



TRANSPORT AND INFRASTRUCTURE
COUNCIL

Australian Transport Assessment and Planning Guidelines

T1 Travel Demand Modelling



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For enquiries or feedback about this publication please contact:

ATAP Steering Committee Secretariat
Australian Transport Assessment and Planning
Guidelines
Commonwealth Department of Infrastructure and
Regional Development
GPO Box 594 CANBERRA ACT 2601
Email: atap@infrastructure.gov.au

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Travel demand modelling

At a glance

- This volume of the Guidelines provides guidance for developing and applying strategic highway and public transport models when appraising major transport initiatives. The focus in this volume is on the modelling of person-based travel demand across road and public transport networks. This guidance is not intended to be comprehensive; rather, it represents the minimum level of recommended acceptable practice.
- The following key areas are covered in this volume:
 - An overview of the transport modelling process and associated high level issues,
 - Standard transport model structures and techniques for modelling person-based travel demand,
 - The data inputs required for the transport models, and the associated collection approaches and techniques,
 - The techniques used in transport model development, and
 - The use of transport models for forecasting and evaluation.
- Development of a volume focussing on freight transport modelling is not included in the Guidelines at this stage.

1. Introduction

1.1 Purpose and structure of this guidance

Any transport model is a tool for understanding and assessing the likely impacts of changes in the drivers of transport, such as transport supply, demographics or land use. In this context, transport modelling can assist with decision-making about the future development and management of urban transport and land use systems.

This document provides guidance for developing and applying strategic highway and public transport models when appraising major transport initiatives in the urban context.

This document is not intended to be a detailed technical treatise on developing individual components of a transport model, but rather a succinct, practical and pragmatic reference for developing, applying and assessing transport modelling. Detailed information on transport modelling theory and methodological approaches can be found in transport modelling references.

The urban transport modelling guidelines represent the minimum level of recommended acceptable practice and are provided to:

- Establish principles of good and consistent transport modelling practice, rather than being prescriptive on transport modelling methodology
- Ensure a consistent understanding in the application of transport modelling
- Provide a better understanding of the transport modelling process.

This document contains five sections:

Section	Summary
Overview of transport modelling	This provides an overview of the transport modelling process and high level issues. Material is readable at a project management level.
Model design	This section covers standard model structures and techniques for modelling travel demand and transport networks. This material is aimed at a technical level.
Data collection	This covers data collection, types of data, collection approaches and techniques. This material is aimed at a technical level.
Model development	This covers the techniques used in the development of transport models. This material is aimed at a technical level.
Forecasting and evaluation	This covers the use of models for forecasting and evaluation. This material is aimed at a technical level.

1.2 Role of transport modelling

Transport systems play a critical role in facilitating the way we work, delivery of the goods we use and facilitating the social and recreational activities we enjoy. The benefits of accessible and efficient transport systems come at a cost. The transport infrastructure requires land and can cause severance in our communities. Our travel consumes resources and generates emissions and noise that impact on our health.

Decisions on whether and how to intervene in our transport systems can thus have far reaching consequences for our economy, environment and society. Effective decision making thus requires an appreciation of the wide range of consequential impacts. Major infrastructure can take several years to construct and will exist for many decades. The information required to understand impacts requires forecasts many years into the future and is subject to the risks and uncertainties inherent in forecasting.

The role of transport models is to provide structured forecasts that can be interrogated to provide information on implications of transport interventions. The model outputs are used both to:

- establish a structured understanding of the performance of the transport systems, today and forecasts of the future, from which to identify the need to consider interventions; and
- compare the performance of transport systems with and without interventions to understand their merits.

There are two particular challenges for the transport modeller. The first is to balance the complexity and cost of the modelling and forecasting tasks to the decision making needs. Too much complexity is simply a waste of resources. Too little and the outputs cannot be used for the intended purpose. Secondly is the requirement to explain the forecasting uncertainty to allow decision makers to understand the reliance that can be placed on particular outputs and the inherent risks.

2. Overview of transport modelling

Transport models are a systematic representation of the complex real-world transport and land use system as it exists. They are powerful tools for assessing the impacts of transport infrastructure options and for identifying how the transport system is likely to perform in future, which is paramount for the development of an effective urban planning practice.

The development and application of transport models is fundamental to the appraisal of many transport initiatives because they:

- Provide an analytical framework to assess existing demands on the transport system and project future demands to systematically test the impact of transport and land use options
- Enable the generation of quantitative measures to provide key indicators in the business case assessment and economic appraisal.

Transport models use mathematical relationships to represent the numerous complex decisions people make about travel so that future demand can be predicted, and to replicate observed travel patterns at various levels of geography.

At the most fundamental level, transport models comprise:

- A demand model (trip generation, trip distribution, mode choice and time of travel)
- A highway assignment model (road-based public transport, private vehicles, freight and other commercial vehicles)
- A rail, bus, and ferry assignment model (public transport and freight).

Generally, the development of a transport model requires:

- A Statement of Requirements
- A Functional Specification of the transport model
- A Technical Specification of the transport model.

2.1 Statement of Requirements

A Statement of Requirements usually details the objectives of the model; the interfaces with other models; the hierarchy of transport modelling applications; transport model attributes; and transport model outputs. Each of these is described below.

2.1.1 Objectives of the model

The overall objectives for a transport model refer to what it is required to do. This can include:

- Providing the technical means for the ongoing development of procedures to quantitatively test and evaluate transport initiatives, strategies and policies
- Assessing the strategic justification for major transport infrastructure projects
- Defining the geographic coverage – initially for specific metropolitan regions, but allowing flexibility to include regional centres within the context of a state-wide model
- Extending the model to test the impacts of transport strategies on a particular location and the intensity of land use development that might occur there.

Establishing a precise statement of objectives, both what is and is not required, is critical to achieving an effective prioritisation of resources to design and implement the model.

2.1.2 Interfaces with other models

This component of the Statement of Requirements defines the interface relationships between the transport model and other models. This interface can provide input to corridor-specific models and the more detailed mesoscopic and microsimulation or operational models.

The key interface attributes are that models share common information and data sources as well as core assumptions, and provide consistency within the hierarchy of transport modelling (see Table 1 below).

2.1.3 Hierarchy of transport modelling applications

Transport modelling development and applications generally fall into the five broad categories described in Table 1. In many cases, planning progresses from the formulation of land use and transport strategy to the investigation of particular projects/schemes to deliver these strategies, and to the detailed operational planning to deliver these schemes.

Table 1 Hierarchy of transport modelling applications

Land use and transport interaction modelling	<ul style="list-style-type: none"> Examines and evaluates the impacts of transport policy and land use changes on urban form and transport. 	
Strategic modelling	<ul style="list-style-type: none"> Examines 'what if?' questions in policy development and the definition of strategies. Identifies and assess broad metropolitan-wide impacts if land use, socio-economic, demographic and transport infrastructure changes. Assists in transport infrastructure project generation. Provides metropolitan-wide forecasts of trip generation, trip distribution, mode choice and assignment of trips to the transport network. Considers travel needs, and multi-modal consideration of whether and how these are best satisfied Models and assesses pricing issues. 	
Scenario modelling	<ul style="list-style-type: none"> Assesses the implications of particular strategies at the metropolitan scale. 	
Project modelling	<ul style="list-style-type: none"> Assesses strategy components, individual projects, specific land use strategies and transport corridor issues. Assesses the performance of the transport network along specific corridors and for nominated projects. 	
Operational design	<ul style="list-style-type: none"> Assesses the detailed operational performance of specific transport infrastructure projects and initiatives (e.g. ramp metering), land use developments and local area traffic management. Prioritise allocation of road capacity between different users (e.g. Bus priority or pedestrian signal phasing). May assist identify the effects on delays and queues resulting from changes in the transport system variables, i.e. signal phasings, lane configurations, ramp metering. 	

Some specific examples of matters model applications aim to assess include:

- Quantifying the effects of land use strategies on transport network performance to identify whether and what interventions may be required
- The assessment of scenarios involving pricing policies (e.g. fuel, tolls, parking charges), transport infrastructure provision and service improvements
- How to best allocate transport system capacity in face of the demand from freight and private vehicles, public transport users and pedestrians and cyclists.

The continuum of modelling requirements, set out in Table 1, draws on different modelling techniques. These range from macroscopic (often applied for Land use and strategic planning purposes) through mesoscopic to microscopic (typically applied for operational design). A broader range of demand responses (Section 3.2, 3.3) are typically represented in macroscopic models together with a more aggregate representation of the transport networks (Section 3.6.1, 3.6.2). In comparison microscopic models provide more detailed representation of driving behaviour and of the performance of the transport networks (Section 3.6.3). Activity based modelling (Section 3.7) involve wider use of simulation techniques for strategic planning.

Selecting a modelling technique is an important part of the Statement of Requirements. The selected tool needs to be sensitive to the relevant issues of a project. Unnecessary complexities should be avoided as they will increase the cost and introduce risks. However, the objectives of the project are paramount, so while the chosen modelling technique needs to be simple, it should not be oversimplified. A good balance needs to be found.

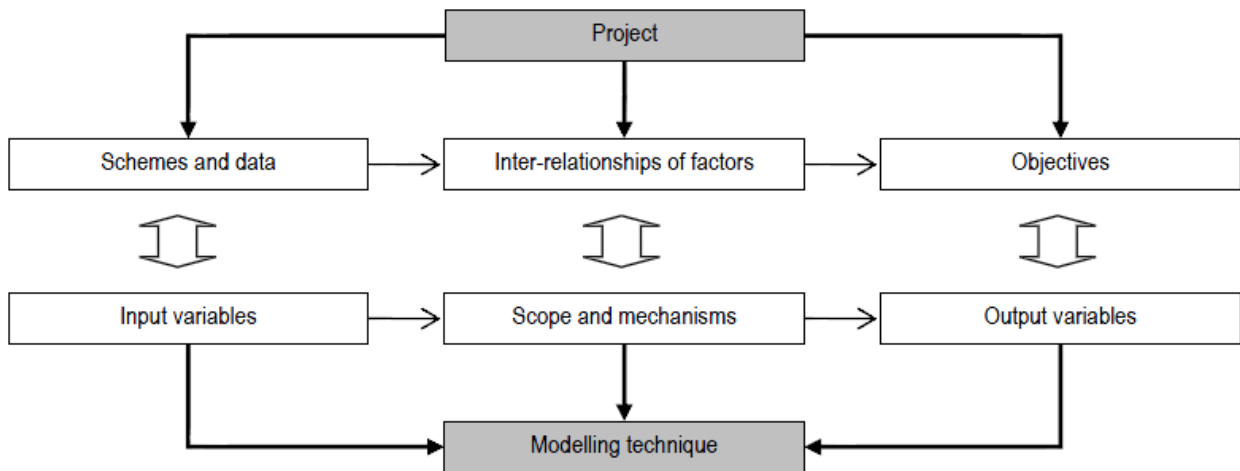
In some instances, the blend of requirements may best be delivered using more than one model. Ensuring consistency using a combination of transport models inevitably adds complexity. Nevertheless, individual tools and methods may provide better focus on individual output requirements.

A particular tension rests in the need to assess value for money where funding decisions are based on user benefits (i.e. travel time savings) which are derived using consumer surplus theory. The typically more limited scope and calibration requirements (Section 5.8) of microscopic modelling techniques tend to limit their suitability for this purpose. That said the greater precision in representing the performance of particular design options and ability visually to demonstrate how infrastructure would operate are particular advantages of microsimulation tools.

The challenge is to match the context of a project to the strengths and weaknesses of each technique. The first step is to contextualise the project, by identifying its key elements. These key elements should be able to cover the schemes and data, inter-relationships of factors, and objectives of the project. These elements can then become specifications of the model to be applied, such as input variables, scope and mechanisms, and output variables (shown in Figure 1), as follows:

- Input variables – should be sensitive to the proposed schemes and make use of available data. Input variables include representation of the demand and the transport network. Demand distinguishes the what, when, where and how travel is made, together with variations in travel behaviours. The transport network is defined by physical attributes (e.g. highway geometry) and traffic control (e.g. traffic signals).
- Scope and mechanisms – cover the relevant inter-relationships of factors considered in a project, including its geographic and temporal scope, traveller responses and other capabilities required of the model (e.g. optimisation).
- Output variables – should be able to represent the objectives of the project. Output variables include the relevant indicators and accuracy requirements. The likely users of the modelling outputs should be considered when preparing the model outputs.

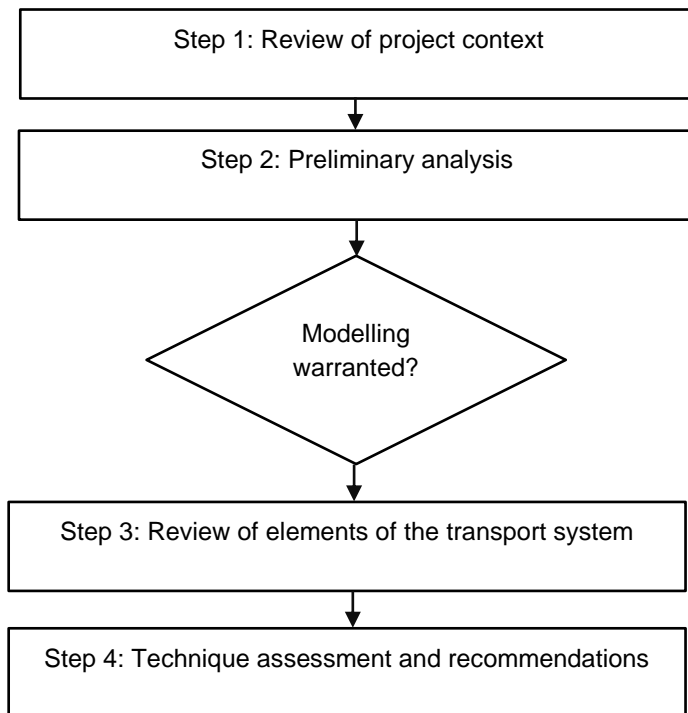
Figure 1 Elements of the traffic system model



No clear science exists for selecting the most appropriate transport modelling technique. The selection needs to balance the requirement for rigorous analysis against the cost. It is also important to filter out case studies that do not require modelling to focus resources on projects that require modelling. Guidelines are therefore needed to facilitate the selection process. It is not the purpose of the guidelines to identify a particular technique. The intent is only to structure the decision-making process. In the end, a subjective judgment is required. The guidelines set out four steps as shown in Figure 2. The first step involves careful consideration of the project objectives. The high level analysis preliminary advocated in step 2 considers the nature of outcomes and impacts that may be expected from which the analyst can form a view on the extent to which a model can quantify these outcomes and the importance of this information in making decisions on whether and how to proceed with the project. Given an initial decision that some modelling is justified, the subsequent step 3 is to consider the aspects of the transport system that require modelling. Finally step 4 is to consider the methods that can best be applied to represent these aspects, reflecting the nature of the project and the expected outcomes.

