broadly into four categories of time period model structure, as shown in Table 10.

Table 10 Time Period Model Structures

Structure	Models
Trips are generated for a 24 hour period, fixed time period factors are applied to apportion demand to model time periods	Brisbane (BSTM-MM), Perth (STEM) and Adelaide (MASTEM)
Tours are generated for a 24 hour periods taking account of weighted average generalised costs across time periods, fixed time period factors are applied to apportion demand to model time periods	Sydney (STM)
Demand is forecast separately by time period (AM peak and interpeak)	Melbourne (MITM)*
Model considers the AM peak only	Canberra (CSTM)

* Note that the Melbourne MITM is currently being recalibrated and will adopt a 24-hour trip generation, distribution and mode choice structure with period specific assignments, bringing it into line with the Brisbane, Perth and Adelaide models.

The Sydney model, which already uses a tour-based approach should, in theory, be more easily adapted to incorporate a time period module, though the feedback loops in the model would need to be assessed carefully. The Canberra model currently considers only the AM peak, so any time period choice modelling would need to be simplified to a peak/off-peak allocation of trips. The Wellington approach could be implemented fairly readily to accomplish this objective. The other four models are structured in a way that the Auckland methodology would be straightforward to implement.

The Auckland methodology is considered to be in line with international best practice and has the added advantage that existing models can be restructured to incorporate time period choice techniques without the need for recalibration. This methodology may need to be implemented over a medium-term time frame as the restructuring is likely to require several months' work. If a short-term solution is required, the Wellington approach may be preferable as a 'bolt-on' solution. In the longer term, the move to activity based models that has been observed in the US may become accepted as international best practice. If that is the case, it will then be desirable for this to be adopted in Australia. However this should not be seen as a barrier to modelling congestion pricing under the current model structures.

2.4. Data Requirements

The data required to calculate tour time period proportions for time-of-day choice modelling within a strategic transport model already exists in the form of household travel surveys. Although the analysis is non-standard, experience suggests it is not difficult. There would be some time and cost required for further analysis of the household survey data in some of the jurisdictions. The main additional data requirements concern parameter values that dictate the sensitivity of traveller time period choices in response to changes in cost. There are several options available for obtaining appropriate values:

a) Apply values used in models of other (comparable) cities.

b) Calibrate the parameters to achieve a demand response that reflects observations of peak period charging in other (comparable) cities.

c) Carry out stated preference surveys to determine traveller propensities for changing departure time in response to changes in travel costs.

The first two options may be an appropriate short term solution in most cases, and require minimal additional data collection. In the longer term however, stated preference research to determine appropriate jurisdiction-specific sensitivity parameters would be valuable in order to provide confidence in the behavioural response forecast by the models.

2.5. Key Findings

The key findings from the review of time period modelling practice are as follows:

- Time period choice modelling is quite complex and will require restructuring of the current Australian models if it is implemented.
- Most time period choice models use a multinomial logit formulation. Because there are no observed Australian data on trip retiming in response to demand management initiatives (E.g. congestion charging), we recommend adopting sensitivity parameters that generate

behavioural responses consistent with other cities' models, at least in the short to medium term.

- In implementing a time period choice model, consideration should be given to using an incremental model. Incremental models are set up so that base year time period choices are replicated by the model, then the relative change in travel cost (rather than the absolute cost) in each time period is used to determine the proportional shift between periods.
- Time period choice should be placed at a similar level to main mode choice, with UK guidance (WebTAG 3.10.13) recommending that it be implemented below mode and above distribution.
- International best practice is to use a tour-based representation of travel, rather than a trip-based approach for time period modelling. This allows the linkage of outbound and return journeys to be taken into account (i.e. retiming an outbound trip may also cause the return trip to be retimed).
- The Auckland Regional Transport Model, which was originally a trip-based model, was converted to a tour-based model without the need to recalibrate existing mode choice and distribution models. This is an important finding and, if shown to be true for the Australian models, will greatly reduce the effort needed to implement time period models in each jurisdiction.
- The data requirements for a time period choice model that uses sensitivity parameters "borrowed" from other cities are not onerous although jurisdiction-specific data obtained from stated preference surveys would be the preferred methodology in the longer term. The household travel survey datasets in most jurisdictions should suffice for implementing time period choice in each Australian model.
- Activity-based modelling approaches are an alternative to the conventional four-step approach, and have been implemented in some major US cities. In the longer term, activity-based approaches might be considered when the methods for applying these approaches have been effectively applied and verified in a range of international contexts and can therefore be adjudged to be international best practice.

3. Public Transport Crowding

3.1. The Theory

The discussion presented in this chapter makes regular reference to public transport crowding in the context of train travel. This is predominantly because much of the research and subsequent modelling in this area has concentrated on train patronage. However it is important to note that the theory of public transport crowding applies to all public transport modes, although the perceived cost of crowding may differ between modes (e.g. standing on trains may be tolerated more than standing on buses).

There are four key effects of public transport crowding that have been identified in the literature. These are summarised in Table 11.

Table 11 Effects of Public Transport Crowding

Effect	Description
In-vehicle discomfort	Perceived disutility from travelling in crowded conditions
Excess wait time	Additional passenger wait time from not being able to board a service
Increased dwell times	Increased journey times caused by vehicles having to remain stationary for longer at stations to facilitate boarding and alighting
Platform crowding	Perceived disutility from waiting in crowded conditions

Each of the above are genuine consequences of crowding and should be considered in the estimation of congestion relief benefits of schemes. However in the context of strategic transport modelling and therefore this report, only two of the four are typically considered for inclusion in the modelling process:

- In-vehicle discomfort; and
- Excess wait time.

Service-by-service analysis of boardings and alightings at individual stations/stops is required in order to accurately estimate the increased journey times resulting from additional dwell time. Given that strategic models consider capacity constraints as an average over the peak period rather than on an individual train basis, this impact cannot be estimated from strategic transport models and is therefore omitted from consideration in the remainder of this report.

In order to estimate the perceived costs associated with platform crowding, it is necessary to consider pedestrian flows through the station or terminal 'network'. This is generally undertaken with the application of pedestrian modelling software such as PEDROUTE or LEGION. Strategic models do not represent terminal networks in any detail and therefore platform crowding cannot be modelled. Instead strategic model estimates of patronage may be used as an input to the pedestrian modelling process.

In the course of this study the issue of public transport reliability has been raised, and how this is reflected in the four key crowding impacts discussed above. It should be noted that reliability is in itself not a form of crowding, rather it is both a cause and consequence of crowding. Reliability is generally something that is not currently incorporated in strategic transport models and usually simplistic assumptions are required. Detailed recommendations on incorporating reliability are not in the scope of this current study.

3.1.1. Definitions

Before the methodologies of handling crowding in public transport assignments are discussed in detail, it is useful to distinguish between **frequency-based** and **schedule-based** assignment models (see Table 12). Strategic transport models universally (in our experience) operate frequency based assignments.

Table 12 Frequency and Schedule Based PT Assignments

Assignment	Description
Schedule	The model includes timetable information and therefore the capacity implications on individual services (E.g. 07:00 Epping to Flinders Street) can be assessed. This form of model would be used more for operational analysis.
Frequency	Only service frequencies (E.g. 6 trains per hour) by individual lines are entered into the model with passengers assigned to lines on a frequency-weighted basis. Capacity assessment with this form of assignment must be undertaken on the basis of averages.

A further related definition is the distinction between vehicle and network capacity. **Network capacity** refers to the number of public transport vehicles that can operate on the network for a given time period. In terms of rail, this is often expressed in terms of 'trains per hour' (tph). **Vehicle capacity** refers to the number of passengers able to travel on any given service.

3.1.2. In-Vehicle Discomfort

As with other components of a public transport assignment, in-vehicle discomfort is dealt with through the application of a penalty or 'crowding factor' – generally a multiplier applied to in-vehicle journey time. The complexity (and requirement for iterations of the assignment) is created by the need to base the crowding factor on load using a **crowding function**. In simple terms, the higher the load, the higher the penalty applied. Further complexity is added by the fact that passengers who are required to stand will perceive a higher level of discomfort than those who are seated.

A study undertaken for Railcorp (Douglas Economics, 2006), estimated values for in-vehicle crowding from stated preference research. The study found that sitting in crowded conditions added 0.17 minutes per minute of journey time. Therefore 10 minutes sitting in crowded conditions is perceived as 11.7 minutes of journey time. Other values were generated for standing for periods shorter and longer than 10 minutes, and in crowded and crush conditions, as shown in Figure 8.

Additional Crowding cost per minute in equivalent minutes of onboard uncrowded seating and in cents

Level of Crowding	Crowding Factor per minute	Crowding Cost Cents per minute
Crowded Seat	0.17	2
Stand 10 mins or less	0.34	5
Stand - 20 mins or longer	0.81	11
Crush Stand 10 mins or less	1.04	11
Crush Stand 20 mins or longer	1.52	17

Source: RailCorp Surveys, Douglas Economics Analysis
SydCrowdRes06_2.xls!RelVal

- **Figure 8 Valuation of On-Train Crowding**

From this information additional crowding factors were calculated that increase with load as depicted below. Assumptions have been made regarding the distribution of standees that must stand for 10 minutes, 10 to 20 minutes and 20 minutes or longer. Note also the assumptions regarding the percentage of sitters and standees by train load. This contrasts with UK models that typically assume that standing only begins once all seats are occupied.

Train Load Passengers / Seats	Pecent Sit	Pecent Stand	Additional Crowding Factor per minute	Additional Crowding Cost Cents per minute
75%	100%	0%	0.00	0.00
80%	98%	2%	0.01	0.10
85%	96%	4%	0.02	0.21
90%	94%	6%	0.04	0.34
95%	93%	7%	0.07	0.49
100%	91%	9%	0.10	0.65
105%	89%	11%	0.13	0.83
110%	87%	13%	0.18	1.04
115%	85%	15%	0.22	1.28
120%	83%	17%	0.27	1.54
125%	80%	20%	0.30	1.84
130%	77%	23%	0.34	2.16
135%	74%	26%	0.37	2.50
140%	71%	29%	0.41	2.86
145%	69%	31%	0.45	3.25
150%	67%	33%	0.50	3.67
160%	63%	38%	0.60	4.60
170%	59%	41%	0.64	5.01
180%	56%	44%	0.68	5.38
190%	53%	47%	0.71	5.70
200%	50%	50%	0.74	6.00

Assumes 30% stand for 10 minutes, 30% for 10-20 minutes and 40% for 20 mins or longer
Value of uncrowded seating = $8.45/hr
Source:RailCorp Surveys, Douglas Economics Analysis SydCrowdRes06_2.xls!RelVal

- **Figure 9 On-Train Crowding Cost with Train Loading**

The values presented in Figure 9 apply to individual passengers travelling on individual trains. In terms of strategic models these factors are applied on a link-by-link basis with a link typically being the route between two stations. Two issues arise:

a) In many cases more than one service (route) will serve a particular link; and

b) In general strategic models use service frequencies (as opposed to service schedules) and therefore individual services are not modelled.

The UK's Rail Passenger Demand Forecasting Handbook (PDFH) recommends that crowding factors should be increased by 10% when applying per-train crowding values to peak period averages. An alternative, more data intensive, approach adopted by London Transport is to incorporate passenger and train profiles by 15 minute periods and apply these penalties at the more disaggregate level. A third approach that is employed by the UK Department for Transport's PLANET model applies a normal distribution (separately by service type E.g. suburban, inter-urban etc) that reflects the variance in load factors within the peak period (or between days).

More recent research undertaken in the UK has recommended the use of passengers per square metre of standing space as a better measure of crowding applicable to standing passengers. Although this has been adopted by Transport for London for planning purposes, it has not been implemented in the London strategic models. Another conclusion from this research was the need

to apply alternative crowding costs by journey purpose. For example commuters tend to have a greater tolerance of crowding than leisure travellers.

Crowding penalties are typically applied on a link-by-link basis, where a link represents the route between two stations or stops. An average crowding value is applied to all passengers that reflects the proportion of passengers that are standing and seated over the peak period.

More detailed models may use a more refined approach where the crowding level at the boarding point is used to determine the penalty. This way, passengers boarding trains at the start of the line (where seats are likely to be available) may have less severe penalties applied than those boarding further down the line. While this approach is theoretically more correct, it is not generally implemented in strategic models, as these models use average flows (on a link-by-link basis) across a time period and do not usually model loads on individual public transport services.

One behavioural consequence of in-vehicle crowding is that passengers on crowded express services may choose to board less crowded stopping services. In theory, the crowding model should account for this behaviour if stopping and express services are coded as separate lines in the model.

3.1.3. Excess Wait Time

It has already been noted that strategic models usually adopt a frequency-based assignment. In frequency-based models it is possible to handle the issue of excess wait time (the probability of not being able to board the first service) through a concept known as ‘effective frequency’. In this method, the perceived cost of travel is increased through an effective reduction in service frequency (that is, the passenger’s average wait time is increased). In other words, actual frequencies may be six trains per hour, but because of crowding and the inability to board the first service, average wait times are extended to a level that reflect an effective frequency of four trains per hour, for example.

Note that the effective frequency method (which is available in the EMME software package) does not restrict public transport vehicle loadings from exceeding capacity. In heavily congested networks this can lead to inaccuracies. For instance, if a particular rail service is operating at capacity, a passenger may not physically be able to board a train travelling from station A to station B. However, if this is the passenger’s only travel choice, the effective frequency method allows this trip to take place (albeit with a high perceived travel cost) even though the train is overloaded.

3.1.4. The Problem of Convergence

Unlike non capacity-constrained assignments, where only a single iteration is required, modelling public transport capacity constraints requires multiple iterations of the public transport assignment.

Indeed, one of the arguments against introducing capacity constraints in strategic models is the extended model run time.

As well as model run time, there is a need to consider the convergence of the assignment. In areas with highly overloaded networks there is a risk of non-convergence in public transport volumes (Citilabs, 2008). As well as convergence within the assignment, there is also the issue of convergence within the model's main demand loop as a result of cost changes associated with crowding. However, on the assumption that the latter is already required to deal with highway congestion, the additional impact on run time from this component may not be severe.

Early efforts to incorporate crowding in the main London models (LTS and RAILPLAN) found that convergence occurred after four iterations with link costs being adjusted to reflect passenger crowding and the following iteration applying the adjusted costs. In order to achieve stability in the results, costs were averaged from the preceding two iterations.

Although overall network convergence was achieved there were two related areas of concern:

a) **Stability of modelled costs**. In certain corridors there was evidence of "flipping" of passengers between services on each iteration (e.g. from train to underground). This was particularly the case in highly congested corridors.
b) **Stability of assigned flows on services**. Large variation in flows for individual services between iterations provoked uncertainty in the results.

As stated above, public transport crowding extends model run times, particularly where multiple iterations are needed in congested networks. It is acceptable practice to switch off the crowding function (or reduce the number of iterations of the public transport assignment) in model tests where a significant impact on public transport patronage is not an expected result. For example in early applications of crowding in the LTS model, in order to reduce computer costs an assumption of constant crowding was made. This meant that crowding costs were calculated (and therefore input to the distribution and mode choice model) but assumed to remain constant and therefore multiple iterations were not required. Note however if a major public transport scheme was to be assessed the assumption of constant crowding cannot be made.

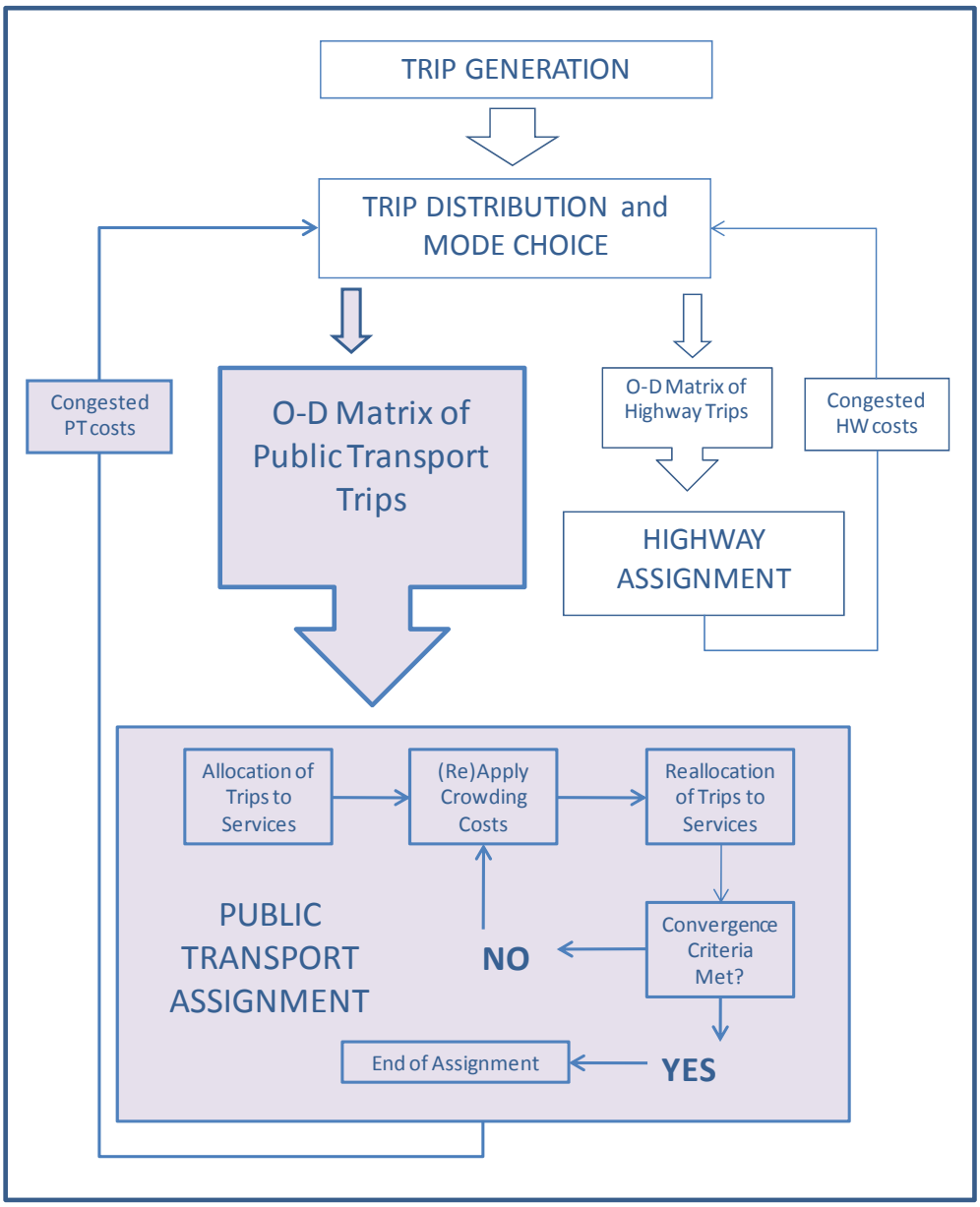
3.2. In Practice

3.2.1. The Process

To aid understanding of the model processes that form a crowded public transport assignment within a strategic transport model, it is useful to consider a diagrammatic representation.

With reference to Figure 10 below, the shaded boxes highlight the flow of data relevant to the public transport assignment. An origin-destination matrix of public transport trips is output from the distribution/mode choice stage of the model; this is the input to the assignment.

The first stage of the public transport assignment is the allocation of passenger demand, in the form of trips, to routes that connect zone pairs. This is done through an enumeration process that calculates the relative attractiveness of the various routes available. In models that do not consider crowding (i.e. the current Australian models) no further iterations are carried out.



- **Figure 10 Crowded Public Transport Assignment Process**

In the case of a crowded assignment (as depicted above) crowding costs are derived from the initial allocation of trips to services. Trips are then reallocated to services based on the revised costs. At this point a convergence test is applied that compares the forecast flows derived from successive iterations of the assignment. If the change in flows is small enough to satisfy the convergence criteria, the assignment is complete, otherwise the cycle of re-applying crowding costs and allocating trips to services continues.

Once the convergence criteria have been met, the assignment step is completed and the model feeds the resulting costs back into the earlier stages of the four-step model. The penalties associated with crowding are included in the feedback costs.

Each of the Australian strategic transport models managed by the NTMWG member jurisdictions operate on either the CUBE or EMME software platforms. The following sections highlight the standard public transport crowding methodologies that are available to CUBE and EMME users.

3.2.2. CUBE

The CUBE public transport program supports two types of crowding models:

a) Link Travel Time Adjustment which relates to the discomfort from in-vehicle crowding; and

b) Wait Time Adjustment which relates to excess wait time.

The user may employ either or both models.

The Link Travel Time Adjustment methodology is described below (as provided by the CUBE user manual). In essence, the travel time along a link (e.g. travel between station stops) is increased to reflect the discomfort from crowded conditions. The level of adjustment is derived from a ‘crowding curve’ that defines crowding factors for given load factors.

Crowded link time is calculated as:
$\mathbf{T_c=T_u .CCrv_{v,c}(U)}$
Where:
$\mathbf{T_c}$ = crowded link travel time
$\mathbf{T_u}$ = uncrowded link travel time
$\mathbf{CCrv_{v,c}(U)}$ = crowd curve value (where the curve is specific to a vehicle type *v* and user class *c*) for utilisation U:

$\mathbf{U = (P-(LDF)_v\ SeatCap))/(CrushCap-(LDF)_v\ SeatCap))}$
Where:
P = passenger demand (per hour)
SeatCap = seating capacity (per hour) for the line
CrushCap = crush capacity (per hour) for the line (seating + standing capacity)
$\mathbf{LDF_v}$ = load distribution factor for the vehicle type. As loads increase this is the proportion of seats occupied when standing starts to occur.

Crowding factors (from CCrv) are set to 1.0 in uncrowded conditions and typically rise to values of 1.0 to 1.4 for seated passengers and 1.5 to 3.0 for standing passengers.

The Wait Time Adjustment applies additional wait time to passengers based on the probability of being able to board a service. Where demand exceeds capacity on a particular line, loads are redistributed to other lines with spare capacity and the passenger incurs additional wait time. If an alternative is not available "*then this transit leg acts as a "bottleneck"—not all of the travel demand is able to use the service during the modelled period. The demand remaining at the end of the modelled period would discharge once peak travel volumes subside; those travellers experience additional delays, which form a second component to the wait-time adjustment*."

One of the advantages of the CUBE approach is that in cases where a passenger is unable to board a service, the later stages of the public transport trip are removed from the network. However, this study did not find an example of this functionality being used in the published literature.

The CUBE guidance warns users that the iterative crowding procedure may not converge towards a solution and instead continue to oscillate, especially in the case of a highly overloaded network. CUBE contains two sub-models that are available to allocate passengers to the transit choices at a stop: the 'service-frequency-and-cost' model and the 'service-frequency' model. It is recommended that 'service-frequency-and-cost' be used, as the route-choice process is more responsive to changes in cost and usually results in better convergence.

3.2.3. EMME

There are two available EMME macros that model public transport crowding:

a) CONGTRAS (CONGested TRansit ASsignment): the original macro written by Heinz Spiess that models the discomfort from **in-vehicle crowding**. The macro is implemented through use of the 'Fixed cost transit assignment', 'Network Calculator' and 'Matrix Calculator' modules. Importantly the macro allows the user to define their own (non-decreasing) crowding function.

b) CAPTRAS: builds on the CONGTRAS macro with the further inclusion of the perceived headway function (to model **excess wait time**). The methodology is highlighted below.

> The mechanism used to model the increased waiting times is that of effective frequency. The effective frequency of a line is the frequency which yields the waiting time obtained by the adjusted headway. It is modelled with a continuous function which increases as the residual capacity of the vehicle decreases. In other words excess wait times increase as spare capacity decreases.
>
> The increased waiting time at a stop may be modelled by using steady state queuing formulae, which take into account the residual vehicle capacity, the alightings and the boardings at stops. The headway increases as the transit flow reaches capacity (but cannot exceed 999 in Emme). One such functional form is the following:
>
> **Min [hdwy/(1-(boardings/residual capacity)^beta),999.98]**
>
> The beta coefficient may be optionally changed in the macro. The results are somewhat sensitive to this value. Also, the entire function may be replaced in the macro by another function if judged appropriate.
>
> If there is a feasible solution but the initial solution is not capacity feasible, then the algorithm will first find a feasible solution and then the approximate equilibrium solution.

Convergence is reached though the method of successive averages (MSA) to minimise a gap function that is defined as '*the difference between total travel time and total waiting time less the total travel times and waiting times on shortest strategies'*.