These guidelines provide an introduction to modelling techniques such as land use modelling and activity based modelling, which have had limited application within Australia. Emphasis should be placed on the need to undertake the modelling to a sufficient standard, regardless of the technique used. A scattergun approach of using resources to attempt too much is not a sensible strategy, and focus is needed in selecting what should be modelled.

Figure 2 Steps in technique selection



2.1.4 Transport model attributes

Desired transport model attributes detailed within a Statement of Requirements may include:

- The model is readily accessible to key decision-makers and can enable a prompt and reliable response;
- It is an integrated multi-modal model updated annually to account for new data as well as for identified errors or changes in core assumptions;
- The model provides sensitivity to changes in demographics, individual travel decision-making, social behaviour and land use or some combination of these;
- The requirements for model governance, accessibility, development and maintenance;
- The model has the ability to model motorised and non-motorised travel.

2.1.5 Transport model outputs

Examples of model outputs contained in a Statement of Requirements might include:

- Road, rail, bus and ferry transport patronage estimates
- Transport network performance (such as vehicle-hours, kilometres of travel and congestion indicators) and accessibility measures (such as services, employment)
- Forecasts of aggregate travel costs and benefits
- Source and extent of diversion
- Input to externalities modelling (such as quantum of emissions)
- Input for economic appraisal and business case development.

2.2 Functional Specification

The Functional Specification of a transport model describes the functions it should include, based on the scope of the transport model (see 2.2.1 below) as defined in the Statement of Requirements. It also outlines the model structure (see 2.2.2 below) as well as the functions and methodologies appropriate for the various components (i.e. trip generation, trip distribution, mode choice, time of travel and trip assignment), the inputs and outputs, and the data source.

2.2.1 Transport model scope

The scope of the transport model is defined by the policy issues the model system aims to address. These may include:

- Land use–transport interaction
- Pricing (toll roads, parking, public transport fares)
- Parking provision (cost, reduction in availability, park-and-ride facilities)
- Road network management (new roads, commercial vehicle priority, traffic management, high occupancy vehicle lanes)
- Public transport networks (extensions, service provision, fares, interchanging, cross-town routes)
- Non-motorised travel (cycling, walking).

Establishing a suitable model scope and structure for transport modelling and analysis is not a simple process. A whole range of modelling approaches exists, ranging from the options of using no formal transport models to the most complex microsimulation models.

The selection of the transport model structure and scope in the Functional Specifications is driven by the modeling and appraisal requirements of the jurisdiction. Generally, for urban transport, each jurisdiction aims to have a single multi-modal model for their metropolitan area that has broad ranging and versatile capability that can be applied to a wide range of studies, or initiatives. This is the only practical and cost-effective way to proceed as it reduces model development and maintenance costs. It also ensures broad consistency in the use of modeling across studies and initiatives.

There will of course be cases where modifications to the model will be required to meet the specific needs of a study, such as creating a sub-model, or changing the resolution of the travel zone system for a study, e.g. for focusing on walking and cycling in a particular area. Typically, the overall aim should be to minimize the production of bespoke models for individual projects.

2.2.2 Transport model structure

A broad transport model structure may include:

- **A database** populated by data from travel surveys across the region by various modes by time of day, together with observed traffic volumes across the road network and patronage levels on the public transport network, including current and projected land use data and demographics (population and employment).
- **The inputs to the modelling process**, such as parking supply, land use distribution, fares, car travel costs, traffic management measures, access restrictions, road and public transport infrastructure, and public transport service provision.
- **A travel demand model** to derive the quantum of travel across the region, comprising trip generation, trip distribution and mode choice modules, including factors such as travel purposes and the quantum of commercial vehicle travel.
- **A freight model** to derive the quantum of freight transported across the region sufficient to estimate the quantum of commercial vehicle travel on the road network and the requirements of the freight task on the rail network.
- **A transport supply model** covering the road and public transport networks, covering factors such as parking supply, road and public transport network capacities, travel times and travel costs.
- **An assignment module** to allocate travel demands to the transport supply model in an iterative manner, to ensure the forecast demands are balanced with the transport supply, taking into account congestion effects.
- **The required outputs**, such as network performance indicators including vehicle-hours and kilometres of travel, passenger-hours and kilometres, congestion indicators and tonnages of emissions.
- **Other information** such as emissions (NO_x, CO, CO₂), traffic volumes, trip lengths, trip costs and benefits and accessibility measures.

2.3 Technical Specification

The Technical Specification of a transport model usually follows the choice of modelling approach and includes the methodologies and processes developed to meet the Functional Specification. It details, among other issues, the input data, model calibration and validation data and the format of the required outputs. Information relating to Technical Specification is covered in subsequent sections of this document.

2.4 Transport modelling process

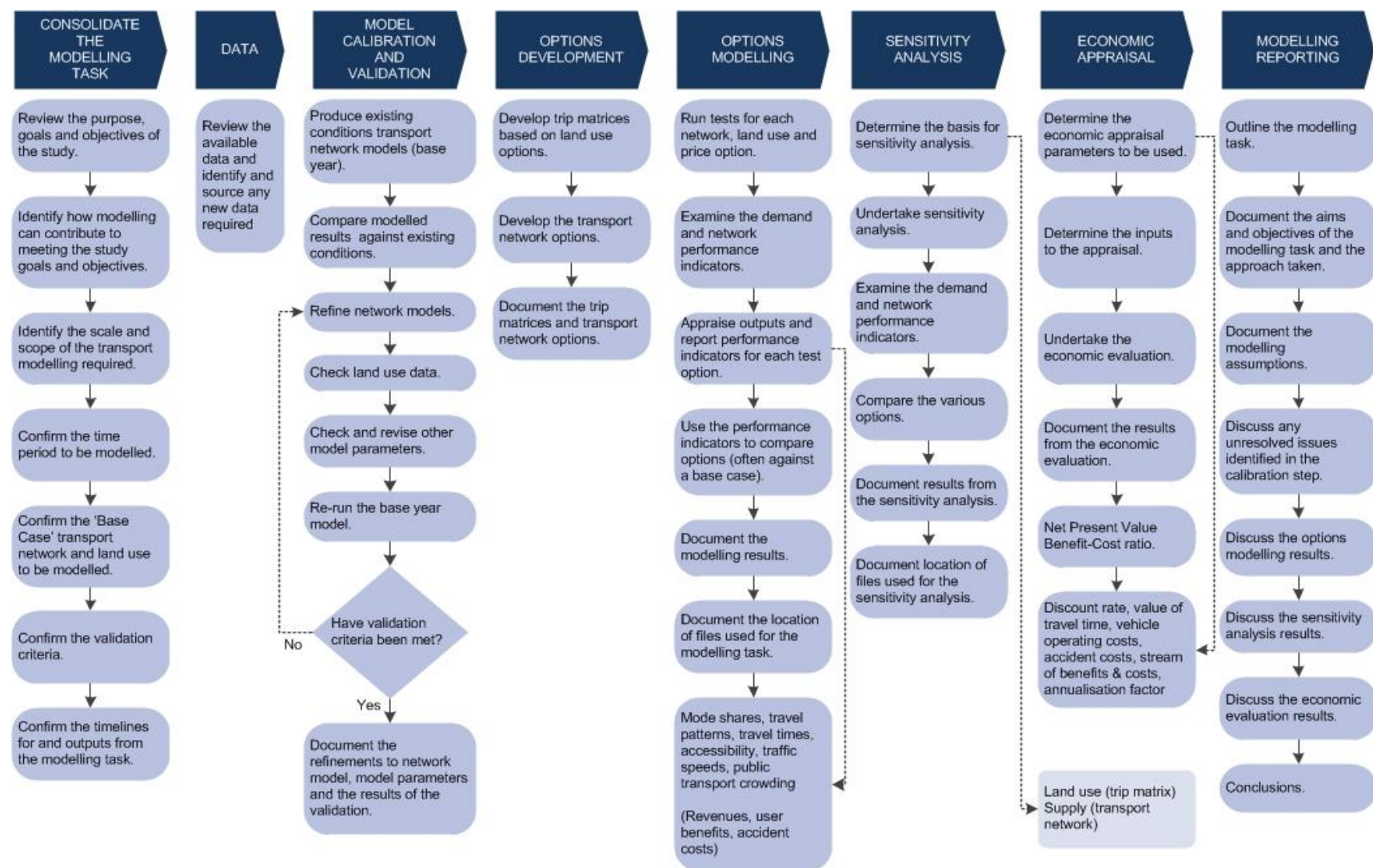
The transport modelling process comprises a number of stages, as shown in Figure 3. These include:

- **Consolidating the modelling task**, which includes identifying the key transport, socio-economic and land use issues as well as the particular problems to be modelled. This stage is also informed by the definition of goals, objectives and the appraisal criteria to be adopted.
- **Data collection**, which is critical to transport modelling and may include highway and public transport patronage data, import/export or production/consumption volumes by commodity as well as census information and targeted or area-wide travel surveys. Usually the data collection is defined after the model scope has been specified. Nevertheless, in practice a good model design would consider existing data available.
- **Model estimation, calibration and validation**, which is required to develop the relationships used in the modelling process and to gauge the performance of the transport model. The process involves checking, refining input data, the suitability of relationships and comparing model outputs against observed data for the base year conditions (Chapter 5 discusses further).
- **Options development**, which usually includes variations of transport network options, land use options or combinations of both.
- **Options modelling**, which might enable further refinement and development of options as well as more detailed design and appraisal. This stage usually involves an iterative process covering options development and modelling through to appraisal.
- **Sensitivity analysis**, which varies input data and model parameter values to identify the robustness of the model relationships and the associated forecasts.
- **Economic appraisal**, which uses results of modelling as input to the appraisal process to assess the performance of the options against the specified goals, objectives and criteria.
- **Modelling report**, which involves the full documentation of each of the previous stages, including the transport model details.

In some cases, it is more efficient to undertake a staged process. For example, a 'long list' of schemes might be appraised using simplified methods or a reduced set of performance criteria to establish a short list where more detailed modelling and appraisal is undertaken. Initial consideration of options during options modelling is often based on a focused assessment of how well they address the underlying issue, with wider considerations of value for money considered in the later economic appraisal stage.

See Appendix A for more information on the transport modelling process.

Figure 3 Transport modelling process



2.5 Alternatives to modelling

An issue of interest is whether it is necessary to use modelling or other analysis methods for specific applications. An alternative to modelling is to use *sketch planning techniques*. Sketch planning methods generate only rough indicators and an enumeration of factors and their potential impact on the schemes being examined. Sketch planning is commonly used to reduce the number of alternatives being considered for further analysis. During the course of a sketch planning exercise, a certain alternative may stand out clearly or all other alternatives are eliminated. In this case it is no longer necessary to conduct further analysis.

An example application of sketch planning techniques is illustrated by Van Hecke et al (2008). In this example, sketch planning was applied to deploy certain operations technology, including detection / surveillance, incident management, traffic flow management, traveller information, and a regional weather information system. Recommendation on whether to deploy any of the technologies was based on criteria employing easy to derive or acquire data, including traffic volume, peak-hour conditions, accident records, traffic generators and weather conditions. The analysis is conducted without the benefit of modelling the effect of operations technology, but it is presumed that under certain conditions it is likely that a technology would be cost-effective. Further analysis may then be conducted on the basis of recommendations of the sketch planning methodology.

Another example of sketch planning is the use of prescribed warrants in recommending signalisation of an intersection. One methodology specifies 11 warrants where, if an intersection satisfies a certain number or combination of warrants, the intersection will be recommended for signalisation (Kell & Fullerton 1991). The warrants include traffic volume, type of approaches (for example, major or minor road), pedestrian volume, school crossing, accident exposure and others. Modelling is not necessary to conclude whether an intersection should be signalised or not. In some cases, crude calculations would be sufficient, and past projects or studies with similar characteristics could also be helpful to reach a conclusion without modelling.

Another approach is to use qualitative comparison of alternatives. Factors to consider include environmental, social, strategic planning and economic considerations. A review of advantages and disadvantages of possible alternatives may be sufficient to reach a conclusion. Qualitative comparison could even highlight important factors beyond the scope of modelling (such as aesthetics, social impacts, strategic impacts and complex behavioural responses).

Modelling is generally a time consuming and expensive exercise. Therefore, it is good practice to first conduct a preliminary analysis of alternatives using sketch planning and/or qualitative comparison. A decision to proceed to more rigorous analysis using modelling techniques should then be conducted under one of the following conditions:

- The preliminary analysis fails to identify the best course of action.
- The project requires a rigorous analysis for approval from decision-makers.
- There are significant risks involved if the recommendations provided are wrong.

It is recommended to apply various alternatives to modelling and to proceed to modelling only when a need is clearly identified.

3. Model design

3.1 Modelling demand

3.1.1 Travel demands

Reference (Base) Year travel demands for highway, rail and ferry travel can be derived in a number of ways. The usual, and most expensive, way of collecting travel demand data is through travel surveys, either one-off or continuous. Survey methods include self-completion travel diaries, household interview surveys and in-vehicle public transport surveys. Vehicle counts are also useful in providing a database for the calibration as well as validation of the transport models.

Travel surveys can be structured to derive personal travel purpose origin–destination matrices for use in the assignment process by collecting information such as:

- Origin and destination by purpose
- Origin and destination by location
- Car availability and use for travel purpose
- Public transport mode used
- Cost of travel
- Duration of travel
- Time of day of travel
- Age, gender, income and employment status of the traveller.

3.1.2 Market segmentation

The starting point for analysis of travel demand is to note that travel is almost always a derived demand – that is, it only occurs because of some other underlying demand. Travel occurs and goods are shipped because people want to undertake specific activities at different locations.

Demand characteristics (price, income and cross elasticities, sensitivity to time, comfort for passengers, growth rates) and transport costs (type of service demanded) will vary for different segments of the market.

Person trips may be categorised in many ways, including factors such as trip purpose, trip frequency, trip timing, trip distance and spatial separation of origin and destination (O-D) as well as travel mode used. Further, the socio-economic characteristics of individual travellers and the households to which they belong are also important determinants in predicting the travel behaviour of those individuals. The breakdown shown in Table 2 can be considered broad brush categorisation of passenger travel.

Table 2 Classification of passenger travel in terms of trip purpose, trip frequency, trip timing, spatial separation and transport mode

PURPOSE	FREQUENCY	TRIP TIMING	TRAVEL DISTANCE	TRANSPORT MODE
Work	Regular	Peak period	Local	Private car:
Education	Infrequent	Business hours	To city centre	<i>driver</i>
Shopping	Occasional	Off-peak	Inter-suburb	<i>passenger</i>
Personal	'One-off'	Late night	Regional	Public transport
business		Weekday	Inter-city	<i>rail</i>
Work related		Weekend	Inter-state	<i>bus</i>
Social			International	<i>tram/LRT</i>
Recreational			Origin-destination*	<i>taxi</i>
			<i>within a locality</i>	<i>ferry</i>
			<i>separated, good</i>	<i>aircraft</i>
			<i>access separated,</i>	<i>ship</i>
			<i>difficult access</i>	Non-motorised
			<i>through</i>	<i>walk</i>
				<i>bicycle</i>

Greater modelling precision, and potentially improved model accuracy, can be obtained by a more refined market segmentation than displayed in Table 2. Such refinement, however, must be balanced against the data requirements to support its implementation.

Knowledge of spatial patterns of travel demand is used in transport planning for network and service design. A common method of describing travel demand in a region is through the use of origin-destination matrices. These are tables of trip or commodity movements between the various O-D pairs that exist in a study region (Taylor, Bonsall & Young 2000, pp. 114–116). Consider the schematic map of such a region as shown in Figure 4 below. The study region is identified by a cordon line around it. Travel movements across the cordon line indicate trips made to and from the region. These are external origins and destinations. Observations on the cordon line can be used to assess the numbers and patterns of these through trips. Internal or local trip movements may also exist for trips where either or both the origin and destination of the trip are located inside the study area. Further information on through trips (such as routes chosen for the segments of those trips inside the study area) and local trips can be gathered by defining screenlines inside the study area and then making observations of vehicle movements at the screenlines. Traffic management studies are often concerned with the proportion of through traffic to local traffic in the study area.

Figure 4 Origins and destinations and trip movements in an identified study region

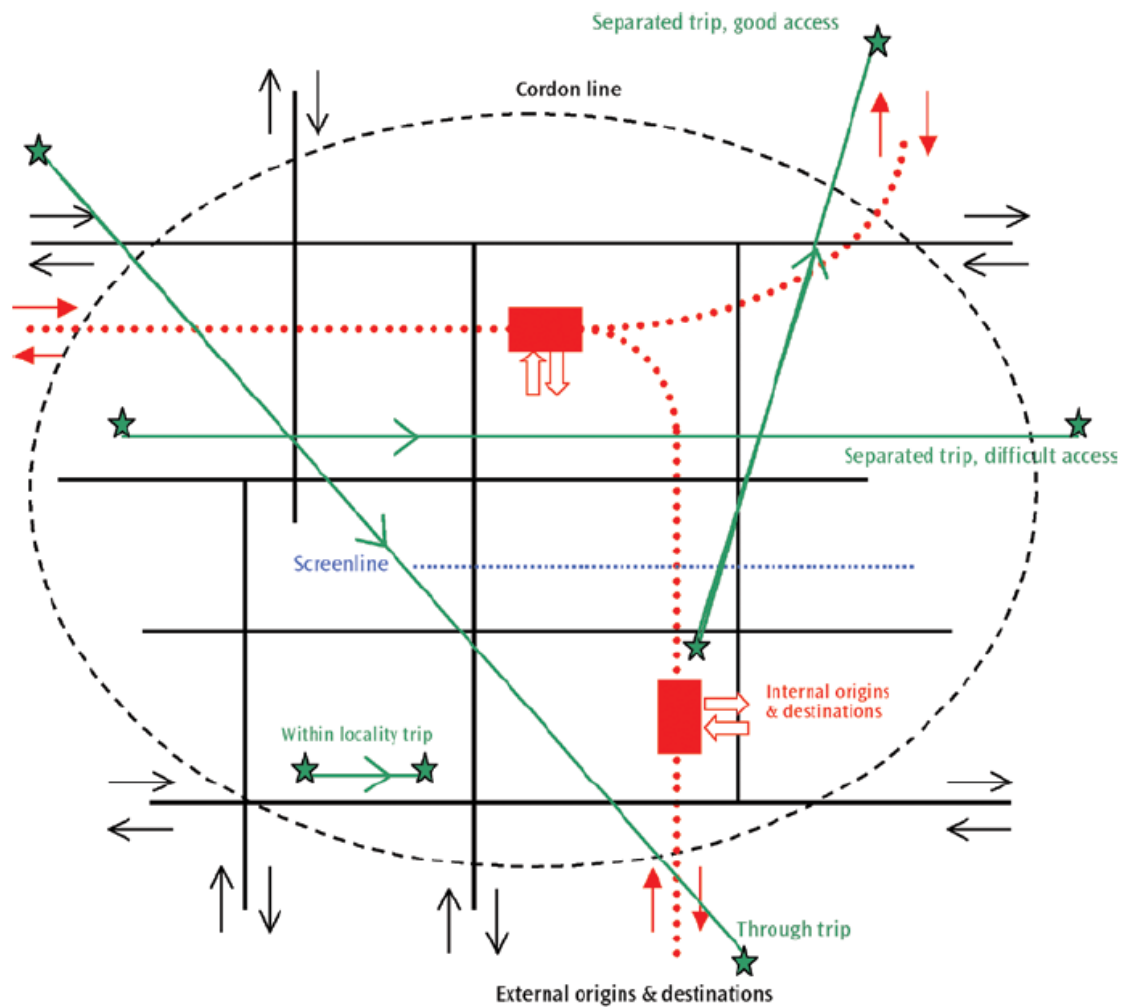


Figure 4 shows different O-D configurations. These include through trips and local trips (those that have at least one trip end – origin or destination – inside the study area). Local trips may be further subdivided into categories of within locality, separated with good access and separated with difficult access, as indicated in the figure. A typical structure for an O-D table is given in Table 3. Travel movements may be expressed in units of vehicles, passengers or commodity flows.

Table 3 Typical structure of an origin-destination matrix of travel movements

ORIGIN		DESTINATION					
		External			Internal		
		1	...	M ₁	1	...	M ₂
External	1	Through trips			Local trips, destination in study region (separated trip, good / difficult access)		
	..						
	N ₁						
Internal	1	Local trips, origin in study region (separated trip, good / difficult access)			Local trips (within locality)		
	..						
	N ₂						

Temporal distributions of travel demand are also important. Travel demand varies over the hours of the day, the days of the week and the weeks of the year. Cyclic and seasonal patterns can be ascertained to describe these patterns and used to predict the demands for transport services.

3.1.3 Peak periods

Specific time period (am peak, inter-peak, pm peak and off-peak) trip matrices should be developed to better reflect the different travel making propensities and characteristics during these periods. This approach is preferable in urban areas, where commuter peaks place the greatest loads on the available transport infrastructure.

Another approach is to develop daily travel demands and then apply time period factors, by trip purpose, to generate the time period matrices for subsequent use in the assignment process. The time period factors indicate the proportion of the daily travel, by purpose, undertaken during the time period to be modelled and are usually derived from travel surveys. For strategic network assignment modelling, the peak period trip matrices are generally for either a one-hour or two-hour time period, depending on the requirements of the analysis.

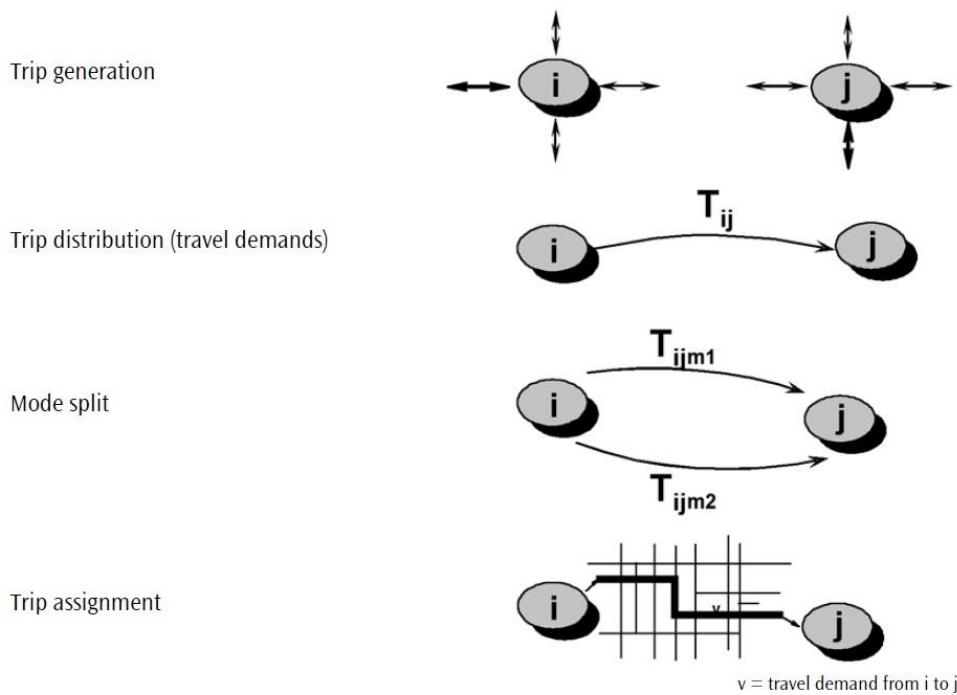
Where the travel forecasts are to be used to inform the public and/or the private sector regarding an investment in transport infrastructure in areas where there is evidence of congestion it is essential that multiple time periods of the day be modelled, at least three, AM peak, PM peak and off-peak.

When time period factors are used to determine time period demand, the challenge here is to consider how these factors change over time where congestion effects cause peak spreading. This is discussed further in section 3.2.5.

3.2 The four step transport modelling process

A commonly used model structure is the 'four-step' transport modelling process. The steps in this process are shown in Figure 5 and described below. An important feature of the four-step modelling process is the iterative feedback of costs arising from trip assignment to trip distribution and mode split. By iterating between the last three steps (trip distribution, mode split and trip assignment), it is possible to replicate the impacts of congestion on travel costs. This iterative process ensures a balance between the final trip pattern and the costs by which it is derived.

Figure 5 The four-step transport modelling process



The four step model is a framework that represents the scope of functions that are typically represented in transport models. The emphasis given and complexity of individual steps, and interactions between the steps is part of the model design task. In contexts where there are substantial changes in accessibility envisaged, or the modelling has been focused on a particular corridor, it may also be important also to model changes in trip frequency (whether trips as defined within the model scope are made or not) and possibly changes in land use and thus expanding and more fully integrating the trip generation step. In other cases, there may be a need to represent changes in when trips are made, in which case a fifth 'step' may need to be incorporated to this standard framework.

3.2.1 Step 1 – Trip generation

Trip generation is the procedure whereby land use, population and economic forecasts are used to estimate how many person trips are produced within, and attracted to, each zone. Trip generation uses average trip rates for the study area to estimate the quantum of trips undertaken by various trip purposes such as:

- Home-based work trips (such as work trips that begin or end at home)
- Home-based shopping trips
- Home-based education trips (such as from home to primary, secondary and tertiary education)
- Home-based recreation trips
- Home-based other trips
- Non home-based trips (trips that neither begin nor end at home)
- Other non-home-based trips (such as service trips and business trips).

The productions and attractions developed in the trip generation step are usually termed ‘trip ends’. Generally, for home based purposes, trip productions depend on the population characteristics of a zone, while trip attractions relate to employment parameters, school places, retail floorspace healthcare provision, etc. In some projects it is important to consider alternative land use forecasts, such as to assess the implications of alternative urban form proposals for the transport networks, or to consider the robustness of the performance of particular schemes to uncertainties in future land patterns.

Table 4 provides examples of the type of data that could be used in this step.

Table 4 Demographic and land use variables used in urban transport modelling

Demographic data	<p>Detailed demographic data by transport zone for the study area including:</p> <ul style="list-style-type: none"> projected resident population by age cohort, and current age cohort of population.
Land use data	<p>Data on land use would include:</p> <ul style="list-style-type: none"> quantities of land / size of developments required for various uses (e.g. retail, health, leisure, residential, commercial, etc) to meet projections of population and employment analysis of land use by industry type proportion of commercial land occupied, register of available open space within study area, and current and projected school enrolments by level: kindergarten, primary, secondary and tertiary at transport zones.
Economic activity data	<p>The following data may be used to provide an economic activity base for the forecasting future trip-making levels:</p> <ul style="list-style-type: none"> current employment levels at transport zones forecast employment by industry and/or occupation classification anticipated employment growth within transport zones assumptions about the employment generating capacity of the region, and estimated input-output function of the study area.

The reader should also be aware that trip generation models might also incorporate variables related to the transport network being modelled – both roadway and transit. This will build into the model the capability of representing induced travel demand in the form of more or less travel being made and by changes to land use patterns.

Accessibility is the main influence of transport provision on land use. Locations with better transport links tend to provide companies with better access to their markets and a larger pool of employees. An individual's choice of where to live is, in part, influenced by their ease of accessing work places, schools and other amenities. Land use transport models represent the rate of development and location choice decisions as a function of accessibility. In some cases, other indicators, such as environmental conditions (derived from traffic flows and vehicle emission rates) are also represented (e.g. see Whitehead et al). From the perspective of the transport model, it is important to establish accessibility, preferably representing all transport modes and weighting land use as a variable in the trip generation model (principles are discussed by Hansen (1959)). While the practice of incorporating accessibility to trip generation model is not common in Australia, it should be considered when the issue of induced demand becomes important for the model scope (see Section 3.4 for further discussion on induced demand).