3.2.4. LTS and RAILPLAN

LTS is the main four-step multimodal strategic model of London. The model employs a CUBE (TRIPS) based capacity constrained public transport assignment with crowded costs skimmed and fed back to the distribution and mode choice module (in the same way that congested highway costs are fed back from the highway assignment). RAILPLAN on the other hand is a stand-alone

public transport assignment model which assigns demand matrices generated by LTS. It uses a crowded assignment, but there is no direct cost feedback to LTS to influence mode choice.

Although EMME based, the RAILPLAN model does not use the CONGTRAS or CAPTRAS macros (described above), rather it adopts a custom built macro that only considers an in-vehicle time adjustment developed by the then London Transport. The process was first developed in the early 1990s and later enhanced.

At the time London Transport implemented modelling of public transport crowding, the standard planning guideline was that no more than one passenger should have to stand for each passenger sitting on average over the peak hour (London Transport Planning, 1992). Today, however, the planning standard is very different where Transport for London's target is to have no more than three passengers standing per square metre of standing space on heavy rail services.

The first step to implement a crowding model was to define the crowding function, this was achieved through **revealed preference** (RP) passenger surveys. Observations were made at a station on London's Victoria Line (underground) where in the morning peak alternate trains would be 'relatively full from stations up the line, or empty from the depot'. Passengers therefore had a trade-off between waiting time or in-vehicle crowding. As values already existed of waiting time for public transport services, penalties associated with the in-vehicle crowding were able to be calculated from this RP exercise.

In order to apply the results from the RP exercise to the London strategic transport models (RAILPLAN and LTS) a number of additional steps were carried out:

a) The London models consider a three hour peak period over which the level of crowding varies. To derive appropriate average crowding factors, fixed profiles of passenger and train numbers were derived by 10 or 15 minute periods.
b) For the LTS model, loads were averaged across links for groups of services with common stops. This was not necessary for RAILPLAN as the EMME/2 model had an 'in-built proportional allocation of passengers between services'.
c) An iterative procedure was adopted whereby rail link costs were adjusted to reflect in-vehicle crowding, followed by a further assignment using the adjusted costs. Results were stabilised by averaging the costs from the preceding two assignments.

The above procedure 'substantially' improved the validation of the LTS PT model.

Section 3.1.4 above highlighted the issues relating to the stability of modelled costs and assigned flows that resulted from the initial iterative process adopted by London Transport. However with the advances that came with release 5 of EMME/2, in particular the enhanced Network Calculator (and as pointed out by Spiess and Florian) the transit assignment algorithm is "in principle straight-

forwardly extended to allow for equilibrium assignments of passengers in a similar fashion to standard equilibrium assignment highway models, using for example the Frank-Wolfe algorithm."

> The essential idea here is that rather than using a single assignment to give results at each iteration [as in the first London Transport approach], results can be combined from a number of assignments (preferably using proportions that have been optimised). The final result is therefore a mix of strategies from all the iterations preceding, in the same way as for equilibrium congested highway assignments. Just as with the Frank-Wolfe equilibrium assignment method in congested highway modelling, the iterative process is guaranteed to converge. As the congestion cost functions on the public transport network are typically less steep than on the highways, at least in London, and are not too far from linear, one would also expect convergence to be quicker than for a comparably sized highway problem.

It should be noted that the Frank-Wolfe assignment took longer than the earlier implementation of public transport crowding, but the running times were considered to be acceptable.

3.2.5. Docklands Public Transport Model

In order to understand the potential impacts from introducing crowded public transport assignments and in particular, the issues with convergence it is useful to note SKM's experience with the Docklands Public Transport Model (DPTM) in London. The DPTM is an EMME-based assignment model covering the Greater London area, with a particular focus on the Docklands regeneration area in East London. The model has been developed and expanded over the years and currently contains over 400 zones.

Introducing a crowded public transport assignment caused the model to be less stable and more difficult to interpret. This was a particular issue with economic business cases. For example where a change is made to the network in one area, demand from large zones at the edges of the model, and a long way away from the study area, can "flip" between available routes. Because of the iterative assignment process, the base and policy scenarios may have arbitrarily different route allocations, giving an entirely spurious benefit or disbenefit. There are various techniques for dealing with this, including "fixing" crowding levels outside the study area between the base and policy assignment (a complex process) or only using part of the matrix in appraisal.

3.2.6. US Models

This section considers two case studies from the US where capacity constrained public transport assignments have been considered, namely:

a) The San Francisco County Chained Activity Modelling Process; and

b) The Washington D.C. START model.

The mode choice model in the **San Francisco** case study includes both crowding and reliability as explicit variables in the public transport utility functions. Analysis was undertaken on stated preference surveys that estimated trade-offs between in-vehicle time, frequency of service, reliability and crowding; where crowding was defined as:

- low = plenty of seats available;
- medium = few seats available but plenty of room to stand; and
- high = no seats available, standing room is crowded.

The analysis estimated that improving the level of crowding from "high" to "low" is equivalent to reducing the typical wait time by five minutes for commuters and nine minutes for other journey purposes. The trade-offs estimated were applied in the public transport assignment, however the results were not 'coincident' with observed boardings and therefore the crowding methodology was not employed.

The **Washington D.C.** START model is a strategic planning simulation model with a coarse zoning system containing 40 zones. The model works on an incremental basis rather than using absolute costs, the mode choice model is therefore driven by cost differentials between base and policy scenarios.

The public transport cost function includes a crowding term in the form of a multiplier on in-vehicle time. A crowding curve was developed that distinguished between four crowding levels:

1) Sitting comfortably;
2) Sitting crowded;
3) Standing comfortably; and
4) Standing crowded.

The crowding formula is applied using a "time-windowed approach' whereby demand is broken down into 30 minute intervals in order to capture the "peakiness" of the peak. This approach appears to be consistent with the European examples presented above.

3.2.7. Activity-Based Models

Rossi et al (2008) note that activity-based models commonly use assignment procedures that are similar to those used in conventional trip-based models. The public transport crowding techniques discussed above are therefore expected to apply to most activity-based models, though the feedback of costs will need to be tailored to the specific structure of the model.

3.3. Application in Australia

3.3.1. WebTAG

There is very little current Australian guidance on implementing crowding in public transport assignments. The Australian Transport Council (ATC, 2006) provides some limited guidance on in-vehicle crowding factors but accepts that "*there is less research on crowding valuation than other public transport attributes, particularly in the Australian context*". It is useful therefore to turn to other international standards for advice. The UK's WebTAG (Transport Analysis Guidance) recommends the following:

Unit 2.10.2

"Crowding should only be modelled where it is likely to have a significant effect on traveller behaviour or where an impact on crowding is one of the scheme's objectives; even where crowding is not modelled volume to capacity ratios should be monitored."

In the context of this study there are two important themes emanating from the above guidance:

a) In terms of congestion pricing, where mode shift to public transport may be a policy driver, it is important that models include the true cost of travel on public transport so that the behavioural switch from car to public transport is accurately represented. This was one of the recommendations made in the earlier report "Review of Transport Model Capabilities for Road Pricing"; and
b) A useful first step, before looking to implement crowding in Australian models, is to conduct analysis on volume to capacity ratios – ensuring that public transport capacities are accurately represented in the models.

Unit 3.1.2

"It is general practice in the UK for public transport models to ignore the potential impacts of crowding upon route choice and perceived costs, though a notable exception occurs in models of London. Where this significant simplification is unacceptable, the assignment process needs to form part of an iterative process under which wait times and/or perceived journey times are recalculated between runs of the assignment model, with the iterations carrying on until a converged position is achieved. However, as is the case with the LTS model of London, the resulting model run times can become very large. However, where crowding exists or could occur as a result of some strategies or plans, it may be important to represent it in the model to ensure that decisions are robust."

In some cities, such as Melbourne, there is clear evidence of overcrowding during the commuter peaks. This would presumably be exacerbated by mode shift caused by some form of highway

congestion charge. In situations like this, it could be argued that public transport crowding should be modelled to support a policy decision on congestion charging.

Unit 3.11.2

"Congestion in highway assignment and capacity problems in transit assignment are not the same. This is for two reasons. Firstly, the cost function is not increasing continuously, but the finite capacity of public transport vehicles will lead to a step function; either a traveller can board the arriving vehicle or not, in which case the waiting time will increase by one headway. Secondly, capacity problems will only be experienced by boarders. Passengers on-board have priority and do not perceive the same increase in cost, although they may experience some increase in discomfort due to crowding. In frequency based models it is possible to handle capacity problems implicitly through a concept referred to as effective frequency. The idea is to increase the perceived costs of boarders through a local reduction in service frequency, reflecting the fact that the passenger may not be able to board a vehicle at a particular point because of overcrowding. This approach is implemented in EMME/2 but can be criticised for two reasons: a) A cost increase based on the number of passengers wanting to board and spaces available is still a continuous cost function; b) an increase in cost does not prevent line capacities being exceeded, leading to inaccuracies elsewhere in the network. Additionally, it is not clear how the correct wait time can be extracted for demand response modelling and appraisal. Scheduled based models can treat capacity problems explicitly and the modeller can see which runs suffer from capacity problems."

This guidance focuses on the 'wait time adjustment' component of capacity constraint modelling. The criticism placed on EMME/2 regarding line capacities being exceeded may be fair but as noted earlier in this report the CUBE crowding function **does not** allow capacities to be exceeded. In our view, this guidance is quite academic and never put into practice.

3.3.2. The Australian Context

A common argument in support of not modelling public transport capacity constraints is that where networks have spare capacity (i.e. services are currently timetabled to run 20 trains per hour but the network capacity is 25 trains per hour), extra services can be supplied as necessary. This is thought to be especially the case with the bus mode which in some Australian cities is the dominant public transport mode.

This argument will not always apply for several reasons:

1) Additional services will often require additional capital and operating expenditure plus government subsidies. If government budget priorities change, it may not always be reasonable to assume additional capacity will be supplied 10 or 20 years into the future.

2) Where governments are appraising schemes aimed at relieving public transport capacity constraints (E.g. cost benefit analysis of purchasing and operating additional vehicles), it is important to take account of the cost of 'base case' crowding in order to calculate an accurate economic benefit.
3) There may be 'pinch-points' on the network such as bus/train or bus/ferry interchanges, where extended dwell times are such that the network capacity is constrained.

SKM recently undertook an appraisal of the proposed Sydney Metro. The demand modelling was carried out using Sydney's Strategic Transport Model (STM) which does not currently incorporate public transport crowding. A 'post-processing' procedure had to be adopted whereby crowding factors (in the form of in-vehicle multipliers) were applied to public transport journey times based on passenger volumes. A journey time elasticity was then applied to 'suppress demand'.

The above 'post-processing' procedure is appropriate for calculating economic benefits, however it does not influence mode choice decisions, as the crowding cost is not fed back into the model iterations. In the context of travel demand management, therefore, a post-processing procedure is not appropriate – crowding must form part of the public transport assignment.

At the start of Chapter 3, the distinction was made between four categories of public transport crowding. Of those four, only two are commonly incorporated into strategic models: in-vehicle crowding discomfort and wait time adjustments. All the Australian models operate on either the EMME or CUBE platforms and therefore in theory both these components of crowding can be modelled.

In the Australian context it also appears reasonable to (in the short term at least) implement only the in-vehicle crowding function. This is because:

1) the London models (where it can be argued crowding is of a greater concern) only incorporate the in-vehicle discomfort component;
2) there are outstanding issues in relation to how the software (especially EMME) deals with passengers who are unable to board the first available service; and
3) the issue of not being able to board the first available service usually occurs when there is disruption; the strategic models, however, model services running at frequencies consistent with the timetable.

If future analysis showed an increased likelihood of passengers not being able to board the first service, it would be appropriate to then consider implementing this second component of public transport crowding and allocating resources to address the software specific issues.

3.4. Data Requirements

3.4.1. Public Transport Vehicle Data

Modelling public transport crowding requires accurate representation of line capacities. Service headways are existing inputs to the models, therefore for each line an average vehicle capacity is required to generate the total line capacity. Models generally contain a notional figure for capacity but it is strongly recommended these are reviewed as part of the process of incorporating PT capacity constraints.

The default CUBE methodology requires input of both **seat capacity** (number of seats) and **crush capacity** (seat plus standing capacity). An alternative method, akin to the values taken from the Douglas report given in Figure 9 would only require seat capacities to be entered and the crowding function assumes the proportion of sitters and standees based on the load factor. Implicitly, however, the function must allow for the vehicle configuration: most of the functions used in London take the load factor (passengers/seats) as primary, but also modify the function to reflect "crush capacity" (max passengers/seats).