Zoning system

A key issue to be resolved when developing transport models is the transport zoning system. Transport zones should ideally contain homogeneous land use (for example, solely residential, industrial or commercial use or parking lots) and they should not cross significant barriers to travel (such as rivers, freeways and rail lines), and should have reasonably homogeneous access to the modelled transport systems. In this context, transport zones should match, as far as practically possible, Australian Bureau of Statistics (ABS) Statistical Area boundaries as defined by the Australian Statistical Geography Standard (ASGS). In general practice, transport zones will be aggregations of the Statistical Area Level 1 (SA1) or mesh block boundaries.

Land uses with specific trip generation characteristics, which cannot be adequately described by the trip generation equations derived for other land uses, should be coded as separate zones (such as airports, ports, universities, hospitals, intermodal terminals and shopping centres).

In theory, the accuracy of a transport model should increase with the number of transport zones. However, it may be difficult to obtain reliable input data (employment, population) at a highly disaggregated level. The trade-off, therefore, is between the accuracy of the transport model and the practicality of having existing input data for transport model development at the chosen level of geography, and also being able to forecast the input data.

Another point to be considered when defining the zoning system is the highway and public transport network detail required to support the defined zoning system. A highly disaggregated zoning system will require a concomitantly disaggregated network to ensure all trips from all transport zones can access the transport network (via the centroid connectors) and that there is a reasonable concordance between the modelled and observed traffic volumes.

Transport zone centroids are defined as the ‘centre of gravity/activity’ of a transport zone and centroid connectors are used to load the trips from a transport zone onto the modelled transport network. Centroid connectors should represent, as closely as possible, zonal ingress and egress at reasonable access points to the network. Ideally, centroid connectors should not be connected to intersections: it is preferable to connect them to mid-block points in the modelled transport network.

3.2.2 Step 2 – Trip distribution

Trip distribution determines where the trip ends – developed in trip generation (Step 1) – will go. These trip ends are linked to form an origin–destination pattern of trips through the process of trip distribution. The logic behind trip distribution is that a person is more likely to travel to a nearby transport zone with a high level of activity (such as employment, shopping or recreation) than to a more distant zone with a low level of activity.

There are several approaches for trip distribution such as growth factor, gravity model, entropy-maximising approach, intervening opportunities (Ortúzar and Willumsen, 2011). The most commonly used procedure for trip distribution is the gravity model.¹ The gravity model takes the trips produced at one particular zone and distributes them to other zones based on the size of the other zones (as measured by their activity or trip attractions) and on the basis of some impedance to travel between zones. Thus, the number of trips between zones is usually related to the degree of land use and activity within each zone and the ease of travel between them.

¹ The ‘gravity model’ in transport modelling is analogous to Newton’s law of gravity, as in both models the attraction between two bodies (or zones) is proportional to their masses (trip generation) and inversely proportional to their separation.

Recent developments in trip distribution have seen the implementation of logit based destination choice models. While destination choice models may use different mathematical functions to gravity models, they share many of the same characteristics and similar to the gravity model, can be either singly or doubly constrained.

Impedance can be measured in several ways. The simplest way is to use either actual travel distance (km) or travel times (minutes) between zones as the measurement of 'impedance'. Alternatively, by ascribing a value of time and a vehicle operating cost rate to travel time and travel distance respectively, together with any tolls paid, a 'generalised cost of travel'² can be used as the 'impedance'. It is necessary that the gravity models or destination choice models should be applied to the network costs representing the effects on future travel patterns. An approach assuming that the base year travel patterns do not change in the future is unlikely to be realistic.

It is usual to have a separate gravity model developed for each trip purpose, since different trip purposes exhibit different trip distribution characteristics. The outcome of the trip distribution step is a matrix of trips from each transport zone to all other transport zones.

3.2.3 Step 3 – Mode choice

Mode choice allocates the origin–destination trips derived from trip distribution (Step 2) to the available travel modes, by trip purpose. This step estimates the choice between travel modes based on the characteristics of the trip maker (income, car ownership, age), the trip itself (trip purpose, the origin and destination) and the characteristics of the travel mode (fares, vehicle operating costs, travel time, parking availability and cost, reliability). The outcome of this step is an estimate of travel by all available travel modes between all transport zones, by the separate trip purposes.

The development of mode choice models usually relies on information such as the observed mode choice (from survey data or other sources), the characteristics of people undertaking the travel (age, employment status, currently studying and at what level, if they hold a licence) and the characteristics of the travel modes (availability, frequency, price, reliability).

Travel modes for personal travel include:

- Walking
- Bicycle
- Car
- Bus
- Tram
- Train.

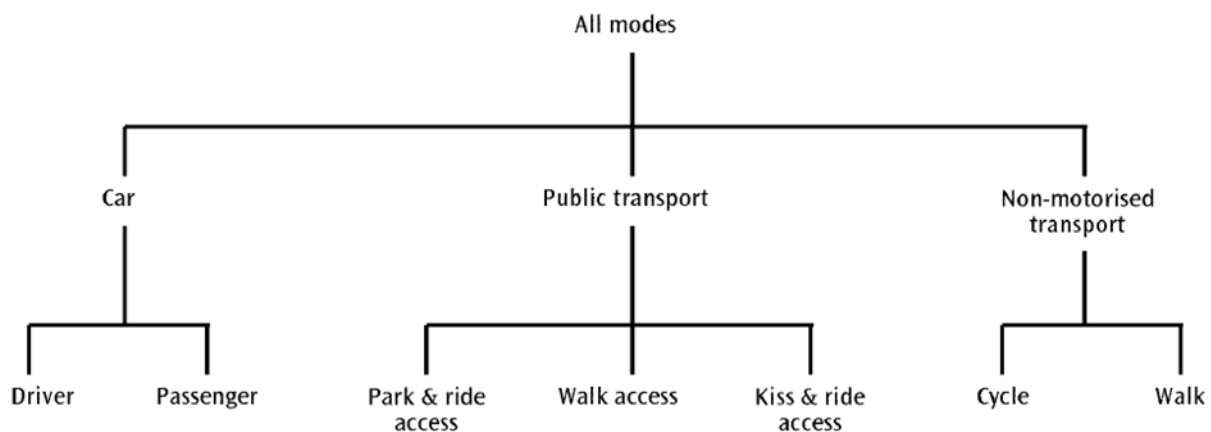
Mode choice can be performed before trip distribution (trip-end mode choice model) or after trip distribution (trip-interchange mode choice model). Alternatively, trip distribution and mode choice may be performed simultaneously using a composite cost function (Otuzar & Willumsen 1994).

² A combination of time, distance, tolls and other out-of-pocket travel costs such as parking charges.

Trip-end mode choice models split the total demand for travel for each transport zone by the available travel modes. The mode choice in this case is based on the attributes of the trip origin (that is, ease of access to each mode and the ability or inclination to use a particular mode). The trip-interchange mode choice models split the origin–destination travel (including intra-zonal travel) between the available travel modes by responding to the specific service characteristics of the available travel modes. In this approach, the number of trips by travel mode is estimated on the basis of the relative utility (or disutility) of travel by different modes, as perceived by the trip maker.

The most commonly used form for mode choice is the 'logit' model – a discrete choice model - which is based on the assumption that an individual associates a level of utility (or disutility) with each travel mode in undertaking travel between transport zones. In practice, a generalised form of logit models known as nested logit models are used to model mode choice. Figure 6 below shows an example structure of a nested logit model.

Figure 6 Structure of a nested logit mode choice model



The example above incorporates three broad modes of travel: car, public transport and non-motorised transport. The car mode is split into car driver and car passenger. Public transport is split into three separate elemental modes, depending on the mode of access taken to use the transit services (note that this model does not distinguish between rail or bus services). Non-motorised transport is split into bicycle and pedestrian modes. The application of nested logit models is documented in a readable way in Hensher et al (2005).

It should be noted that traditional logit (MNL and nested) does not allow for differences in user specific taste. Modelling user heterogeneity and their difference choice patterns requires the development of specific models for each of the demand segments or the use of mixed-logit models, which are not the standard practice.

A brief account of discrete choice models, in general, can be found at Appendix B. For further information on the development, estimation and application of discrete choice models, the determination of elasticity values from discrete choice models and the application of the models in project evaluation, see: Ortuzar and Willumsen (2011); Taplin, Hensher and Smith (1999); Hensher and Button (2000); and Louviere, Hensher and Swait (2000).

3.2.4 Step 4 – Trip assignment

Trip assignment assigns the various mode-specific trip matrices, by trip purpose, to the alternative routes or paths available across the transport network. Public transport trips are assigned to the public transport network (where path choice includes all public transport modes); and vehicle trips are assigned to the highway network. This step provides an indication of the likely distribution of travel across the available transport network.

Trip assignment results can be used to:

- Identify and assess deficiencies in a transport network
- Assess the transport network performance
- Evaluate the impacts of transport infrastructure proposals
- Evaluate alternative transport system and land use policies
- Provide inputs to economic appraisal.

Section 3.6 *Network models* provides further details on trip assignment.

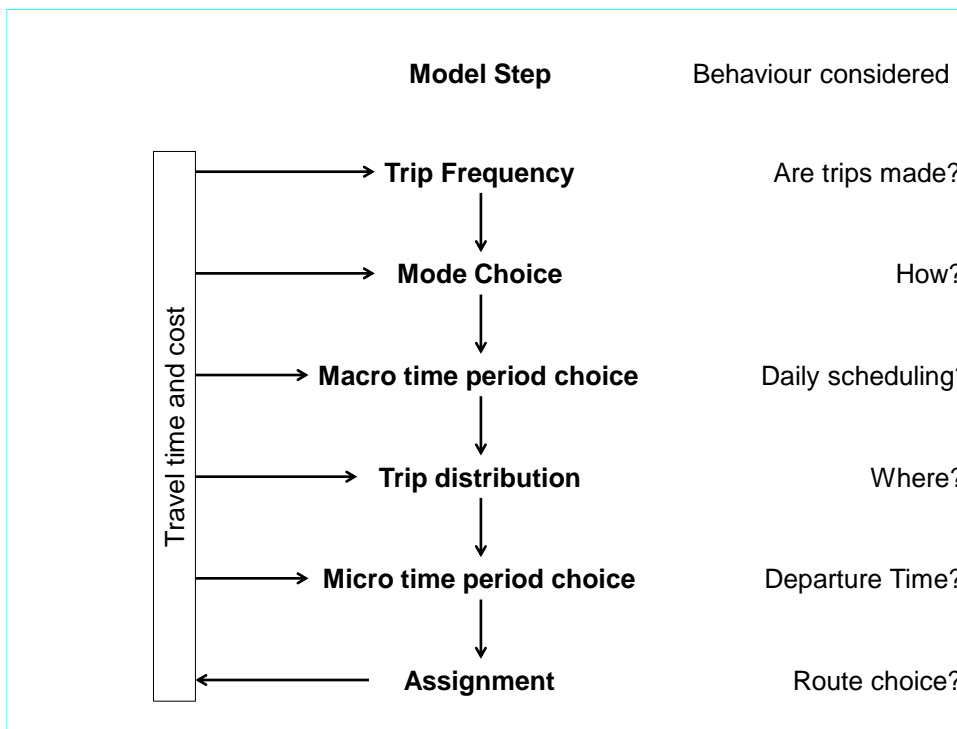
3.2.5 The five step transport modelling process

At its simplest, the four step model involves the assignment of daily highway demand into the network. For daily traffic assignment, practitioners would usually estimate the daily capacity for a link by applying a factor to its hourly capacity, based on the relationship between daily traffic and hourly traffic counts. This method is simple to develop and operate and may be suitable for small regional towns with low traffic congestion. The approach does not distinguish marked differences in traffic pattern between AM and PM periods. In larger towns where there is congestion, time period factors are applied to disaggregate demand between individual modelled periods and thus representing variations in trip patterns, such as typical commuting patterns towards employment centres in the morning. This provides a significant improvement over the all-day assignment, since it is able to represent traffic demand and congestion over different time periods. The time period factors are defined by travel purpose and distinguish direction of travel to and from home and are typically derived from household surveys.

A five step transport model would incorporate an additional step called *time period model*, to split the daily demand between time periods. Currently, almost all Australian models have fixed time period factors which are applied to split daily demand into AM, Inter-peak, PM and Off-peak periods. However, the assumption of fixed factors of time period for future year models might overestimate the level of traffic congestion during the peak periods as travellers would consider changing their time of departure to avoid traffic congestion.

Recent developments in five step transport models incorporate the capability to model the departure time choice of a traveller in response to changes in travel conditions. In many circumstances, travellers will be more likely to change their time of travel, rather than their trip destination or the mode of travel, in response to changes in travel conditions. The incorporation of a departure choice step, for example, can better enable the modelling of the peak spreading phenomenon. As discussed above, the use of fixed trip timing assumptions can result in overstatement of modal and distribution responses in forecasting where there is significant peak period congestion.

Figure 7 An example of a five step model including travel time choice



When fixed assumptions are made about the proportion of trips at different times of day for different purposes, consideration should be also given to other factors such as trip length, reflecting for example the earlier departure time frequently observed for commuters making long journeys. Care is required also to reflect the objectives and scope of the model; the time a long journey traverses the main modelled area may be of more interest than the departure time.

It is useful to distinguish behaviours about scheduling activities, which may be associated with changing travel times by one or more hours, from those about how best to make a journey, which may involve adjusting travel times by a few minutes.

Approaches to represent the former, macro-time period choice, are mathematically similar to those used for mode choice modelling although the linkage of individual trips into tours starting and ending at a traveller's home is usually advisable to reflect the interactions between different trips. Hess et al 2008 discusses methods and Fox et al 2014 provides a commentary on different approaches that have been applied.

Experience on the latter, micro-time period choice, is more limited. The most common approach is to apply a choice model for departure time that incorporates a scheduling penalty for arrival or departure before or after the ideal time. However, integration of this in an area wide model also requires network models that can reliably differentiate and represent the differences in network conditions and travel times for small differences in departure time. The applications have therefore tended to be localised and context specific.

3.3 Demand elasticities

Analysis using demand elasticities is based on the assumption of a direct relationship between the change in a policy-dependent variable and the corresponding change of a particular transport choice. The elasticity of demand, with respect to a given parameter (explanatory variable) may be seen as the percentage change in quantity demanded resulting from a one per cent change in the value of the parameter.³ Both the magnitude of the percentage change and the sense of that change (positive or negative) are important. Direct elasticity refers to the change of demand for one transport service (or mode) in terms of the change in a parameter affecting that service (or mode). Cross elasticity refers to the change of demand for a service or mode resulting from the change in a parameter affecting a different (competing) mode or service. Thus, for example, the change in patronage on a rail service as a result of the increase in the fare charged for that service could be estimated using the direct demand elasticity for rail with respect to fare. The increase to an alternative mode (such as bus) resulting from passengers switching modes could be estimated using the cross elasticity of demand for bus with respect to rail fare.

Similarly, the elasticity of demand with respect to income measures the proportionate change in demand resulting from a proportionate change in the income of the consumer. As consumers have more income, their choices may expand or change.

Elasticity models are used to estimate these effects. If the value of the parameter is P and the demand (such as number of trips) is Q , then the elasticity η is given by:

$$\eta = \frac{\frac{\Delta Q}{Q}}{\frac{\Delta P}{P}} = \frac{P}{Q} \frac{\delta Q}{\delta P}$$

The partial derivative $\frac{\delta Q}{\delta P}$ is used to indicate that all the other explanatory variables (parameters) that can affect demand are assumed to be held constant. This derivative is the slope of the demand curve that relates to Q and P . The slope of the curve may vary along its length so the value of η as defined by the equation above is only valid for the particular point at which the slope is measured. It should strictly be called the 'point' elasticity.

Elasticity values can be derived for many parameters, such as fares, costs and charges, travel times, service reliability, service frequency or service quality (e.g. passenger comfort or possibility of damage to or loss of commodities). Provided the relative change in the value of each of these parameters is small, the overall change in demand can be estimated as a simple sum of the individual change estimates

$$\frac{\Delta Q}{Q} = \eta_A \frac{\Delta P_A}{P_A} + \eta_B \frac{\Delta P_B}{P_B} + \eta_C \frac{\Delta P_C}{P_C} + \dots$$

³ More formally, the elasticity of demand with respect to a particular parameter is defined as the ratio of the proportionate change in demand to the proportionate change in the relevant parameter.

for parameters P_A , P_B , P_C , etc. Models of this type have been used for many years by transport operators. They provide a quick estimation of the likely effects of proposed service changes, based on previous experience, as long as the service changes are incremental.

Point elasticity as defined by equation above is rarely available for practical applications, because knowledge of the mathematical shape of the demand curve would be required to determine it – and this is seldom the case. Rather, most elasticity values used in practice are arc elasticities, estimated by considering measured differences in demand at different values of a given parameter. If the demand Q_1 corresponds to value P_1 and demand Q_2 corresponds to value P_2 of the parameter, then the arc elasticity η is given by

$$\bar{\eta} = \frac{(Q_2 - Q_1) / \frac{1}{2}(Q_2 + Q_1)}{(P_2 - P_1) / \frac{1}{2}(P_2 + P_1)} = \frac{\Delta Q \bar{P}}{\Delta P \bar{Q}}$$

where P and Q are the respective mean values. Given the non-linear shape of logit and most demand curves, the arc elasticity is commonly used in log form as below, to be applicable across a slightly wider range of cost changes:

$$\eta = \frac{\text{Log } \frac{Q_2}{Q_1}}{\text{Log } \frac{P_2}{P_1}}$$

The demand to use a particular mode or service can be affected by changes in travel parameters applying to competing modes as well as changes in the parameters of the given mode. The effect on demand for use of mode H of changes in a parameter P_G on mode G is given by the cross elasticity:

$$\eta_{H^G}^G = \frac{\frac{\Delta Q_H}{Q_H}}{\frac{\Delta P_G}{P_G}}$$

Elasticity values are generally estimated from time series data. For instance, transport operators may collect information on patronage or commodity movements over time and this can be used to suggest the effects on demand stemming from changes in transport costs or other service parameters (for both their own operations and those of their competitors).

Elasticity values for passenger transport by transport mode may be found in reported studies such as Oum, Waters and Yong (1992) and Luk and Hepburn (1993). A substantial database of elasticity values has been compiled by the Bureau of Transport and Regional Economics and is available on the BITRE website (www.bitre.gov.au) under databases and products. Taplin, Hensher and Smith (1999) provided a discussion on the conceptual and theoretical requirements on the estimation of elasticity values. When applying the elasticity values from literature to any project, one should examine the applicability of these values considering the place, time and the source of data used when they were derived, and their valid range.

Certain conventions need to be followed when interpreting published values of elasticities. In the case where η denotes a demand elasticity with respect to parameters such as cost or trip time, the value of the elasticity is negative – an increase in the price of a service would normally be expected to lead to a decrease in the demand for it, but common practice among economists is to quote only the magnitude (modulus) of the value (as a positive number, with the implicit assumption that the value is actually a negative number). Cross elasticity values are generally positive – an increase in the charges for use of a competing service would be expected to result in an increased use of the other service. The dimension of demand should be checked for example whether it is expressed in number of trips or trip kilometres before applying the appropriate elasticity.

3.4 Induced Travel Demand

The issue of induced travel demand has been discussed at length in literature (U.K Department of Transport (1993), Abelson and Hensher (2001), Litman (2008) and Ian Wallis Associates for Department of Transport Victoria (2009)). The Victorian Auditor-General's Report (Victorian Auditor-General's Office, 2011) recommended road authorities to assess the significance of induced traffic for all major road projects and consider it when forecasting traffic and estimating the economic benefits. Subsequently Victoria Department of Transport (DOT) (2011) released a draft position paper on induced travel demand.

3.4.1 Sources of induced demand

Induced travel demand refers to the impacts of new transport projects and services in encouraging some people to switch routes, modes or time of travel to take advantage of the improved travel times and service levels. In addition, induced demand can refer to the tendency of some people to travel more when travel conditions are improved. Longer term effects may include some households and businesses locating close to the new or improved transport infrastructure and services, and/or locating further away from their destinations. Induced travel demand can arise from both road and public transport (PT) projects (DOT, 2011). Overall, induced demand resulting from a transport improvement may include six following components:

- 1) **Change in route:** The transport improvement may make one route faster. Traffic travelling between A and B switches to the improved route, resulting in induced trips on the improved route although not necessarily in the network as a whole.
- 2) **Time of day:** The transport improvement may improve travel speed at one time of day relative to another (e.g. peak hour vs off-peak). Trips travelling between A and B switch from the slower to the faster time of day (e.g. from off-peak to peak), resulting in induced trips at the faster time of day (e.g. peak hours) although not necessarily more trips on the network as a whole over the day.
- 3) **Changes in mode choice:** An improvement in one mode will cause some people to switch to it from other modes, for example, a road improvement would cause public transport users to switch to car travel, resulting in induced car trips. This is the most commonly achievable variable matrix approach in most capital city transport models (SKM 2009);
- 4) **Trip redistribution:** Trip destination change. Improved travel speeds may encourage people to switch from a close destination to a more distant one that becomes more attractive. This results in induced travel kilometers of travel.
- 5) **Trip generation:** As the transport improvement makes travel less costly, new trips may be made that were not made previously on any transport mode.
- 6) **Land use changes:** In the longer term, the new or improved part of the transport system may encourage higher population and business activity near the improved facility, and/or encourage households and firms to locate further away from their destinations - both contributing to increased traffic flows (see section 3.5 for discussion of modeling of land use and transport interaction).

Depending on the scale, large projects such as a new freeway may generate all six components of induced

demand, while small projects like a small town bypass may cause only a change of route. The extent of induced demand was further discussed by DOT (2011) as follows.

Evidence of the induced demand effects of trip generation and trip redistribution for urban transport projects is limited. In terms of impact on travel time, the extent of new trip generation and trip redistribution in peak periods appears to be negligible. The impact on off-peak travel times is considered to be smaller still.

In large cities where rail's share of the commuting trips to the central area is substantial, it was found that modal shift from public transport can account for up to half of the estimated induced traffic on a road corridor. As a proportion of total screenline traffic, literature suggests that induced demand as a result of modal shift can account for between 2% to 3% of total screenline traffic flow.

Studies examining different road schemes generally find trip re-assignment to be a substantial factor contributing to induced demand, which could range from 10% to 25% of total screenline traffic depending on location-specific factors such as time savings created by the specific project and the extent of congestion on existing/alternative routes.

Prior to the construction or enhancement of a major road link (or public transport service), some travellers may choose to travel outside peak periods to avoid congestion; however, they may reschedule their trips if the time advantage of doing this is no longer as great. This means a road (or public transport) improvement could induce travellers to retime their trips, adding to the numbers travelling during peak periods. Surveys have found that between 10 per cent and 30 per cent of respondents reacted to road improvements by reverting to travel on those roads during peak periods. Trip retiming could be a significant source of induced demand during peak periods. However, trip retiming does not add to the increase of a total daily trips or VKT.

New roads and upgrades to existing roads can alter land use patterns, and the location decisions of both firms and households. In particular, activities that are reliant on accessible locations would tend to increase around new road developments such as distribution/warehousing activities, large mall and superstore developments, and offices requiring good access for employees and visitors. It is likely that significant public transport improvements would also encourage land use changes over the medium to long term. However, the empirical evidence of induced traffic from land use changes is scarce. Nevertheless, induced demand from land use changes would be largely a medium to long term phenomenon.

3.4.2 When is Induced Demand Significant?

Induced travel demand effects are of greatest importance for the demand modeling of transport projects in networks with:

- a high degree of congestion (typically in urban areas, especially at peak periods); and/or
- high elasticity of demand (typically in urban areas, especially where alternative modes offer strong competition); and/or
- relatively large changes in travel costs (typically for larger schemes providing substantially enhanced capacity).

For public transport network improvements, induced demand effects are also most significant when similar conditions apply – that is, when demand is elastic and increases in response to improved service, and when the service is already congested or crowded.

3.4.3 Modelling Induced Travel Demand

The Transport Analysis Guidance (TAG) (Department for Transport London, 2014) suggests three broad approaches to representing travelers' response to cost:

- a fixed demand approach, or Fixed Trip Matrix (FTM) approach, in which demand is independent of cost, and the trip matrix is adjusted using trip ends and no behavioural model is required;
- an own cost elasticity approach where demand in each cell of the trip matrix can vary, but the source of any variation is limited to the corresponding cell of the cost matrix only; or
- a full variable demand approach, or a Variable Trip Matrix (VTM) approach, where demand in each cell of the matrix can vary according to demand in other cells of the trip matrix and costs in all cells of the cost matrix. This is usually implemented using discrete choice models.

Use of the FTM approach is only valid for generally small or short term schemes where it can be demonstrated that changes in travel cost will not generate a noticeable change in demand. This method should only be used if the network improvement would only generate route changes. As such, FTM models are inadequate for most transport schemes which are aimed at resolving congestion or relieving overcrowding on public transport. The FTM modelling could also materially overstate the economic benefits a scheme could deliver (see Abelson P. & Hensher D., 2001 and Litman, 2008).

Own-cost elasticity models do not constrain total demand according to the size of the population. This means they are not adequate for representing either the transport market as a whole, or modes with a high share of overall travel, such as car. However, they have advantages over choice models when analyzing rail schemes as it is much less expensive to build. DOT (2011) provided several elasticities with respect to travel time and network capacities. Own-cost elasticity” models are in common use in other countries. They can produce accurate forecasts if based on detailed observed passenger origin-destination data such as from smart card or other detailed ticket data.

The VTM approach is required to assess induced demand. Generally, a four step transport model would provide variable demand and be able to address at least the issue of induced demand with respect to redistribution of trip (by trip distribution module), change of mode (by mode choice module) and change of route choice (by trip assignment module). The level of accuracy would depend on model design.

Where strategic transport models for Australian major cities do not model time of day choice (Planning and Transport Research Centre, 2014), they are unable to assess the induced demand due to travelers who change their time of travel. There are two distinctly different aspects of time of day choice:

- *Macro* time period choice - representing the choice between broad time periods within a day, e.g. whether travel is in a peak period or an off-peak period
- *Micro* time period choice (peak spreading) - representing departure time choices of a few minutes.

Variable demand models only usually include macro time period choice to represent transfer of traffic between broad time periods. Logit type choice model can be used for both macro and micro time period choices. For example, macro time period choice (the allocation of trips between broad time periods – see Section 3.2.5) takes the form:

$$T_{ijms} = T_{ijm} * \frac{\exp(-\lambda_{time} G_{ijms})}{\sum_t \exp(-\lambda_{time} G_{ijms})}$$

Where:

T_{ijms} is the number of trips between zones i and j by mode m in time period s.

G_{ijms} is the disutility or generalised cost of travel between zones i and j by mode m in time period t, which may typically be peak and inter-peak and λ_{time} is the choice sensitivity parameter for the time period step.

Currently, most Australian transport models were developed with static trip generation rates, i.e. trip generation rates do not change with improvement of transport system. The development of a dynamic trip generation module with trip generation rates being a function of transport accessibility (Ortúzar, J. and Willumsen, L., 2011) would enhance the model in this aspect. The cost of development of this component needs to be balance against the benefits of having it. Separately DOT (2011) indicates that there is a general agreement among transport planners that entirely new trips represent a relatively small share of the increased traffic appearing on a new or improved highway facility.

Where the variable demand (VTM) model is used to forecast responses to scheme related cost changes, there is a need to ensure satisfactory convergence of the demand-supply iteration in addition to the network model convergence (Section 5.9) particularly when estimating user benefits. Where the model is used to estimate user benefits (see section 3.4.4 below), the demand/supply gap should be measured as follows:

$$\frac{\sum_a C_a^n |D_a^n - D_a^{n-1}|}{\sum_a C_a^n D_a^n}$$

Where

C_a^n is the generalised cost for matrix cell a (spanning origin, destination, mode, time and segment) for iteration n

D_a^n is the demand forecast by the demand model using cost C

A demand supply gap of less than 0.001 may be satisfactory in most cases, but where the scheme is small relative to the model tighter convergence may be necessary. Assessed user benefits from previous demand/supply iterations of the model can indicate the stability of the user benefits calculation.