It is noted that more recent British research states that passengers per square metre of standing space is a 'better' measure of crowding (MVA Consultancy, 2007), however Australian data are not currently available to apply this measure in Australian models. In some public transport systems, for example the London Underground, seating is intentionally reduced to create more room for standing passengers.

Whilst base year capacity information should be straightforward to access, assumptions may be required in relation to future rolling-stock characteristics.

3.4.2. Crowding Function

The crowding function is used to calculate an in-vehicle time adjustment factor based on a given vehicle loading. Australian values are available from Stated Preference (SP) survey work conducted by Douglas Economics for Railcorp in Sydney. The use of these values in the initial crowding modelling appears to be an appropriate and cost effective solution. Similarly, since the values appear to apply to an individual train, then adopting the PDFH guidance[7] of adjusting these values by 10% over the peak period is sufficient in the short term.

It is noted that people's valuation of crowded conditions is related to their value of time (VOT). Values of time differ by income and journey purpose and therefore it can be argued that the valuation of crowding will be different in each Australian city. However as the general approach

[7] See page 19 for further discussion of the PDFH guidance.

is to apply in-vehicle multipliers, VOT only becomes an issue where routing choice involves trade-offs between fare and time.

3.5. Key Findings

Four principal impacts of public transport crowding have been identified:

a) In-vehicle discomfort;

b) Excess wait time;

c) Increased dwell times; and

d) Platform crowding.

In terms of strategic transport modelling, it has been argued that only in-vehicle discomfort and excess wait times can be incorporated into the modelling. Indeed both the main software platforms (EMME and CUBE) have established procedures for handling such effects. However, in considering Australian conditions and international practices, it is our view that the focus for implementing public transport crowding should be on in-vehicle discomfort.

With regards to data requirements, Australian valuations for passenger in-vehicle discomfort (which define a crowding function) already exist, reducing the immediate need for primary research. However, one of the principal actions that is recommended in the implementation of crowding is an audit of existing capacity data (frequencies, seat and crush capacities) that may already be coded into NTMWG member jurisdictions' models.

With public transport crowding being applied in the assignment model (post-processing "bolt-on" crowding procedures are not considered appropriate), the assignment must undergo several iterations, thereby extending the model run time and introducing convergence issues. Problems associated with oscillation between competing routes may also lead to spurious model outputs, potentially affecting the calculation of economic costs and benefits. The literature review has identified techniques which can be implemented to assist convergence.

Because of these implications, international guidance recommends implementing public transport crowding only where it is likely to have a significant effect on traveller behaviour, for example as indicated by high volume-capacity ratios on modelled public transport services. In considering the effects of congestion charging, it will be important for the jurisdiction modelling groups to make a judgement on whether crowding will become significant within forecasting time frames.

The timing of implementation options will differ by jurisdiction (see Section 4) however a suggested timetable for implementation is provided in Table 13.

- **Table 13 Public Transport Crowding Implementation Timeframe**

Time Frame	Action
Short term	▪ Ensure public transport capacities are accurately coded into the model; and ▪ Assess need for modelling crowding.
Medium term	▪ Implement in-vehicle crowding functions based on published values.
Long term	▪ Obtain jurisdiction specific crowding valuations through primary research.

4. Implementation Options

4.1. Overview

Each jurisdiction's strategic transport model uses a different structure with respect to trip purposes, household types, cost formulations, parameters, networks and other assumptions (Sinclair Knight Merz 2009). Time period choice and public transport crowding solutions will therefore need to be adapted to suit each individual model.

The structure of each model will need to be carefully considered when implementing time-of-day choice modelling. By contrast, public transport crowding is more straightforward and the methodology is likely to be consistent across jurisdictions. However, the need for crowding modelling will need to be assessed for each city and parameters specifically tailored to represent local conditions.

Whilst the recommendations below are jurisdiction specific, there is considerable commonality between the various models. The collaborative approach demonstrated by the NTMWG should therefore be continued so that the jurisdiction groups can share research and information, and ensure a consistent approach wherever possible.

This chapter commences with a look at general considerations for implementing time-of-day choice and public transport crowding into the Australian models. This is followed by a more detailed assessment of solutions for each jurisdiction's model.

4.2. General Implementation Considerations

4.2.1. Time-of-Day Choice

The key considerations for implementing a time-of-day choice model are discussed in Table 14. These have been developed on the basis that an Auckland-style time-of-day model represents best practice for implementation in Australia.

Table 14 Time-of-Day Choice Implementation Considerations

Consideration	Description
Existing model trip-making unit (i.e. trip or tour)	Each of the Australian capital city models (except Sydney's) currently uses a trip-based approach. Each model would need to implement a tour-based approach for home-based travel.
Number and definition of modelled time periods	Time periods differ between jurisdictions, so model parameters and segmentations will also differ.
Suitability of existing household travel data	Implementing a tour-based approach will require further analysis of existing survey data. Household travel datasets will need to be assessed to ensure that they support trip-linking to form tours (though this should usually be the case).
Model lifecycle	Including time-of-day choice is a major structural change. It may be best suited for implementing as part of a wider model recalibration exercise.
Choice parameters	Because of the lack of Australian data on the sensitivity of departure time choice in response to congestion charging, parameters may need to be "borrowed" from overseas models.

4.2.2. Public Transport Crowding

As previously noted, the processes to implement public transport crowding already exist in the Cube and EMME software packages. Most of the issues in implementing public transport crowding relate to jurisdiction-specific conditions such as current and planned public transport network capacity. The key considerations for implementing public transport crowding are discussed in Table 15.

Table 15 Public Transport Crowding Implementation Considerations

Consideration	Description
Is crowding an issue now or in the future?	If there is spare capacity to accommodate the expected growth in patronage, a public transport crowding model may not be required.
Accurate representation of transit capacity.	An audit exercise is recommended to check that public transport capacities are accurately represented in the model (e.g. frequency of services, stopping patterns, seating capacity).
Availability of demand profiles.	Because public transport loadings will generally not be uniform across the peak period, demand profiles may help to correctly represent average peak loading conditions on public transport.
Availability of a crowding function	Crowding functions are available from international sources as well as Australian research. There is scope for consideration of jurisdiction-specific revealed and/or stated preference research exercises.

4.3. Canberra Strategic Transport Model (CSTM)

Implementation	Summary
Time-of-Day Choice	Implement an incremental choice model that factors the peak period car matrices prior to assignment based on the change in the peak/off-peak cost differential.
Public Transport Crowding	Achieve good public transport validation in the recalibrated 2006 model. Conduct analysis of current and future volume to capacity ratios to determine whether crowding should be modelled.

4.3.1. Time-of-Day Choice

The ACT CSTM is a four-step strategic transport model covering the entire ACT and is managed by the ACT Department of Territory and Municipal Services (TAMS). Trip demand matrices are segmented by six journey purposes at the trip generation, trip distribution and mode choice stages. Unlike the other jurisdictions, the CSTM only models a single period (AM peak). Slow modes (walking and cycling) are not included in the model and commercial vehicles are excluded on the basis of data availability.

Because the CSTM is an AM peak model, its capacity to model time period shifts is limited to estimating the "spill" of trips from the peak to off-peak in response to demand management initiatives. In order to implement an Auckland-style methodology, a substantial model development exercise would be required to expand the model to include multiple time periods. Given that the CSTM is currently undergoing a recalibration to a 2006 base year, and modelling resources in the ACT are constrained, there is unlikely to be support to expand the model in the short to medium term.

A simpler Wellington-style methodology is likely to be more appropriate for the CSTM. An incremental choice model could be implemented prior to assignment which factors the AM peak matrices (separately by journey purpose) based on the change in the peak/off-peak cost differential. Whilst the model does not include an explicit representation of the off-peak, off-peak costs can be estimated by skimming times and distances from an uncongested network. As a starting point, it is recommended that the Wellington model sensitivity parameter be applied and adjusted depending on the response generated by the model. Further, the jurisdiction may consider commissioning stated preference surveys in order to generate Canberra-specific elasticities.

The above technique is effectively a "bolt-on" to the existing model and should not require any significant modifications to the existing sub-models. Implementation should be straightforward.

4.3.2. Public Transport Crowding

The public transport network is "quite basic" and forecasts of public transport require improvement – this is important for the model to accurately represent mode shift effects of road pricing schemes. However the model is in the process of being recalibrated to a 2006 base year and the accuracy of the public transport model is being addressed. Public transport in Canberra is currently solely in the form of bus with anecdotal evidence suggesting services are operating close to or at capacity during the AM peak. A business case has been developed for the introduction of light rail services.

The priority for the CSTM with respect to public transport is to improve the model to achieve a validation consistent with international practice. As part of this process it is expected that care will be taken to ensure the supply side (service frequencies and capacities) is accurately represented. Once this is achieved it is recommended that analysis of volume to capacity ratios be undertaken for 2006 and each forecast year in order to understand whether crowding is likely to become an issue into the future. It will also be useful to have some knowledge of the local policy and/or contractual conditions which govern the supply of additional services to meet increasing demand. If it is likely that additional services will be supplied to meet demand, then public transport crowding may not be required in the CSTM.

Note that the current model run time for the CSTM is approximately 2 hours. This would increase if crowding was implemented but would remain well within acceptable bounds.

4.4. Sydney Strategic Transport Model (STM)

Implementation	Summary
Time-of-Day Choice	Because the STM already uses a tour-based approach, the addition of a time period choice component should, in theory, involve little restructuring. However, because the model is differently structured to those of the other jurisdictions, a more detailed assessment of the model will be required before an Auckland-style approach can be implemented.
Public Transport Crowding	With current crowding levels in Sydney, it is likely that some form of crowding model will be required. Given the long model run times, investigations should be carried out by the jurisdiction to see whether crowding can be omitted from some iterations of the model in order to speed up run times.

4.4.1. Time-of-Day Choice

The Sydney model differs from the other jurisdictions' models in its use of tour-based demand modelling. The tour-based approach models the full round trip of a traveller (for example, home-work-home), rather than individual trips as in a traditional production-attraction trip-based approach. Fixed time period factors are applied to the matrices prior to assignment.

Giving that international best practice in time-of-day models is to use tours rather than trips, it would appear that the tour-based approach of the STM offers scope for TDC to develop a time-of-day choice model without substantially restructuring the current model. Further investigation of the model structure will be required in order to understand the full complexities of integrating time period choice.

4.4.2. Public Transport Crowding

Crowding is a present issue on peak-period public transport in Sydney and is likely to continue to be significant in future modelled years. One of the issues affecting Sydney is that the peak service provision is for a one hour period, whereas the modelled peak period is two hours in duration. In developing crowding penalties, it is desirable that the profiles of demand and supply are taken into account so that the average penalties are appropriately based on conditions over the two hour period.

The existing EMME crowding macro is a suitable basis for the public transport assignment but further development work may be required to suit STM's needs. The cost skims generated by the crowded assignment need to be fed back to the earlier steps of the model. The initial attempt at

implementing a crowding function should be based on the values provided by Douglas Economics (2006) – these values are specific to Sydney and therefore well suited to the STM. Consideration needs to be given to whether these values can be applied to public transport modes other than rail. Further work to consider the international practice for bus (and possibly ferry) may be required.

The STM currently takes around 24 hours to run and the addition of multiple iterations of the public transport assignment will have an adverse impact on run times. SKM's experience from London Docklands Light Rail Model, is that a crowded public transport assignment can take 10 to 30 iterations to converge. Therefore the public transport assignment can be expected to take substantially longer plus the additional time taken to calculate the crowding penalties between iterations (in the network calculator). With model run times being an important issue, consideration should be given to including crowded public transport assignments only on some model iterations.

4.5. Brisbane Strategic Transport Model – Multi Modal (BSTM-MM)

Implementation	Summary
Time-of-Day Choice	Model structure is compatible with the Auckland methodology. The jurisdiction needs to check that sufficient local household travel data is available to estimate tour time groups and related time period factors.
Public Transport Crowding	Components of public transport crowding have already been implemented. Given the long model run times, investigations should be carried out by the jurisdiction to see whether crowding can be omitted from some iterations of the model in order to speed up run times.

4.5.1. Time-of-Day Choice

The BSTM-MM forecasts demand for a 24-hour period and applies fixed time-period factors to allocate trips to the AM peak, inter peak, PM peak and off-peak. Demand is segmented by eight resident trip purposes at trip generation, trip distribution and mode choice stages. BSTM-MM has a mode choice model that includes seven modes: car driver, car passenger, walk to public transport, park and ride, kiss and ride, cycle and walk.

The Auckland methodology can be directly applied to the Brisbane model, though a specific concern in Brisbane is the data availability. It has been noted that the household travel survey was "stretched" in order to derive the existing time period factors, so there are concerns that there may be difficulties expanding the use of this data to calculating tour time groups.

The first stage to implementing the time-of-day model in the BSTM-MM should be to review the available household travel survey data to assess whether it is suitable for this purpose. If it is shown to not be suitable, consideration should be given to employing factors derived from surveys in other jurisdictions. The model could then be enhanced once the next scheduled round of Brisbane household surveys takes place, ensuring that the survey has adequate coverage.

4.5.2. Public Transport Crowding

Recognising that public transport crowding is an issue in Brisbane, the BSTM-MM is more advanced in its readiness to implement public transport crowding than the other jurisdictions. An exercise to check the accuracy of public transport capacity data in the model has already taken place. Further crowded public transport assignments using the default EMME macros have been run with in-vehicle crowding and excess wait time. The functionality to model the impact of increased dwell times has also been investigated.

The main issue for BSTM-MM is data availability, in particular appropriate crowding functions. In the short to medium term it would be reasonable to assume publicly available crowding relationships, such as those provided by Douglas Economics (2006). In the longer term stated preference studies aimed at estimating separate crowding functions by mode might be considered.

The model methodology needs to be ensure that the crowded costs for the public transport assignment are fed back to earlier steps in the modelling pipeline.

As with the Sydney model, the BSTM-MM takes approximately 24 hours to run, so it will be useful to experiment with the number of model iterations for which a crowded public transport assignment is included.

4.6. Metropolitan Adelaide Strategic Transport Evaluation Model (MASTEM)

Implementation	Summary
Time-of-Day Choice	The Auckland methodology appears to be a good fit for this model. Peak hour factors provide the opportunity to model time period choice at a finer (more microscopic) level of time segmentation.
Public Transport Crowding	Analysis is required to decide whether capacity constraints are an issue for all public transport modes. Appropriate crowding functions applicable to light rail should be identified.

4.6.1. Time-of-Day Choice

MASTEM forecasts demand for a 24-hour period and applies fixed time-period factors to allocate trips to the AM peak, PM peak and off-peak periods. As well as peak periods, the model also uses peak hour assignments to model the busiest part of the peaks.

The Auckland methodology is suitable for implementation within the Adelaide model. The MASTEM model implements trip distribution before mode choice for all trip purposes, so time period choice would need to be implemented between the trip generation and distribution steps.

It is important to note that work is underway to expand MASTEM to include a fourth time period; this work needs to be completed before implementing the time-of-day choice methodology.

As the MASTEM includes a representation of peak periods and peak hours (fixed factors defining the relationship between the two), there is potential to model congestion charging and micro time choice via adjustments to peak hour factors. A methodology to do this has not been identified by this study, but it is envisaged that it would be possible to implement an incremental model that forecasts changes to the peak hour factor. This would allow DTEI to model the impact of alternative peak hour and shoulder peak pricing.

4.6.2. Public Transport Crowding

Work has been undertaken to implement the Cube public transport crowding assignment in the MASTEM model. Although this will lengthen the model run time, the current run time is relatively short (approximately two hours).

As well as bus and train, the Adelaide public transport network also includes tram services. Decisions will need to be made whether crowding needs to be applied to some or all of these modes; mode specific crowding functions may need to be applied. Further work needs to be undertaken in order to form a conclusion on both these issues.

In implementing the crowding functionality, the cost skims that are fed back from the assignment into earlier steps should incorporate the crowding costs.

4.7. Melbourne Integrated Transport Model (MITM)

Implementation	Summary
Time-of-Day Choice	Model structure is suitable for employing the Auckland methodology. Recent household travel survey is expected to contain sufficient sample size for developing tour time groups.
Public Transport Crowding	Crowding is an acknowledged issue in Melbourne. A method for minimising the impact of crowding on model run times is required.

4.7.1. Time-of-Day Choice

The MITM is currently undergoing a recalibration exercise to rebase the model to 2007/2008 household travel survey data. Fixed time period factors will be applied to 24 hour demands in order to generate matrices for four time periods: AM peak, inter-peak, PM peak and off-peak. The structure of the model is such that the Auckland methodology can be readily incorporated to model time-of-day choice.

The household travel data (VISTA) is recent and it is expected that there is sufficient sample size within each trip purpose category to estimate tour time groups with an appropriate level of confidence.

4.7.2. Public Transport Crowding

Public transport crowding is acknowledged as being an issue in Melbourne. Indeed, infrastructure projects such as the Regional Rail Link and Melbourne Metro are being planned to add significant capacity to the public transport network. The network includes three main modes (train, tram and bus) with most radial commuting movements being undertaken by train and tram.

The MITM running times are amongst the longest of all the jurisdiction models. The impact of introducing public transport crowding could potentially result in run times approaching two days. This is clearly undesirable and supports the need for work to be undertaken to find acceptable methods that will reduce the time and computing demands.

4.8. Perth Strategic Transport Evaluation Model (STEM)

Implementation	Summary
Time-of-Day Choice	Existing model is well suited to Auckland methodology. The jurisdiction needs to ascertain whether suitable data already exists.
Public Transport Crowding	It is recommended that analysis on capacities and demand volumes be undertaken to enable the jurisdiction to form a view as to whether crowding is an issue.

4.8.1. Time-of-Day Choice

The Perth STEM applies fixed time period factors prior to assignment. Trip generation, mode-choice and distribution are undertaken on a 24 hour basis. The model includes four time periods: AM peak, inter-peak, PM peak and off-peak. The Auckland methodology can be readily implemented with the introduction of time period choice between the trip generation and mode choice/distribution models.

The Department of Planning and Infrastructure modelling group has indicated that it is supportive of this methodology but acknowledges the significant time and resources required for implementation.

The first action is for the household travel survey to be revisited to ensure appropriate data exists from which tour time groups can be derived.

4.8.2. Public Transport Crowding

The need for modelling public transport capacity constraints in Perth is not clear. It is therefore recommended that analysis be undertaken in order to form a view on this requirement. In order to do this, the representation of public transport capacity in the model should be checked for accuracy. The model run time of the Perth STEM is relatively quick (approximately one hour) and therefore the implication of public transport crowding on run times should not be a significant barrier to implementation.

If a decision is made that public transport crowding should be implemented, the next step will be to derive appropriate crowding functions. In the short term it is recommended that data available from existing sources be applied before undertaking any primary research.

Appendix A: Data Sources

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Appendix B: Auckland Regional Transport Model

Please note that this paper has been submitted to the ATRF conference taking place in Auckland between 29 September and 01 October 2009. Whilst the abstract has been accepted, the paper is yet to be peer reviewed. However it does provide an accurate and detailed mathematical explanation of the time-of0day choice modelling implemented in the Auckland Regional Transport model.

Innovations in modelling time-of-day choice

The Auckland Regional Transport Model (ART3, 2008)

R. Wood, D. Ashley
Sinclair Knight Merz Ltd
Melbourne, Australia
rwood@skm.com.au

D. Young
David Young Consulting
Auckland, NZ
david.young@ihug.co.nz

J. Bates
John Bates Services
Abingdon, Oxon, UK
113300.3565@compuserve.com

Abstract—**With road user charging and toll roads potentially on the agenda for transport strategies in Auckland, it is important that traffic forecasts reflect the impact of charges varying by time of day. Consequently, for the new regional transport model (ART3), an innovative design for a time of day choice model was developed. This model recognises both international findings on the way in which this topic should best be modelled and sensible limits to the effort involved in developing and applying such techniques.**

One important innovation in the development of ART3 is that the procedure estimates road user charges and other costs experienced on the complete tour (rather than for isolated trips), thus considering the times of travel of both the outward and return trips. Another significant innovation is that the procedure has been overlaid on a conventionally estimated aggregate hierarchical distribution and mode choice model system. As such, neither the costs of estimating this type of model, nor the run times taken to apply it are significantly affected.

In principle, the procedure presented in this paper could be added to existing multimodal transport models without the need for re-estimation.

I. Introduction

Strategic transport models seek to represent the travel behaviour of a population across a transportation network. In doing so, such models allow for the assessment of alternative scenarios leading to informed and appropriate transport policy decisions.

In principle, the fundamental task of any strategic transport model is to forecast the transport *choices* made by the modelled population in the context of a future scenario. Such choices relate particularly to mode, destination, route or the subject choice of this paper; time-of-day (ToD).

It is well known that a population's behaviour with regard to the time of travel is not static. That is, individuals will alter their time of travel in response to changes in congestion levels.

Recent global interest has emerged with regard to policies that tackle congestion via road user charging. In many instances, such scenarios seek to influence travellers' ToD decisions by the application of differential pricing across the day. It is clear that strategic transport models used to assess such policies must represent the population's sensitivity to such cost changes with an appropriate level of fidelity. However, the great majority of currently implemented strategic transport models do not and thus cannot hope to model such scenarios with any degree of certainty.

In 2007, the Auckland Regional Council (ARC) commissioned Sinclair Knight Merz Ltd, in conjunction with Beca Infrastructure Ltd and David Simmonds Consultancy, to develop new regional land use and transport models; the latter known as the Auckland Regional Transport Model (ART3). It was a requirement that this transport model have the capability to assess road pricing strategies with potential variation in cost by ToD.

The underlying structure of ART3 is a conventionally estimated, 4-stage, aggregate hierarchical model (Ortúzar & Willumsen, 2001). In order to incorporate time-of-day choice into this model, it was necessary to re-arrange the model so

that the representation of travel for ToD choice could operate as tours rather than trips.

The paper proceeds as follows; in the following section, a brief overview of the current state of practice with regard to ToD choice modelling is presented. Section III then provides an overview of the ART3 model, with particular focus on the ToD choice component. The choice modelling methodology is then formally presented in section IV. This is followed by section V; an overview of the procedure used to calibrate the ToD choice model. The paper concludes with a brief summary.

II. BACKGROUND

There exists an abundance of literature regarding the implications of departure time choice for highway project modelling. Booz Allen Hamilton, 2003 provides an extensive review of this literature, suggesting that although some developments exist in the USA, the UK is further advanced. The UK Department for Transport (DfT) provides a web-based guidance for appraising multimodal transport projects and proposals known as WebTAG. This guidance states;

"…Thus, as a core requirement, properly formulated variable demand and traffic assignment models are required to refine the preferred options and to support the business case. The variable demand model should include modules representing trip frequency, mode choice, macro time of day and trip distribution."(WebTAG, unit 3.12.2, para 1.1.9)

In terms of how macro time period choice (between the broad modelled time periods) should be incorporated in models, the guidance further states that:

"There is limited evidence on the strength of the macro time choice mechanism. Recent Departmental research suggests that time period choice is generally more sensitive to changes in travel conditions than mode choice."
(WebTAG, unit 3.10.3, para 1.8.4)

Further discussion in this WebTAG unit makes clear that the likely position of macro time-of-day choice in most hierarchical models would be at a similar level to mode choice but higher than distribution, which is usually found to be more sensitive (WebTAG unit 3.10.3, paras 1.9.4, 1.11.15-17).

It has been demonstrated that if one wishes to use discrete choice theory for ToD choice modelling, the theoretically consistent way to proceed, given these hierarchical requirements, is to move to a tour-basis (Gordon et al., 2007). Using a tour-basis, the simultaneous choice of outbound and return time periods are modelled, conditional on the tour cost for that time period combination.

As the DfT guidance currently stands, there is some tension between the general recommendations for PA modelling and ToD choice modelling (though tour modelling is not ruled out). In other words, there is no recommendation to use a tour approach, but at the same time the hierarchical requirements for time of day modelling remain. In light of this, it is likely that most TIF models[1] will either ignore time of day modelling completely, or resort to their own devices (the appropriateness of which will depend strongly on the expertise of the model architects).

Two exceptions should be made to the above discussion, in the UK context. The first is the APRIL model, which was specifically developed in the 1990s to assess road pricing in London: this contains a tour-based time of day choice model, as well as income segmentation. More recently, the PRISM model, developed by RAND Europe for the West Midlands region, has implemented both effects in its TIF work. However, this model contains several features that are different from conventional UK models. Although substantial model documentation is available, it has not been widely examined.