The transport system and land use system are closely interrelated. An improvement in the transport network would improve accessibility which would drive change in land use redistribution that in turn would redistribute trips and sometimes generate additional trips. The induced demand due to land use changes requires using a land use transport interaction model – see section 3.5.

The following table summarises the recommended modelling approach – FTM or VTM - to undertake to model the different types of induced demand.

Table 5 Recommended modeling approaches to model induced demand

Type of Induced Travel Demand	Modelling Approach
Changes in route	FTM
Changes in time of day	VTM
Change in mode choice	VTM
Change in trip redistribution	VTM
Change in trip generation	VTM
Change in land use	VTM

In the next version of the ATAP Guidelines, detailed guidance will be provided on the recommended application of the FTM and VTM approaches.

3.4.4 Measuring User Benefits

Part T2 Cost-Benefit Analysis of the guidelines, discusses the measurement of user benefits. Section 7.4 therein indicates that travel demand models are required to estimate user benefits in complex urban settings, and provides user benefit equations to be used. It indicates that the user benefit calculations should be undertaken within the travel demand model as follows:

- The user benefit calculations first need to be undertaken at a disaggregated level for each origin-destination pair, for each mode, for each time period and for each forecast year
- The disaggregated results are then aggregated to yield overall use benefits.
 - aggregating across the entire demand matrix, i.e. across all origin-destination pairs
 - repeating the process for all modes and time periods
 - repeating the process for each model forecast year.

Where induced demand is expected as a result of a transport improvement, the Variable Trip Matrix (VTM) methodology should be applied in demand modelling and user benefit estimation. A VTM approach should be used, in conjunction with a variable demand model as discussed above. The VTM approach differs from the Fixed Trip Matrix (FTM) approach in that, for a given forecast year, the demand in the Option Case is usually higher than that in the Base (Do Minimum) Case.

Consistency must be maintained in calculating user benefits across all origin destination pairs, modes and time periods represented in the transport model, as discussed further by Jones (1977). Issues that may need specific consideration include the following:

- Introduction of new modes, or where the changes in cost are large and the demand curve cannot adequately be approximated by a straight line. In this case approaches include the use of composite cost derived for more aggregate representation of choices, or through testing a sequence of 'interim' supply curves providing a better approximation to the demand curve.
- Changes in land use, whether forecast by an integrated land use model, or with development constrained without the intervention. In this case the land use related costs are not included in the cost per trip and the user benefit calculation must be constrained to fixed land use assumptions, with separate calculations undertaken on the benefits of the development (or land use changes).
- Instability or lack of convergence in the transport model (see also section 3.4.3 above). Testing with for example one additional transport model iteration can illustrate the level of uncertainty in the user benefit calculation. In some cases, where model noise is attributable to issues remote from the intervention, actions to constrain the changes in cost represented in the model (either by excluding remote origin-destination movements from the user benefit calculation or constraining the travel cost changes represented in the transport networks may be justifiable.

One of the reasons for applying the 'rule of a half' calculation is the ability to report separately what changes the user benefits derive from (e.g. travel time, monetary cost, perceptions of travel quality). Similarly, the value of travel time savings is judged to be greater for business travellers than for other travellers and these should be distinguished in reporting. It may be that particular population segments need to be distinguished, depending on the objectives the intervention is intended to address.

3.5 Land use transport interaction (LUTI)

A key input to strategic transport models is land use information. There is little argument about the fact that there is a relationship between transport demand and urban structure. The opposite relationship, that urban development is related to the transport supply, is also accepted yet not fully understood. It is generally accepted that transport accessibility is an important ingredient for understanding the potential for land use development. However, there is still some uncertainty as to the most appropriate method of implementing transport land use interaction models given the reoccurring tension between theoretical preferred options and practical implementation. The aim of this section is to provide reference material on the evolving area of land use transport interaction. More guidance will follow in the next update.

3.5.1 Overview of types of land use transport interaction models

The following section provides a brief overview of the different approaches used for land use transport interaction models, as summarized below.

Structure \ Mode	Static	Dynamic
Linked	Separate Land use and transport model, run iteratively to convergence representing single forecast year	Separate land use and transport models, run sequentially, say in 1 or 5 year increments, representing dynamic evolution over time
Integrated	Interaction of land use / activity patterns directly mapped to transport needs, run iteratively or through simulation if disaggregate, to equilibrium	E.g. using system dynamics software, directly linking land use / activities to transport, and representing lags in rate of response

Static equilibrium models

Static equilibrium LUTI models are analogous to the four step transport model in that they are generally macroscopic in nature. Early LUTI models such as the Lowry model (Lowry, 1964) used gravity formulations or input-output formulations. Static LUTI models are usually directly linked to four step models and can be used to estimate equilibrium patterns of land use by iterating with a four step models, which in turn create measures of accessibility to be input to the land use model. In a four step model, land use changes are forecast first based on planned developments, with no direct input from the transport model. In static equilibrium LUTI models, the land use model includes functions representing how accessibility affects land use, and the land use and transport models are run iteratively to an equilibrium with land use forecasts input to the transport model and accessibility (travel cost) forecasts input to the land use model. Static equilibrium models can be implemented by combining separate land use and transport models through an iterative process, or can be fully integrated.

Dynamic models

Dynamic models (Wegener, 2013) are generally classified as either macroscopic (General spatial equilibrium models) or microscopic (agent based models). They are based on random utility theory and theories of competitive markets. In some instances, these are referred to as based on systems dynamic theory, that is representing the time dependent interactions and lags between land use and transport related systems. They can be fully integrated with transport models rather than being exogenous inputs to each other. Dynamic agent based models are more analogous to activity based transport models.

Linked versus integrated models

In fully integrated models the destination choice is undertaken within the land use part of the model. Therefore, the land use and transport components of the LUTI model cannot be separated. In contrast, in linked LUTI models the destination choice is undertaken in the transport part of the model, as in a regular four step model. This allows the land use and transport models to be separate from one another but link to each other in an iterative manner (DfT, 2014).

The advantage of fully integrated models is that the travel formulation and land use formulation is entirely internally consistent as the processes are endogenous. However, having these processes fully integrated assumes a high level of confidence in the land use model. Fully integrated models may find it difficult to reach unique solutions, which then pose a challenge for undertaking economic assessments of infrastructure projects.

Linked models may lack the internal consistency of fully integrated models; however, they are more flexible in their application in that the interaction between the transport and land use models can be turned on or off.

3.5.2 Use of LUTI models in Australia

The Planning and Transport Research Centre (2014) provides several references to the application of land use models in part of Australian cities. These include:

- Metropolitan Land Use Forecasting System (MLUFS) by the Ministry for Planning, Western Australia (1996)
- UrbanSim application in Logan City Queensland (Brits, 2013)
- Large Scale Urban Model (LSUM) applied in South East Queensland to simulate potential future patterns of population and jobs at a spatially disaggregated level (Stimson et al., 2012)
- Queensland Small Area Model (QSAM) constructed by Demographics Australia for use by the Queensland Government to project total population and dwellings for up to 500 small areas within an urban Local Government Area (Wilson, 2011).

Apart from UrbanSim, a dynamic disequilibrium model with capability to connect with a four step model, the other land use models are static equilibrium, without location choice or capability to link to transport model.

In most transport jurisdictions within Australia transport and land use models operate independently from each other and only an occasional interaction usually when assessing major infrastructure projects. When applied, the LUTI models generally have the land use model and transport model linked rather than integrated. There are differences in view with some practitioners adopting a take the form of static equilibrium models with the land use model and transport model linked, but not necessarily run to a convergence. There is not complete agreement whether it is sensible to model a converged land use transport interaction model, or to represent the evolution of land use over time using a 'systems dynamic' approach.

Given that land use and transport models have been separately developed, linkage of these tools is relatively low cost route to establish a LUTI model. The key actions are as follows.

- Establish a file management structure to control the iterations between transport and land use models. For a static model this will include a process to measure and test convergence, for which it would be adequate to measure stability of transport model metrics. For a dynamic model, the process would be arranged to operate the land use model typically for each year through the modelled period. The transport model may be run in say 5 year intervals, taking inputs from the relevant forecast year of the land use model and providing outputs to the land use model for the subsequent few years. In both cases the transport model would be run to convergence.
- Link land use model forecasts of population and employment to provide inputs in a suitable form for the transport trip generation model.
- Link the transport model generalised cost outputs in a suitable form to represent accessibility changes input to the land use model.
- In some instances, there can be other interfaces, such as environmental indicators based on traffic volumes in an area, depending on the capabilities and relationships represented in the land use and transport models.

The additional iterations between transport and land use model require consideration in verifying and interpreting forecasts. In a dynamic model for example the rate of change over time may need to be considered, in addition to the final outcomes. It is also often helpful to run the models separately to separate the effect of the individual transport and land use relationships represented in the LUTI model and this better explain the forecast outcomes.

3.5.3 Appropriate use of LUTI models

Static equilibrium LUTI models provide a tried and tested method of modelling the interaction between transport and land use, albeit with some significant behavioural shortcomings. These static models will likely be the LUTI model of choice when combining with a four step models for the purpose of producing land use forecasts to be used in the appraisal of major transport infrastructure projects.

Relative to a dynamic model, the static model is simpler to implement. It also provides outputs that can be interpreted in appraising the impacts of transport schemes more easily to allow the analyst to explain the forecast impacts of the transport intervention on land use and the wider economy.

However, for the purpose of understanding transport and land use interactions for the purpose of developing policies a 'system' dynamics' approach may provide more insight to policy makers. Land use changes (and some transport behaviour) evolve over years and decades. A dynamic model more realistically represents the evolution of changes. The added complexity for the analyst is to investigate a number of forecast years to understand these interactions. This is complicated by the absence of equilibrium principles in the model process.

A particular value of LUTI models is the capability to represent internally consistent visions of the future, or different scenarios. The use of different scenarios helps the decision maker understand the factors that cause pressure for development or stress in the transport systems and how these relate. They also provide a basis to help interpret when particular interventions may be appropriate, and what drivers may cause the need for intervention to come forward or recede in time.

3.5.4 Validation and data requirements

For static land use models, regression analysis looking at the correlation between planning data (residential intensity, employment intensity) and accessibility (as derived from the transport model) draw upon the information that would be required for conventional four step transport modelling. In some cases, the land use model tools have been developed drawing on a range of research evidence to establish suitable functional relationships with outputs available from the transport model. Usually additional segmentation is adopted distinguishing employment types than are commonly applied to transport models.

More sophisticated land use models consider also constraints of the planning system, the extent of land available for development and in dynamic models the speed of change that can be achieved. Particular data requirements in these cases are the extent of land that may be developed, and for what purposes, over the forecasting period.

Land use changes arise from a range of sources, beyond those related directly to the transport systems. It is important therefore to take a dynamic approach to testing and verifying the performance of the land use models. This would first compare the rate and nature of forecast population and employment growth over time, comparing this with historic trends and existing policy based plans. Secondly the responsiveness of the land use changes to transport changes should be considered, reflecting both the scale and location of forecast changes.

3.6 Network models

Transport network models generally comprise a combination of interconnected links (sections of roads) and nodes (representation of intersections) and are termed 'link-based' network models. Public transport services are represented in part by the sequence of nodes (stops) and links traversed. The transport network model, or 'supply side' component of a transport model is intended to reflect, as accurately as possible, the actual available transport network, by incorporating the following link attributes:

- Distance
- Free speed on the link or travel time
- Capacity, as related to the number of lanes or available train paths
- Direction indicator (one-way or two-way link)
- Volume delay function.

The transport network model should be sufficiently refined to support the adopted model zoning system and, as a minimum, should cover the following road classifications:

- Freeways and tollways (coded as one-way links with associated ramps coded separately)
- Divided and undivided arterials
- Collector roads
- Local roads (the extent to which these are included is at the discretion of the modeller and the requirements of the particular study)
- Rail lines (freight and public transport)
- Ferry lines and services
- Bus-only corridors.

3.6.1 Highway traffic assignment

One of the most commonly used assignment techniques is the capacity restrained assignment that involves the allocation of traffic to routes according to the ability (or capacity) of the route to accommodate traffic. It should be noted that the capacity of a route is not like the capacity of a bottle; rather, it is more like the capacity of a balloon. A bit more capacity can usually be squeezed in, but the balloon (or route) becomes more stressed and resistant to any further increase. In this context, capacity restrained assignments are recommended where networks are congested.

The application of a capacity restraint does not imply that once a certain level of traffic is reached, no more traffic can be assigned, as the theoretical capacity may be exceeded albeit with resultant lower travel speeds. All the traffic derived from the demand forecasting will be distributed to the road network in one way or another, and usually on the basis of volume delay functions.

It is common for traffic assignment models to employ volume delay functions, which describe how the speed or travel time on a particular link will deteriorate as traffic builds up.⁴

A number of specific techniques are available for undertaking a capacity restrained assignment (such as equilibrium, stochastic, volume-averaging, incremental). Detailed information on these techniques is provided in the available literature.

The capacity restrained assignment generally begins by estimating the shortest path from each origin to all destinations (expressed in terms of the minimum generalised cost composed of some combination of travel time, travel distance and tolls). Trips for each origin–destination pair are then assigned to the links comprising the minimum path. As traffic volumes build up on a particular link, the speed on that link declines and the travel time increases making the link less attractive to any further traffic, leading to alternative paths to the same destination becoming more attractive.

The outputs from the highway traffic assignment are traffic volumes across the highway network, vehicle-kilometres and vehicle-hours of travel, trip length, peak period and daily traffic volumes, congested speeds and travel times and volume-to-capacity ratios. It is desirable that traffic assignment should be performed for peak periods, and off-peak periods with daily traffic volumes computed by combining the peak period and off-peak period traffic volumes. The output from the traffic assignment can be used in economic appraisal and congestion analyses.

Most commonly static assignment methods are used in strategic models. These assume network conditions and routeing does not vary within the modelled period. A dynamic assignment approach (Chiu et al, 2001) is more complex, representing variations in conditions and routeing choices within the modelled period. This allows the model to represent the formation of queues, and the metering of demand downstream from constrained junctions, providing a more detailed understanding of the network performance. In some cases, the modelling also distinguishes lanes allowing for example an improved representation of effective network capacity and the implications for delays and impacts at merges and diverges where traffic may not be spread evenly between different lanes.

It is however common to represent more detailed aspects of network performance using microsimulation tools complement strategic models, as discussed further in Section 3.6.3.