Thus, time-of-day choice modelling is a relatively new topic for which there is a range of different methods being discussed, researched and used internationally but, as yet, no conclusively leading methodology. Nonetheless, the ART3 implementation of ToD choice modelling, which we

[1] This is an acronym for "Transport Improvement Fund", but in this context can be treated as synonymous with road pricing.

describe in this paper, appears to lie within the range of current thinking. Most importantly, the implementation is developed within the constraints of a conventional, trip-based, aggregate four step model.

III. TIME-OF-DAY MODELLING IN ART3

ART3 is a 4 stage, multimodal city transportation model linked to the land use model; ASP. An illustration of the base structure of this model (i.e. excluding the ToD choice element) is presented in figure 1. With reference to this figure, the trip end, mode choice and distribution sub-models were to be estimated on 24 hour data (trips and generalised costs), following which time period factors would be applied to create peak and interpeak matrices for assignment purposes. The challenge was to design a ToD choice procedure which did not change (or indeed complicate) the estimation of the model presented in figure 1. In doing so the risks regarding estimation, budget and delivery timeline would be minimised.

The methodology developed for modelling ToD choice within the ART3 model involved introducing a ToD split within the destination and mode choice hierarchy, based on tour concepts (see figure 2). However, re-estimation of the model was not required.

Initial research demonstrated that the base model (i.e. figure 1), which had been estimated on a 24 hour trip basis, could be implemented on a tour basis and obtain consistent forecasts. With this new structure, the tours were classified into *tour groups* representing combinations of outbound and return time periods, and a ToD choice model was incorporated to predict changes in the proportions of tours in these groups as a result of, for example, congestion charging. In this way, while retaining consistency with the estimated 24 hour trip-based model, the implemented tour-based model became sensitive to time-specific transport strategies.

For ART3, five time periods were defined. Within the context of these time periods, four tour groups were defined (A-D in table 1). These groups were based on whether the outbound and return trips of the home-based tour were in either or both of the AM and PM peak periods. The base split of trips

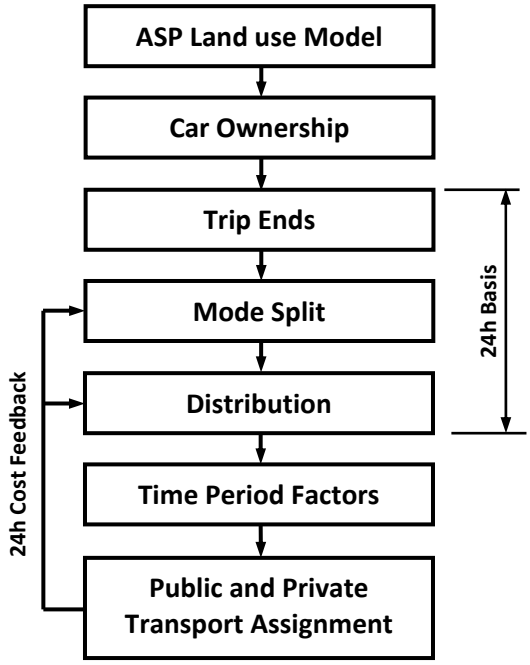


Figure 1. Base ART3 model structure

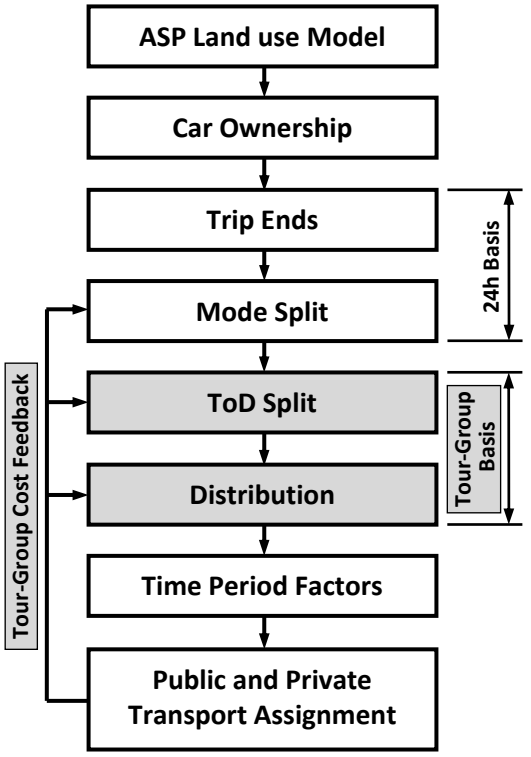


Figure 2. Modified ART3 model structure, incorporating ToD choice

between the four tour groups for each mode and purpose combination was determined from the household travel survey, as presented in table 2.

The ToD split was implemented as an incremental logit model. That is, for the base scenario, the model splits tours into tour groups in accordance with the proportions given in table 2. For forecast scenarios, the time of day model modified the base split in accordance with changes in the relevant costs of travel by ToD. Section IV discusses this in more detail.

In summary, a methodology was developed by which ToD choice was represented in the ART3 model. This methodology was implemented in a manner consistent with discrete choice theory and enabled changes in the times of travel to be forecast.

TABLE I. ART3 TOUR GROUPS

Outbound Time Period	Return Time Period				
	AM Peak	*Inter Peak*	*School Peak*	*PM Peak*	*Off Peak*
AM Peak	B	B	B	A	B
Inter Peak	D	D	D	C	D
School Peak	D	D	D	C	D
PM Peak	D	D	D	C	D
Off Peak	D	D	D	C	D

TABLE II. ART3 TOUR GROUP SPLITS BY MODE

Mode	Purpose	Tour Group			
		A	*B*	*C*	*D*
Car	*Work*	39%	21%	15%	25%
	Education	14%	59%	5%	22%
	Shop	5%	13%	16%	66%
	Other	7%	21%	16%	56%
Public Transport	*Work*	53%	23%	14%	10%
	Education	19%	65%	6%	11%
	Shop	5%	19%	11%	65%
	Other	18%	31%	14%	37%

IV. TIME-OF-DAY MODELLING METHODOLOGY

In this section, we formalise the ToD choice modelling methodology used for ART3. This methodology was based on two key innovations; (a) the concept of modelling tours rather than trips, and (b) the inclusion of a ToD split within the destination and mode choice model. These two innovations are detailed in the following two sub-sections. Although all examples presented are specific to the ART3 model, in the interests of generality model concepts are presented irrespective of the model specifics. For brevity and readability, in the main text we restrict discussion to an outline of the methodologies. Precise mathematical details are set out in the appendices.

A. *Tour groups and associated costs*

The conventional basis for modelling person travel is the *trip*; each trip representing a single leg of the full home-to-home journey. However, as discussed in section II, when modelling ToD choice it is necessary to model travel behaviour on the basis of *tours* rather than trips. Each tour represents both the outbound (from-home) and return (to-home) trips made by a single traveller. For brevity, in this paper we address the modelling of home-based trips only, the modelling of non-home-based trips being trivial by comparison. Herein, outbound and return quantities are defined by the subscripts fh and th respectively.

To formalise our discussions regarding the modelling of temporal variation, we must first introduce our definitions of time segmentation. In the case of strategic transport models, typically discrete time periods are defined within which aggregate travel demand is modelled. In the case of the ART3 model, the following set of time periods were defined (essentially for the purposes of assignment):

$$t \triangleq \left\{ \begin{array}{c} \text{AM-Peak (AM)} \\ \text{Inter-Peak (IP)} \\ \text{School-Peak (SP)} \\ \text{PM-Peak (PM)} \\ \text{Off-Peak (OP)} \end{array} \right\}. \qquad (1)$$

A *tour group* is defined as a set of tours sharing common outbound and return time periods, denoted: $[t_{fh}, t_{th}]$. For example, the simplest such tour group contains tours with outbound and return trips occurring in the AM and PM periods respectively (i.e. [AM,PM]). For a model having τ time periods, τ^2 potential tour groups exist. However, modelling all such groups separately is likely to be impractical. Consequently, aggregation is necessary to reduce the number of modelled tour groups to a manageable

quantity. For the ART3 model, the set of modelled tour groups g contained the following four elements:

$$g_1 \triangleq \{[t_{\text{fh}}, t_{\text{th}}] | t_{\text{fh}} = \text{AM}, t_{\text{th}} = \text{PM}\},$$
$$g_2 \triangleq \{[t_{\text{fh}}, t_{\text{th}}] | t_{\text{fh}} = \text{AM}, t_{\text{th}} \neq \text{PM}\},$$
$$g_3 \triangleq \{[t_{\text{fh}}, t_{\text{th}}] | t_{\text{fh}} \neq \text{AM}, t_{\text{th}} = \text{PM}\},$$
$$g_4 \triangleq \{[t_{\text{fh}}, t_{\text{th}}] | t_{\text{fh}} \neq \text{AM}, t_{\text{th}} \neq \text{PM}\} \quad (2)$$

Each of these tour groups were known to have significantly different characteristics, and experience significantly different costs of travel. Although possibly obvious, it is worth making the following remark; the information formally represented by the two variables trips and time-periods is now represented by the variables tours and tour-groups.

Figure 3 provides a top-level overview of the proposed methodology for modelling ToD travel choices. Central to this methodology is the mode, time-of-day and destination choice (MTD) model. It is this component of the model that seeks to emulate traveller decisions, splitting tours by production zone i: $T_i^{*,*,*}$ into tours by mode m, tour group g and attraction zone j: $T_i^{mg,j}$. Driving these choices are a set of associated costs: $GC_i^{m,g,j}$; the generalised cost of travel experienced by mode m, tour group g tours, produced in zone i and attracted to zone j.A detailed discussion of this element of the model is deferred until the next section of this paper. At this point it is useful to explicitly define the subscripts: m, g, t, i and j as denoting mode, tour-group, time-period, origin/production and attraction/destination respectively.

It is necessary that the MTD model interface with the assignment element of the strategic transport model. In general, this element of the model operates on the basis of trips and rather than tours. Consequently, two mappings are required to allow for this interface. A discussion regarding these two mappings is the subject of the remaining text of this section.

To generate inputs to the MTD model, the generalised cost of travel for trips by origin-destination (OD) zone and time period: $\overrightarrow{\text{GC}}_{i,j}^{m,t}$ is used to generate the cost of travel for tours by production-attraction (PA) zone and tour group: $GC_i^{m,g,j}$. Herein, the arrow accent: $\rightarrow$ is used to denote quantities with respect to an OD base, as distinct from quantities with either a PA base or no defined direction. In principle, this mapping is achieved as follows; as we have generalised costs by time period, and there is a correspondence between the time periods and tour groups, it is merely a matter of averaging the time period values (according to the distribution of trips) to obtain the appropriate value for the tour group. This averaging is conducted both temporally and spatially to represent geographic variation in ToD travel behaviour. Specific details of this process are contained in Appendix A1.

The second mapping necessary for the interface of the MTD model with trip assignment maps tours by mode, tour group and PA zone: $T_i^{m,g,j}$ to trips by mode, time period and OD zone: $\vec{\text{T}}_{i,j}^{m,t}$. As with the mapping of generalised cost, this process is little more than a weighted averaging, the specific details of which are outlined in Appendix A2.

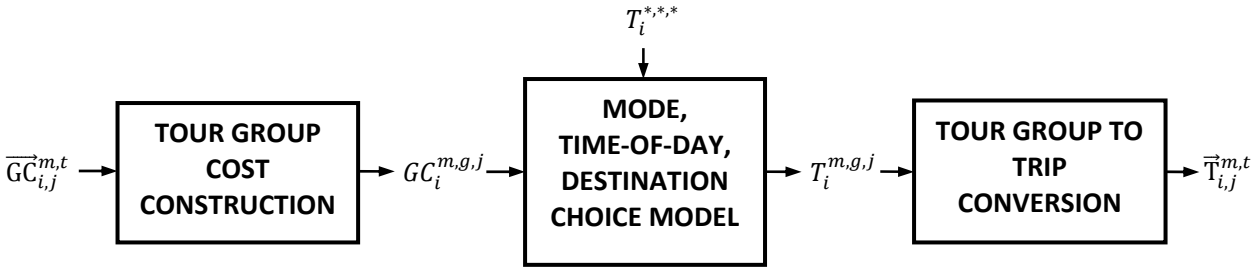


Figure 3. Top-level overview of methodology for modelling ToD travel choices

B. *Choice modelling*

The central choice modelling element of a conventional 4-stage strategic transport model is the distribution and mode split (DMS) model. It is this component of the model that seeks to represent the decisions travellers make with respect to destination and mode of travel. If one wishes to model the additional choice regarding time of travel, the DMS model is thus the natural component of the strategic model in which to impose this.

The functional form of the conventional DMS model is that of either a nested or multinomial logit model. Three potential model hierarchies (configurations) exist, as depicted in figure 4. These configurations differ by the order in which trips are split by mode and destination. To be tractable with discrete choice theory, the sensitivity of the model must be lower at the upper level of the model hierarchy. For example, for the case of the pre-distribution mode choice DMS model (see figure 4(b)), the destination split is more sensitive to changes in cost than the mode split. In the case of a simultaneous model (see figure 4(a)), both splits are equally sensitive to cost changes. DMS models are typically calibrated to survey data using maximum likelihood techniques, the model hierarchy being determined by this calibration. It is a common misconception that the model hierarchy implies the order in which travellers make their decisions. However, this is not the case; nesting is simply used to relax the independence assumption required for the construction of the multinomial logit model (Greene, 2008).

Key to inserting a time-of-day split into the DMS model hierarchy is a judgement regarding the required ToD sensitivity of the resulting model relative to mode and destination (see section II). In this paper we present the specifics for the 'insertion' of a tour group split into a pre-distribution mode choice DMS model (i.e. figure 4(b)), however the principles demonstrated may be easily extended to apply to the other hierarchical structures.

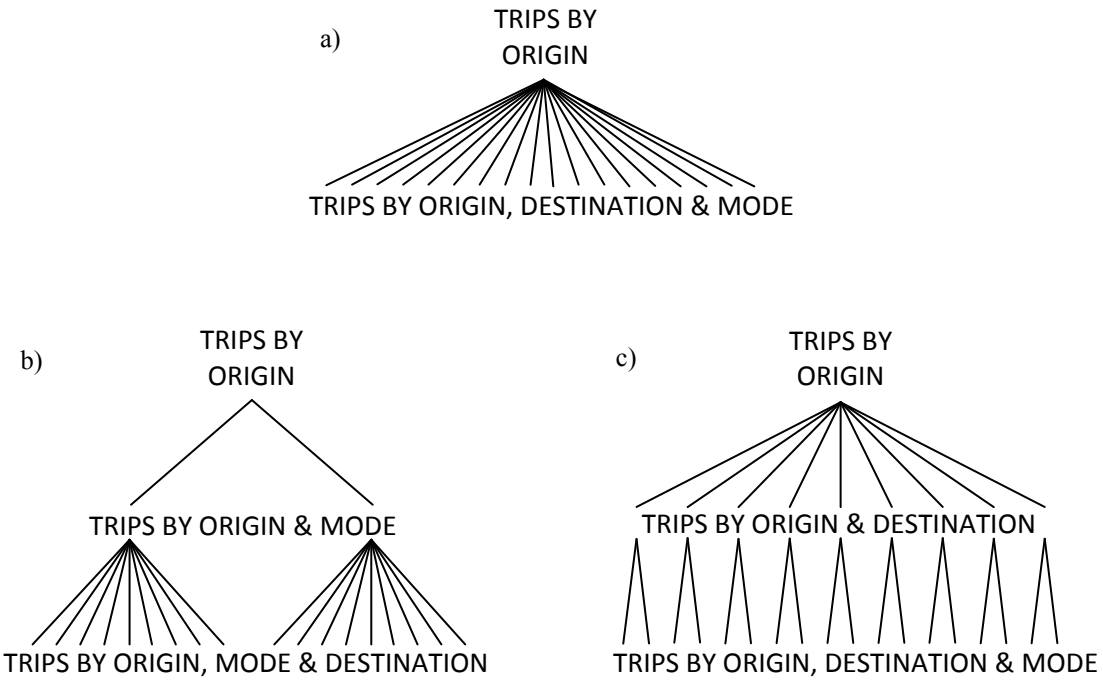
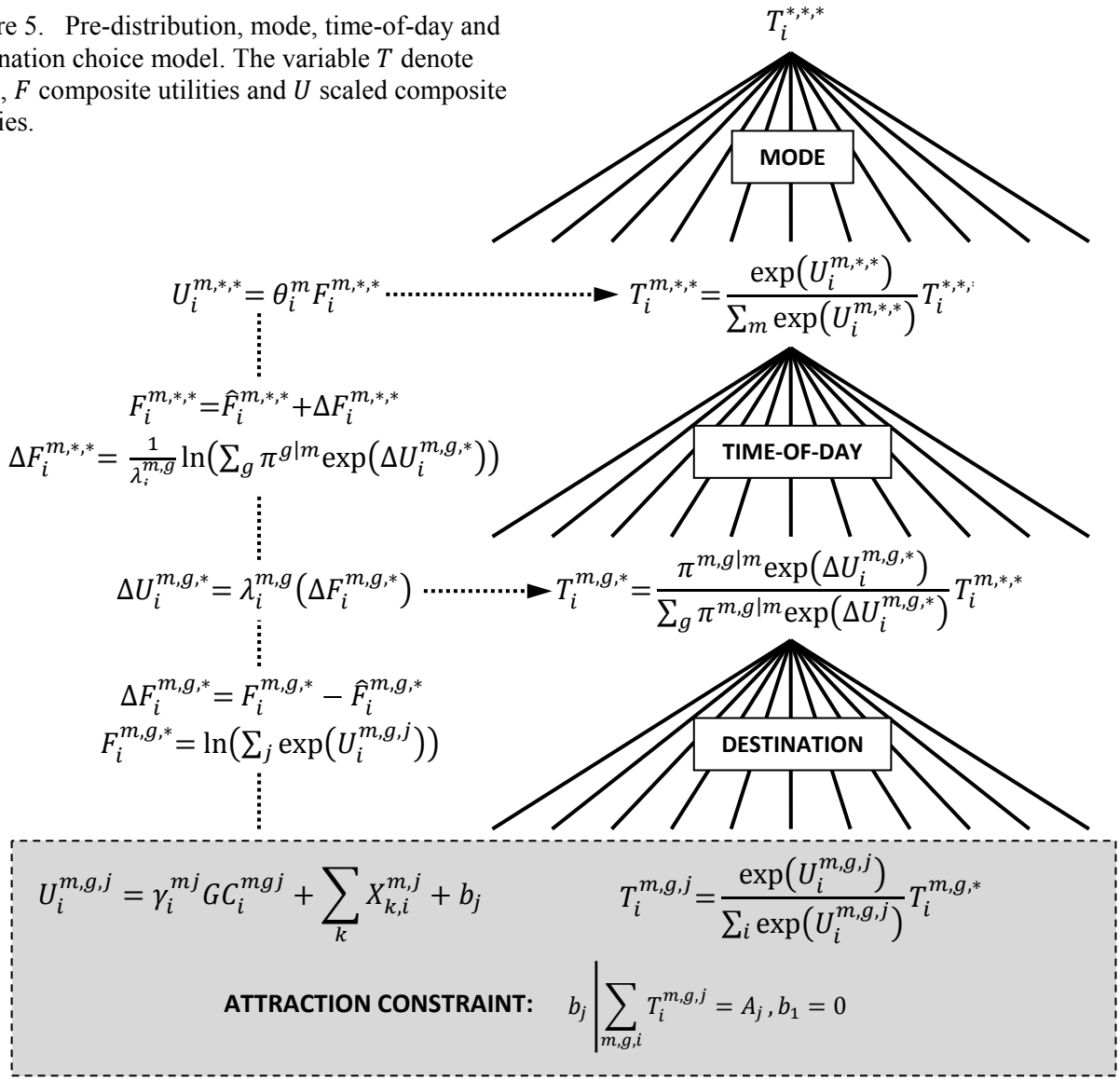


Figure 4. Conventional DMS models; a) simultaneous distribution and mode choice, b) pre-distribution mode choice, c) post-distribution mode choice.

Inserting a tour group split into a pre-distribution mode choice DMS model is of particular interest as this split is placed between the mode and destination splits. A pictorial summary of the resulting MTD model is presented in figure 5. For brevity, the remainder this section is dedicated to a top-level overview of this model, the precise mathematical workings being delayed until Appendix B1.

With reference to figure 5, the MTD model can be considered as being composed of two elements. The first of these performs the mode, tour group and destination splits that emulate traveller's decisions with regard to these alternatives (i.e. the RHS of figure 5). The second of these elements constructs the composite utilities (i.e. scaled costs) used to drive these splits (i.e. the LHS of figure 5). These two elements are linked by the attraction constraint. This constraint ensures trip attractions forecast by the MTD model agree with those forecast by the attraction model (a separate component of the 4-stage strategic model). The attraction constraint is imposed by a set of destination specific additive perturbations to the base utilities; b_j, the exact values of which are solved for via an iterative process as follows; at each iteration the attraction constraints are updated via a simple feedback law.

Figure 5. Pre-distribution, mode, time-of-day and destination choice model. The variable T denote tours, F composite utilities and U scaled composite utilities.



This alters the base utilities, which in turn alters the composite utilities and the MTD splits in such a way that the error in the attraction constraint is reduced (see Appendix B1). As a consequence of the iterative procedure employed, exponential convergence of this error is guaranteed.

In general, DMS model sensitivity parameters are calibrated using maximum likelihood techniques that rely on cross-sectional variations in base data. It is unlikely that sufficient cross-sectional variation with regard to cost by tour group (i.e. cost by ToD) will exist in this data to allow for the calibration of MTD models using the same approach. An appropriate methodology for obtaining these parameters (as used for ART3) is as follows; firstly, a conventional DMS model (i.e. without ToD) is estimated using the base data. The parameters of this model are then used in the MTD model for the mode and destination splits[2]. The process used to calibrate the sensitivity of the model to variations in cost by ToD involves 'manually' tuning the relevant parameter(s). A separate discussion regarding this process is presented in section V.

The functional form of both the mode and distribution components of the MTD model is that of two absolute logit models. As the sensitivity parameter for the tour group split is known with less certainty, it is appropriate that this split be implemented as an incremental rather than an absolute logit model. Additional complication arises in the implementation of this model as a consequence of 'inserting' an incremental logit model between two absolute logit models (see Appendix B1).

V. MODEL CALIBRATION

As discussed in the previous section, the maximum likelihood technique used to calibrate the sensitivity parameters for the mode and destination splits of the MTD model is unlikely to enable calibration of the ToD split as a consequence of limitations in survey data. Consequently, an alternative approach to this calibration is required.

The ultimate goal of ToD choice calibration is to ensure that the sensitivity of the modelled ToD split with respect to differential changes in cost by ToD reflects the behaviour expected by the modelled population. The first task in calibration is thus to gain a quantitative measure regarding this behaviour, the most natural measure being the sensitivity of the proportion of travel in the peak periods to changes in the differential cost of travel between periods. Having done this, the ToD sensitivity parameters may be adjusted such that model results agree with this measure.

For the calibration of the ToD component of the ART3 model, a review of international findings pertaining to the sensitivity of ToD travel choices was conducted. Material reviewed regarded both peak-contraction as a result of the provision of extra capacity in congested contexts (e.g. Lian, 2005 and Bly, 2005) and of peak spreading following differential pricing initiatives (e.g. Kroes et al., 1996). The result of this review was an estimate of the elasticity of peak period traffic share to change in peak period generalised cost of -0.5. The ART3 sensitivity parameters were adjusted such that this elasticity was reflected by the model.

Having calibrated the ART3 model ToD choice sensitivity to international findings, an attempt was made to validate this sensitivity using data specific to Auckland. An analysis of historical screenline data for Auckland suggested an elasticity of peak period travel flow to change in total traffic flow of the order of 0.2. It is important to note that this figure is in no way comparable to the value of -0.5 discussed above, as it regards a different measure of sensitivity. Furthermore, this elasticity is only indicative as the observed changes in traffic flow over the observed period cannot be attributed to differential changes in cost of travel by ToD alone. Scenario testing of the ART3 model implied an equivalent elasticity of 0.16, comparable with the results of the historical analysis.

Further to the above validation, a road user charging scenario was conducted to ensure the model produced sensible results. A monetary charge

[2] The MTD model represents travel using a tour basis. An average tour will experience twice the cost of travel of an average trip. Consequently, if the DMS model is estimated on a trips basis, the sensitivity parameters used for the MTD model will be ½ of those estimated to ensure the mode and destination split sensitivities of the models are equivalent.

was applied to travel across a cordon around the Auckland Isthmus. The charge was applied in the peak direction during the peak periods, that is, inbound in the AM peak and outbound in the PM peak. As a result of this charge, vehicle volumes crossing the cordon in the charged period/directions were predicted to decrease significantly. A smaller decrease in the non-priced period/directions was also observed as a consequence of the tour-based nature of the choice model.