Treatment of tolls

There is variation in the willingness of travellers to pay and, where there are choices between tolled and non-tolled routes, it is important for this to be represented. There also tend to be marked differences in the congestion or delay on the tolled and non-tolled roads, and differences in perception of time spent in queues can also influence route choice. A range of approaches has been applied to model demand for toll roads. Depending upon the needs of the study, one of these options would represent current best practice:

- Explicitly represent the choice between use of the tolled road and use of other routes through a choice model e.g. logit.
- Segmentation of demand between different value of time categories explicitly to represent the distribution of value of time
- An assignment algorithm incorporating an explicit representation of the value of time distribution.

⁴ Defined by the volume-to-capacity ratio.

Further discussion of toll road patronage forecasting will be available in subsequent updates to the ATAP Guidelines.

3.6.2 Public transport assignment

Public transport assignment procedures predict the route choices for public transport trips on the basis of the different attributes of the public transport network. Some of the more critical attributes are:

- Supply of public transport services as defined by the capacity of the public transport vehicle and its corresponding frequency. The public transport network consists of the route segments (links) and public transport stops (nodes) that form the public transport routes (lines).
- The estimated cost of using public transport services is the average fare paid to take the trip.
- The generalised impedance of travel by public transport is a function of the in-vehicle time, the time spent waiting, the time spent getting to a public transport stop, the time spent transferring from one route to another, comfort and convenience, public perception of the quality and reliability of each mode and the fare paid.
- Some of the main outputs from the public transport assignment include public transport patronage and line or service loadings, boardings and alightings at stops, interchanging within and across modes, and network-wide indicators such as passenger-hours of travel and passenger-kilometres of travel. Other outputs often required include station entries and exits (subtly different from boarding and alighting).

For studies where public transport passenger demand forecasting is the focus, then it is highly desirable to separately model the mode of access to the public transport system, e.g. walking/cycling, park-and-ride and kiss-and-ride.

3.6.3 Traffic simulation methods

The management of a road network often requires the forecasting of the impacts of implementing various traffic management measures. The impact involves the road itself, the whole corridor and its abutting areas. These measures include, for example, signal coordination, high-occupancy vehicle (HOV) lanes, one-way systems, different types of intersection control (priority sign, signal or roundabout), signal priority, driver information systems and incident management. Apart from road vehicles, trams, light rail vehicles, pedestrians and cyclists can also be simulated.

Simulation techniques for traffic assignment can be broadly classified into the following five types:

1. **Macrosimulation:** Assignment models at strategic level, part of the traditional four-step models and applied to large-scale areas. Typically, they are applied to time period O-D matrices, they use simplified representations of network links and nodes and make use of relatively simple volume-delay functions.
2. **Mesosimulation:** Traffic models that operate at a less disaggregated level of detail than the microscopic models. They are based on traffic flow theory and apply analytical procedures that do not require random sampling from statistical distributions of input variables. They are particularly useful for area-wide traffic management and congestion management issues.

3. **Microsimulation:** Simulation models that provide a very detailed view of the traffic by tracking movements of individual vehicles through the network and updating frequently (seconds) the position, speed and trajectory of each vehicle. They operate on the basis of traffic flow theory (e.g. car following theory, gap acceptance and lane changing behaviour), accounting for the behaviour and characteristics of the traffic participants (driver, pedestrian, cyclist). They require a detailed description of the network (design of links and nodes/intersections).
4. **Nanosimulation:** The most refined level of traffic modelling, seeking to replicate the behaviour of individuals using different modes of travel. It is particularly concerned with modelling waiting times, interaction between individuals, etc. The model requires network description similar to microsimulation, however enriched with data on pedestrian spaces and corridors. They can also be used in the design of transport terminals (such as railway stations) and access to buildings and other facilities.
5. **Hybrid modelling:** Combination of mesoscopic and microscopic models in a single modelling framework. It allows the modeller to perform microscopic simulations within focus areas inside the full network mesoscopic simulation of the network.

In recent years, Intelligent Transport System (ITS) measures such as adaptive signal control algorithms, incident management strategies, active bus/tram priority and driver information systems have been introduced to freeways and arterial roads. These are complex traffic processes and traffic flow theories are often unable to accurately predict the impacts in terms of delay, queue length, travel times, fuel consumption and pollutant emissions. Computer models equipped with advanced graphical facilities have been developed in recent years to meet the needs of road managers.

Computer software has long been available to simulate traffic management processes amongst road authorities in Australia (see for example Cotterill et al. 1984; Tudge 1988). Past research also includes the development of car-following and lane changing algorithms for microsimulation (Gipps 1981, 1986), the review of eight small area traffic management models (Luk et al. 1983) and the comparison of macroscopic and microscopic simulations (Luk & Stewart 1984; Ting et al. 2004).

More recent research includes the assessment and further development of car-following and lane-changing algorithms (Hidas 2004, 2005; Panwai & Dia 2004). A key finding is that microscopic simulation models require careful calibration to produce meaningful results, especially in relation to lane changing behaviour in congested conditions.

3.7 Activity-based modelling

An alternative approach to the four step and five step models (from now on referred to as four step models for simplicity) are activity based models. Activity based models attempt to address some of the deficiencies inherent in four step models and introduce a disaggregate basis for estimating transport demand.

3.7.1 Deficiencies with four step models

The four step models provide strategic modelling frameworks that have been widely adopted by the transport modelling community throughout the world. The success of the four-step model in becoming the most commonly used form of strategic transport model can be attributed to:

- the four (or five) steps being conceptually relatively easy to understand;
- the ability to implement the models using off the shelf proprietary software without the need to be able to code in complex programming languages; and
- the ability of these models to be able to appear to provide answers to the questions policy makers put to transport modellers, particular with respect to network performance

However, limitations and deficiencies of the four step process have long been recognised (see McNally and Recker, 1986; USDOT, 1997). The deficiencies of four step models can be summarised as:

- not explicitly recognising that travel is derived from people's activity patterns and focusing on individual trips or tours, rather than reflecting the patterns of behaviour, and interactions within particular households;
- presenting travel behaviour as an outcome of a clean choice process, rather than being defined by a range of complex constraints such as being influenced by household dynamics and social structures;
- four step models inadequately specify the interrelationships of travel and activity between individuals and scheduling of activities in time and space.

3.7.2 Characteristics of activity base models

Activity based models attempt to address these deficiencies of four step models by using the household activity pattern as the basic unit of analysis. Activity-based models recognise that travel is derived from the demand for activity participation and therefore need to consider the interdependencies and constraints involved in scheduling activities. This allows activity based models to be able to address many transport policy questions that traditional four step models are unable to adequately model, particularly with respect to travel demand management policies that do not relate to the provision or removal of transport infrastructure.

Activity-based models apply functions to simulate which activities are conducted when, where, for how long, and with whom. These activity patterns help determine the travel choices available. Because of the complex nature of household activity patterns, activity based models lend themselves to be microsimulation in nature. This does not relate to the level of spatial disaggregation, rather it is an indication of whether the model is based on the individual decision making process, that is microscopic, or whether the model tries to simulate the overall transport pattern - macroscopic.

The development of activity based models can be distinguished by three different approaches:

- constraint-based models attempt to determine the travel and activities that are feasible within particular space-time constraints; an early example of a constraint based model is PESASP (Lenntorp, 1976);
- utility maximising models assume that individuals tried to maximise their utility of their daily activity schedule (Ben-Akiva, et al., 1996), and PCATS (Kitamura and Fujii, 1998); and
- computation process models use decision heuristics, an example being ALBATROSS (Arentze and Timmermans, 2000).

A common component of activity based models is a population synthesizer, which is used to create a synthetic population. Activity patterns and travel are determined at the disaggregate level and then aggregated up for analysis. A typical activity based model may contain the following features:

- population synthesis
- daily activity pattern formulation
- tour formulation
- time of day and mode choice

A consequence of this process is the need for computation resources that substantially exceed those generally used for four step models. Activity based models are also generally developed in an open source environment as the execution codes have yet to be implemented in a standard form to allow use in propriety applications for widespread use.

Activity based models are more common in the US than the rest of the world; however, even in the US they are still in the development stages and not yet standard practise. Where activity based models are used, the focus is generally on testing non infrastructure related policies such as road pricing and demand management strategies. An example of this is in the Netherlands where the activity based ALBATROSS model is used to test transport and land use policies that four step models are not able to adequately address, whereas, infrastructure projects are generally modelled with a tour based model.

3.7.3 Potential application in Australia

Activity based models are gaining some traction in the US and the Netherlands with proponents for activity based models arguing that activity based models address many of the deficiencies of four step models. However, the uptake of activity based models has not progressed at a rate to suggest they will replace the four step model as the most widely used strategic transport modelling tool in the near future.

A number of factors may be contributing to this slow uptake, chief amongst these could be the perceived increase in model complexity in moving from macroscopic four step models to microscopic activity based models. The current inability of activity based models to be implemented for large metropolitan areas without the need to use complex open sourced software, significant hardware costs and associated limits on the stability of model outputs is a barrier to widespread adoption.

It is also not entirely clear whether activity based models are superior to four step models for the appraisal of infrastructure projects. Infrastructure appraisal requires transport models to produce unique well converged solutions; the economic analysis is very sensitive to small changes in costs output by the transport models.

If an activity based model is considered for implementation, travel diaries in the form of activity are required rather than trips or stops in the traditional household travel survey. All activities that are conducted out of home would need to be collected. The more detailed the model, the higher the breakdown of these activities should be. The other dimensions of activities such as their location, time, companion (people who do activities together) and transport mode would also be required. Arentze et. al provides a detailed discussion on the data need for the development of activity based model.

3.8 Freight and commercial vehicle modelling

The focus of this volume is the travel demand modelling of person trips. The modelling of freight and commercial vehicle trips is also vitally important for planning and infrastructure planning purposes. Freight and commercial vehicle modelling is a complex field and hence requires a separate volume to cover adequately. The development of a volume focusing on freight and commercial vehicle modelling will commence later.

4. Data collection

4.1 Background

It is important that government funds are invested in areas that provide the greatest return. Capital investment in transport infrastructure projects must be underpinned by good information on travel demand patterns (how, why, when and where people travel). Effective allocation of resources to manage and operate transport systems requires good information on the transport system performance. This information can only be obtained from comprehensive and regularly updated surveys of travel activity and demand.

The availability of reliable existing travel demand data, together with the costs involved in collecting new data, may dictate the specification and structure of the transport modelling system. Being able to establish a valid Reference (Base) Year demand is critical in undertaking the modelling of any major transport infrastructure proposal. Attempts should always be made to make best use of available demand data. The appropriateness of available data (for example, its currency, coverage, robustness and reliability) should be ascertained early in any model development and application undertaking.

4.2 Travel demand surveys

The collection of travel demand data usually requires large-scale travel surveys using either a mail out/mail back self-completion survey or a household personal interview survey.

The mail out/mail back self-completion survey questionnaire is mailed to a household and mailed back to the survey firm or agency, after all questions are answered by all members of the surveyed household. Postage costs are usually borne by the survey firm or agency. The Victorian Activity and Travel Survey (VATS) is an example of a mail out/mail back survey.

The household personal interview survey involves face-to-face personal interviews and records all responses by all members of the surveyed household. Personal interview surveys have, to date, provided the major form of data collection for developing and updating transport models. Household personal interview surveys generally have high response rates (in the order of 70–80%) and can be undertaken over a much shorter time period than mail out/mail back surveys.

Other forms of travel demand survey may involve a combination of the mail out/mail back and face-to-face interview surveys, as well as computer aided telephone interview (CATI) surveys. Increasing use is being made of GPS devices to track individuals and assist in the collection of activity or travel diary information.

One critical issue to be addressed in designing a travel demand survey is the survey sample size. Generally, the more detailed the travel demand model, the larger the survey sample size required to obtain statistically reliable estimates of the model parameters. Funding limitations will, to some extent, limit the survey sample size and will dictate the level of detail in the travel demand model. One way of dealing with this issue is to conduct relatively small annual travel demand surveys that accumulate to increasing sample sizes over the ensuing years, making it possible to develop a travel demand model that becomes more detailed over time.

4.3 Person travel demand data

The travel demand data collected by the above-mentioned survey approaches represent a snapshot of travel patterns on a particular day and may include the following:

- Household information:
 - dwelling type
 - ownership status of dwelling
 - household size
 - number of registered motor vehicles by type
 - number of bicycles
- Data about people in the household
 - age
 - sex
 - relationship to head of household
 - employment status
 - resident or visitor
 - licence holding
 - occupation
 - industry of employment
 - personal income
 - if currently studying – primary, secondary, tertiary
 - undertaking other activities
- Travel data for all travel made on the travel day, on a ‘stop’ basis
- Travel origin
- Time of travel, including departure time and arrival time
- Purpose for the travel
- Location of destination
- Mode of transport used
- If the travel was made by vehicle
 - vehicle used
 - number of occupants
 - roads used
 - any toll paid and by who
 - parking location, any parking fee paid and by who
- If travel was made by public transport
 - type of ticket
 - type of zone ticket
 - type of fare paid
 - reason for not travelling on the travel day.

GPS based household travel surveys are becoming more prevalent in Europe and North America. Such surveys require independent travellers, from households, to carry GPS devices such as loggers, or phone

based applications. These surveys, particularly in combination with prompted recall interviews, enable the collection of more accurate and precise personal travel behaviour data. Further information will be provided in the next update.

4.4 Other data sources

Other data sources may include:

- Up-to-date traffic counts by hour and by direction aim to cover, as is practically possible, the main highway sections included in the model. Consideration should be given to establishing a regime of screenline traffic counts to provide information for model validation.
- Traffic signal count data.
- Bluetooth data for developing origin-destination movements and observed travel times.
- Smart card system data is an alternative source of public transport patronage data and may eliminate possible bias in survey design and conduct. Further detail on the advantages and possible limitations of this data is provided at the end of the section.
- On-board surveys or surveys at stations can provide data and information on boardings and alightings, loadings, and origins and destinations. These surveys may be used to augment household interview surveys or to provide detailed public transport patronage and demand data for specific areas of interest.
- Automatic number plate recognition (ANPR), matching vehicles passing distinct locations, both to provide information on travel times and, where the locations are organised in screenlines, a geographically coarse sector based identification of demand patterns. There are examples of similar use of Bluetooth detectors, although consideration should be given to potential bias from the vehicles and travellers sampled. Research, particularly in the US, seeks to exploit vehicle weight detection and the magnetic impulse characteristics of individual vehicles to match vehicles passing different locations.
- Automated Vehicle Location (AVL) data.