VI. CONCLUSIONS

In this paper, a methodology for the modelling of ToD choice within strategic transport models has been presented. In principle, this methodology transforms a conventionally estimated distribution and mode choice model system into a mode, time-of-day and destination choice model via the insertion of a ToD split. This methodology has been successfully implemented and is currently being used in the Auckland Regional Council's ART3 model. In principle, the procedure presented in this paper could be added to existing multimodal transport models without the need for re-estimation, although the software code would require significant amendment.

ACKNOWLEDGEMNT

The authors would like to thank Sinclair Knight Merz Ltd for encouraging continued development in the field of strategic transport modelling and the Auckland Regional Council (ARC) for allowing the publication of the results presented in section V.

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APPENDIX A1 – TOUR GROUP COST CONSTRUCTION

The conversion of generalised cost from an OD trip basis to a PA tour basis is done separately for each purpose[3]. This conversion is driven by the following set of conditional probabilities, as derived from base year data:

$\vec{\pi}_{i,j}^{t|m,d}$: For trips originating in zone i, destined to zone j, the conditional probability that a mode m, direction $d \in$ {fh,th} trip will occur in time period t.

$\pi^{d|m}$: The conditional probability that a mode m trip will be made in direction $d \in$ {fh,th}.

Before proceeding further we note that the approximation $\pi^{d|m} = 0.5$ is valid only if travel behaviour may be approximated as symmetric within purpose-mode segments, that is, if the travel data suggests a one-to-one mapping between outbound and return trips of the same purpose and mode. Such symmetry is by no means gaurenteed.

Define the variable: $\overrightarrow{\mathrm{GC}}_{\mathrm{i,j}}^{\mathrm{m,t}}$, denoting the generalised cost of travel for trips by OD zone and time period (i.e. the assignment quantity). For tours, the generalised cost of travel is calculated by direction $d \in$ {fh,th} as a weighted average of these costs:

$$\overrightarrow{\mathrm{GC}}_{i,j}^{m,g,d} = \frac{\sum_{t \in d \text{ legs of } g} \vec{\pi}_{i,j}^{t|m,d} \overrightarrow{\mathrm{GC}}_{i,j}^{m,t}}{\sum_{t \in d \text{ legs of } g} \vec{\pi}_{i,j}^{t|m,d}}, \qquad d \in \{\mathrm{fh,th}\}. \tag{A1}$$

The total tour cost is obtained as the sum of the costs in each direction, weighted to account for asymmetry:

$$GC_i^{m,g,j} = 2 \sum_d \pi^{d|m} \overrightarrow{\mathrm{GC}}_{i,j}^{m,g,d}, \qquad d \in \{\mathrm{fh,th}\}. \tag{A2}$$

It is clear that the conditional probabilities: π and $\vec{\pi}$ will vary from the base to the forecast year as a consequence of changes in ToD travel choices. However, the influence of this change on the ToD choice model (i.e. via the construction of tour group costs) is secondary to the effect of the ToD choice model itself.

3 However, for readability, our notational convention is to omit subscripts denoting purpose.

APPENDIX A2 – TOUR GROUP TO TRIP CONVERSION

The mapping of tours by tour-group, mode and PA zone to trips by time period, mode and OD zone is achieved by weighted averaging of tour groups as follows; firstly, tours are disaggregated by direction $d \in$ {fh,th} as follows:

$$\vec{\mathrm{T}}_{i,j}^{m,g,d} = \pi^{d|m} T_i^{m,g,j}, \; d \in \{\mathrm{fh,th}\}. \tag{A3}$$

The next step requires the conditional probabilities of a trip occurring in each time period given its tour group. These probabilities are calculated from those probabilities derived from the base data (i.e. $\vec{\pi}_{i,j}^{t|m,d}$ and $\pi^{d|m}$, see Appendix A1) as follows:

$$\vec{\pi}_{i,j}^{t|g,m,d} = \begin{cases} \dfrac{\vec{\pi}_{i,j}^{t|m,d}}{\sum_{t \in d \text{ legs of } g} \vec{\pi}_{i,j}^{t|m,d}} & \text{if } t \in d \text{ legs of } g \\ 0 & \text{if } t \notin d \text{ legs of } g \end{cases}, \quad d \in \{\mathrm{fh,th}\}. \tag{A4}$$

Using these values, tours by tour group, mode and direction are mapped to trips by time period, mode and direction as follows:

$$\vec{\mathrm{T}}_{i,j}^{m,t,d} = \sum_g \vec{\pi}_{i,j}^{t|g,m,d} \vec{\mathrm{T}}_{i,j}^{m,g,d}, \qquad d \in \{\mathrm{fh,th}\}. \tag{A5}$$

Summing across directions, we arrive at trips by mode and time period:

$$\vec{\mathrm{T}}_{i,j}^{m,t} = \sum_{d \in \{\mathrm{fh,th}\}} \vec{\mathrm{T}}_{i,j}^{m,t,d} \tag{A6}$$

APPENDIX B1 - MODE, TIME-OF-DAY AND DESTINATION CHOICE MODEL

Figure 5 illustrates a complete description of the of the MTD model. This appendix is intended to augment this figure.

The order of execution of the various components of the model is as depicted in figure 5. That is, (a) the composite costs are calculated for each split, (b) the splits are performed, (c) the attraction constraint parameters are updated and (d) the process is repeated until convergence. Rather than discussing the details of this execution in a chronological fashion, we address the four principle elements of the model (i.e. mode split, time-of-day split, destination split and attraction constraint) individually within the following sub-sections.

To aid in explanations to follow, at this point it is useful to make the following variable definition:

$T_i^{m,g,j}$: Tours by production zone i, mode m, tour group g and destination zone j.

The superscript $*$ is used to denote summation. Equivalent notation is used for utilities, scaled utilities and scaled composite utilities.

A. *Mode Split*

The mode split component of the MTD model splits tours by production zone: $T_i^{*,*,*}$ into tours by production zone and mode: $T_i^{m,*,*}$. It achieves this via the application of the logit model:

$$T_i^{m,*,*} = \frac{\exp\left(U_i^{m,*,*}\right)}{\sum_m \exp\left(U_i^{m,*,*}\right)} T_i^{*,*,*}, \qquad \text{(A7)}$$

were $\mathrm{U_i^{m,*,*}}$ is the scaled composite utility:

$$\mathrm{U_i^{m,*,*}} = \theta_i^m \mathrm{F_i^{m,*,*}}. \qquad \text{(A8)}$$

Here, the scaling parameter θ_i^m represents the relative sensitivity between the mode and destination splits (as derived from the calibration of a DMS model). The composite utilities: $\mathrm{F_i^{m,*,*}}$ are derived via the time-of-day split.

B. *Time-of-day Split*

The time-of-day split component of the MTD model splits tours by production zone and mode: $T_i^{m,*,*}$ into tours by production zone, mode and tour group: $T_i^{m,g,*}$. It achieves this via the incremental logit model:

$$T_i^{m,g,*} = \frac{\pi^{g|m} \exp\left(\Delta U_i^{m,g,*}\right)}{\sum_g \pi^{g|m} \exp\left(\Delta U_i^{m,g,*}\right)} T_i^{m,*,*}, \qquad \text{(A9)}$$

where $\pi^{g|m}$ denotes the base probability that a tour of mode m will be made in tour-group g (i.e. the base proportion of trips by tour group for each mode), and $\Delta U_i^{m,g,*}$ is the scaled composite utility difference:

$$\mathrm{\Delta U_i^{m,g,*}} = \lambda_i^{m,g} \left(\mathrm{\Delta F_i^{m,g,*}}\right). \qquad \text{(A10)}$$

The scaling parameter $\lambda_i^{m,g}$ represents the relative sensitivity between the destination and tour group splits. In principle, this parameter could be made to vary by mode, tour-group and production zone. However the manner in which it is calibrated renders this unnecessary, and in general: $\lambda_i^{m,g} = \lambda \; \forall, g, i$. The composite utility difference $\Delta F_i^{m,g,*}$ is calculated as:

$$\Delta F_i^{m,g,*} = F_i^{m,g,*} - \hat{F}_i^{m,g,*}, \qquad \text{(A11)}$$

where $\hat{F}_i^{m,g,*}$ are the base composite utilities and $F_i^{m,g,*}$ the scenario composite utilities, derived via the destination split component of the model.

For the purposes of the mode-split component of the model, the following composite utilities are computed:

$$\Delta F_i^{m,*,*} = \frac{1}{\lambda_i^{m,g}} \ln\left(\sum_g \pi^{g|m} \exp\left(\Delta U_i^{m,g,*}\right)\right), \qquad \text{(A12)}$$

These are incremental composite utilities and as such must be added to the base composite utilities: $\hat{F}_i^{m,*,*}$ prior to being used in the mode split model; this model having the functional form of an absolute logit model. That is:

$$F_i^{m,*,*} = \hat{F}_i^{m,*,*} + \Delta F_i^{m,*,*}. \qquad \text{(A13)}$$

The observant reader will have noticed the additional scaling used in the construction of the composite utilities defined by equation A12. This scaling is necessary to preserve the relative sensitivity between the mode and destination splits

(i.e. to ensure this relative sensitivity is not 'upset' by the introduction of the tour group split).

C. Destination Split

The destination split component of the MTD model splits tours by production zone, mode and tour group: $T_i^{m,g,*}$ into tours by production zone, mode, tour group and destination zone: $T_i^{m,g,j}$ as follows:

$$T_i^{m,g,j} = \frac{\exp\left(U_i^{m,g,j}\right)}{\sum_i \exp\left(U_i^{m,g,j}\right)} T_i^{m,g,*}. \quad \text{(A14)}$$

were $U_i^{m,g,j}$ is the utility of travel by mode, tour group and PA movement, computed as:

$$U_i^{m,g,j} = \gamma_i^{mj} GC_i^{mgj} + \sum_k X_{k,i}^{m,j} + b_j. \quad \text{(A15)}$$

Here, γ_i^{mj} are a set of parameters defining the sensitivity of the model with respect to generalised cost of travel. The variables $X_{k,i}^{m,j}$ are set of k constants representing travel attributes not encapsulated in the generalised cost (e.g. comfort and safety). Both these parameters are derived from the calibration of a conventional DMS model and thus may vary by mode and trip geography (i.e. PA zone), but not tour group. As introduced in the main text, b_j are a set of destination specific constants used to ensure the attraction constraint is satisfied. The exact value of these parameters is arrived at via iteration, as discussed in the next sub-section.

For the purposes of the time-of-day component of the model, the following composite utilities are computed:

$$F_i^{m,g,*} = \ln\left(\sum_j \exp\left(U_i^{m,g,j}\right)\right). \quad \text{(A16)}$$

D. Attraction Constraint

Upon the first iteration of the MTD model, the tours by mode, time-of-day and destination resulting from the splits discussed above will in general not satisfy the attraction constraint:

$$\sum_{m,g,i} T_i^{m,g,j} = A_j. \quad \text{(A17)}$$

To address this, the destination specific parameters b_j are adjusted iteratively such that this constraint is asymptotically satisfied. Defining $[k]$ as the iteration number, at each iteration these parameters are updated via the feedback law:

$$b_j^{[k+1]} = \begin{cases} b_j^{[k]} \dfrac{A_j}{\tilde{A}_j^{[k]}} & \text{if } j \neq 1 \\ 0 & \text{if } j = 1 \end{cases} \quad \text{(A18)}$$

where $\tilde{A}_j^{[k]}$ are the synthesizesd attractions arrising from iteration $[k]$. That is:

$$\tilde{A}_j^{[k]} = \sum_{m,g,i} T_i^{m,g,j} \Big| b_j^{[k]}. \quad \text{(A19)}$$

It is a straightforward exercise to demonstrate that the dynamics resulting from this iterative process are exponentially stable.

As specified in equation A18: $b_1^{[k]} = 0 \; \forall [k]$. The rationale for this is as follows; the destination split is driven by the absolute differences between the utilities of travel to the alternative destinations. As such, if all destination specific constants were allowed to vary, they would have one additional degree of freedom. This is not a problem in itself, however it will introduce problems if convergence tests utilise these parameters. The decision to fix $b_1^{[k]} = 0 \; \forall [k]$ removes this degree of freedom. In principle, this condition specifies the cost of travel to zone 1 as a reference, although the decision to use this specific zone is an arbitrary one.