There is emerging work to collate data tracking GPS devices (based on direct location data) and mobile phone devices (based on the location of phone masts the device is linked to at different times). A number of products are available providing information on travel times, tracking GPS related devices. These can be linked to in vehicle devices (such as for vehicle theft or route finding) and can provide vehicular journey time and speed. It should be recognised that the source data may be biased (e.g. comprising a large proportion of commercial vehicles) and suitable care taken in drawing on these data sources. There is also emerging evidence of these data sources being used to establish trip matrices, based on a range of assumptions to interpret that data for this purpose. One fundamental issue here relates to sampling and expansion. Most GPS based sources involve particularly small and biased samples that may render them unsuitable as a primary source of data for travel patterns. While mobile operators generally have access to a large sample of the population, there are significant variations in market share, and quite different behaviours (e.g. in older and younger individuals) that require careful consideration. Consideration is required in respect of privacy legislation. Careful consideration of the processing methods and assumptions, together with direct verification of the outcomes is needed in exploring the usefulness of these data.

Use of Smart Card System Data

Potential advantages of using smart card system data are:

- The collection of large effective samples sizes, compared to household travel survey data

- Travel by individuals can be analysed over time
- Boardings and alightings can be accumulated to accurately estimate the passenger load on any segment of a public transport service
- As smart card data is usually timestamped at stops, it can also be used to estimate the speed and the reliability of public transport services even without an Automatic Vehicle Location (AVL) system (refer Austroads National Performance Indicators for Public Transport in Australia)
- Data is generally available within days of collection
- Low cost to acquire
- As the data is collected continuously, the data can be analysed and adjusted for daily variability and seasonality. Variability and seasonality are key issues to understand network reliability and crowding.

Potential limitations of using smart card system data are:

- The absence of information on travel purpose and on traveller characteristics. Inference is required to determine these details
- The difficulty in reliably identifying trips involving interchanging. Inference is required
- The difficulty in allocating origin and destination of travel to specific stops and transport zones. Again inference is required.

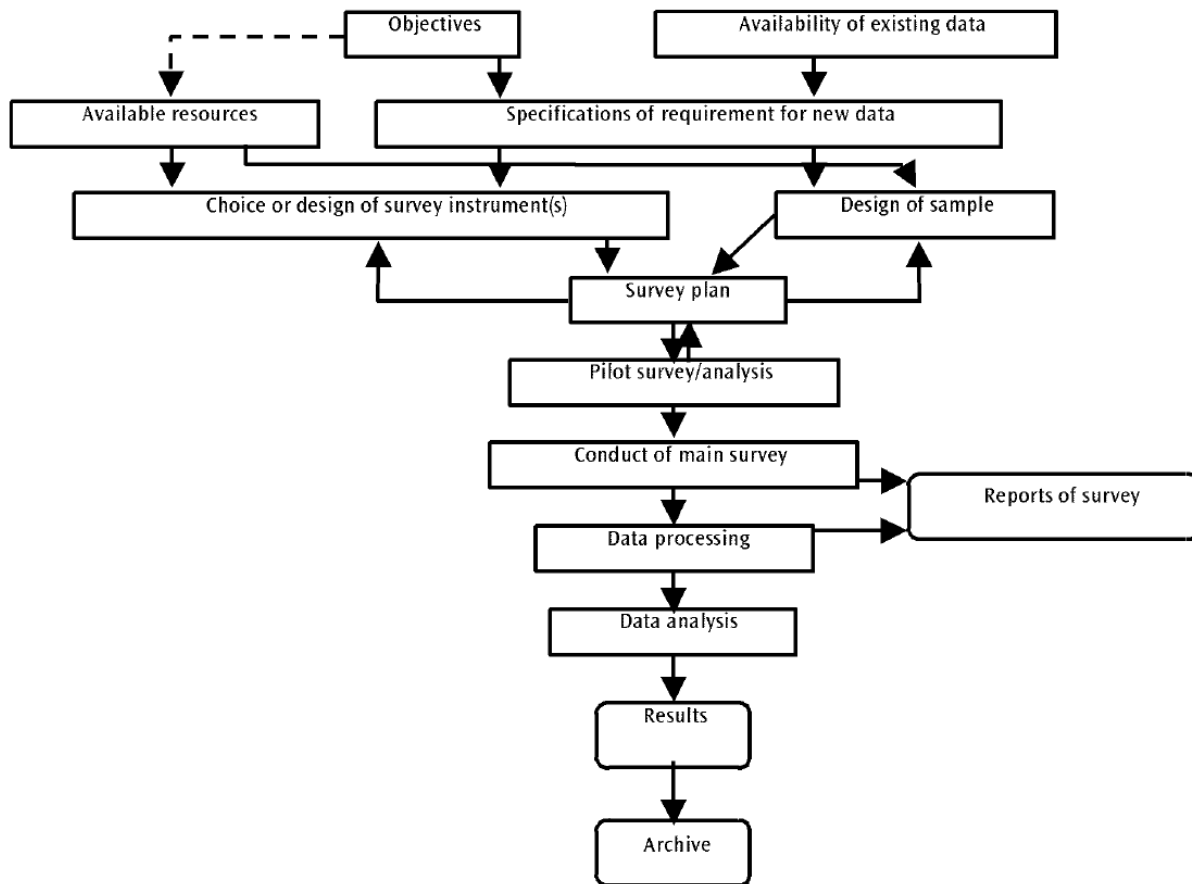
4.5 Survey Methodology and Data Requirements

Models and analytical procedures need data. The data needs to be relevant, current and accurate if useful results are to be gained from modelling and analysis.

Data collection is expensive, time consuming and not always straightforward, so care is needed in the planning, design and conduct of surveys. Without this attention, resources – time, people and money – can easily be wasted for little gain. High quality and relevant data are essential for analysis and serve to support policy formulation and decision-making. Poor quality or inappropriate data are to the detriment of informed decision-making.

One useful way to approach data collection is to view the survey process from the systems perspective. Figure 8 below provides one such process model. This figure represents a transport survey data collection as a process, starting with the specification of objectives of the survey and running through to the archiving of results. Note the existence within Figure 8 of various feedback loops indicating that survey design is not a purely sequential process; for example, analysts must be prepared to modify their survey instruments and sample frames in the light of the outcome of the pilot survey.

Figure 8 Survey process model



Source: Taylor, Bonsall and Young 2002, p.138

This process model identifies a number of steps and stages in the collection and analysis of data. These steps may be grouped into three broad stages:

1. **Preliminary planning**, in which the purpose and specific objectives of the survey are identified, specifications of the requirements for new data are determined (in light of existing data sources) and resources available or required for the survey are identified.
2. **Survey planning and design**, in which the appropriate survey instrument is selected and the sample design (including target population, sampling frame, sampling method and sample size) is undertaken, leading to a survey plan and the conduct of a pilot survey to test all aspects of the plan and to ensure that it works and provides the required data, and that they are compatible with the proposed analysis. This is an iterative stage, in which pilot survey outcomes may lead to revisions in the survey plan. Good and successful surveys necessarily pay significant attention to getting this stage right.
3. **Survey conduct**, in which the full survey is undertaken, data extracted and analysed, study reports prepared and databases archived for future reference.

This process is fully explained in Taylor, Bonsall and Young (2000, pp.137–145).

4.6 Survey techniques

Surveys are used to obtain data, which are then used to estimate model parameters for predicting the behaviour of transport users in order to make demand forecasts and to estimate the economic and financial values of projects. Most transport data surveys are sample surveys, in that only a small fraction of the overall population (for example, travellers, vehicles, network links or customers) is surveyed to provide data that are then extrapolated to provide a description of the total population. Data are collected at a few locations taken to represent transport activity, travel movement and traffic flow across the study area or a sample of individual travellers, customers or operators is surveyed because it is infeasible, impractical or uneconomic to survey the entire population. This means that survey data often need expansion from the sample to represent the full population. As discussed in the following sections, care in survey organisation and attention to detail are needed to ensure that survey data can properly represent their parent population.

There are two broad approaches to data collection:

4. **Observational (passive) surveys** – where surveyors (human or mechanical) record the occurrence (and often time of occurrence) of specified transport events or phenomena, such as the passage of vehicles past a point on the road, the arrival of trucks at a warehouse, or the number of passengers exiting from a railway platform in a specified time interval
5. **Interview (active) surveys** – where the surveyors make contact with the individual travellers, customers or decision makers to seek information directly from them

The information gathered in active surveys can be much richer than information available from passive surveys because:

- Observations are limited in scope to the direct area under study. For instance, the arrival of a vehicle at a cordon line indicates the point at which the vehicle entered or left the study area, but provides little information on the actual origin or the ultimate destination of the trip, nor the frequency with which the vehicle makes that trip or the purpose for which it is made. An active interview or questionnaire survey could obtain this additional information.
- Observational surveys are limited to study of actual behaviour at the study site. They provide information on 'revealed demand' – the actual behaviour that is occurring under the environmental conditions pertaining to the study area at the time of the survey. Revealed demand is the observed use of an area or facility. Environmental states, such as traffic congestion or lack of parking and seasonal conditions (including time of day), may restrict the ability of some individuals to access the specific site or facility or to choose to use an alternative (for example, another destination). This phenomenon is known as 'latent demand' and its extent cannot be gauged using observational surveys. An active survey method could seek to determine the existence and extent of latent demand, especially if the survey is designed and applied to include 'non-users' of facility or service as well as the users.⁵

⁵ For example, on-board surveys conducted on bus, train or tram are often used to collect data on public transport users, but could not indicate much about those travellers who are potential users of public transport, but are currently using some other mode. This one reason for the use of home interviews in general travel surveys.

The passive surveys aim to make no interference with the normal operation of the survey site and to not disturb the behaviour of the individuals under observation. The active surveys cannot avoid some interference and may even create disturbances that could affect the behaviour of the respondents. Great care is needed in the survey design for both observational and active surveys to ensure any interference is minimised and that significant bias is not introduced into the survey results because of how the data were collected.

Active ('interview') surveys may be conducted in three alternative ways: direct personal interviews, questionnaire surveys and remote interviews (generally conducted by telephone, but also possible over the internet).

4.6.1 Direct personal interviews

Personal interviews may be conducted in a variety of locations. Interviews in people's homes have been widely used for collecting detailed data on the travel behaviour of households and individual. Most metropolitan areas and other large cities have databases of personal travel conducted using 'household interviews'. Household interview surveys were conducted in Adelaide in 1999 and Perth in 2002-03, among other cities, while Sydney has a rolling cycle of home interview surveys running continuously.

Direct interviews can be used to collect detailed data about businesses, households and individuals and their travel behaviour, and about other traits such as attitudes and perceptions. In some cases, direct interviews may be conducted in a laboratory setting as well as 'in the field'. Stated preference studies are often undertaken in a laboratory where specialised resources can be used (for example, to create a simulated environment for the respondent to be immersed in the situational context behind the survey). Hensher, Broatch and Gunn (1989) described a methodology for surveying rail passengers using active survey techniques. Hensher and Golob (1998) described an interview survey of shoppers and freight forwarders conducted in Sydney in 1996.

One problem with the direct interview is that it can take a considerable period of time to complete, which may cause significant inconvenience to the (volunteer) interviewee. A second problem is that the interviewer must make direct contact with the survey respondent. This may involve considerable time spent travelling by the interviewer to visit the respondents and the need for multiple 'call backs' if the respondent is not 'at home'.

4.6.2 Questionnaire surveys

One solution to overcome the time constraints associated with direct interviews is to use questionnaire surveys, often to be returned through the post ('mail back') at some future time. Examples of these surveys are roadside or i-vehicle surveys. These can be attempted by direct interview, but individual travellers may be delayed and inconvenienced in the process, or may reach their destination before the conclusion of the interview. It may be more reasonable and effective to distribute a written questionnaire to the travellers, asking them to complete and return the survey once the journey is finished.

The questionnaire can contain questions similar to those posed in an interview, but there are many limitations. For example, the questions must be clear and unambiguous as it stands, as there is no opportunity for an interviewer to offer an explanation. Fewer questions can be asked; as excessively long questionnaires reduce the number of completed responses. There is also the possibility for the respondent to offer false or misleading answers that an interviewer would recognise as such, but that are much harder to detect on a written form. However, the major problem with questionnaire surveys of this type is the likelihood of a low response rate. While response rates of the order of 10–20% may be acceptable in some areas (such as general market research on consumer goods), there is a considerable body of transport research that suggests that much higher rates of response – 80% or better – may be necessary to properly gauge true levels of travel activity in a population. It is necessary to recognise that the problem of low response rates may introduce sample bias. To overcome this problem, the survey process needs to incorporate a random procedure to select respondents and require the interviewer to visit a household multiple times to meet the selected respondent for interview. Richardson, Ampt and Meyburg (1995) provide a full discussion of this issue, as well as detailed advice on the conduct of interview and questionnaire surveys.

4.6.3 Telephone and internet surveys

The third alternative is the use of telephone (or internet-based) surveys. These are similar to the direct interview except the interview is conducted remotely over a telecommunications network, with telephone interviews usually using random dial-up access. The advantages of this survey technique are cost and convenience. The interviewer stays in the one place (a call centre) and can make contact with a large number of respondents in a short time. Data entry can also be automated, as responses are directly entered into a computer database during the interview.

The disadvantages of the technique include the relatively short length of the interview that is normally possible over the telephone and perhaps a growing 'consumer resistance' to the telephone interview, given the method is widely used in general social and market research surveys and in direct marketing. Richardson, Ampt and Meyburg (1995), among many other transport survey researchers, maintain that good quality data on travel behaviour (at least of quality commensurate with that obtainable from face-to-face interviews and questionnaires) cannot be collected using telephone interviews.

Internet-based surveys are more like observational surveys in that respondents to the surveys generally find the survey website of their own volition, rather than through active encouragement by surveyors. This technique is being used, for instance, in studies on driver route choice, where detailed information is required that is quite difficult to obtain through more conventional survey approaches (see Abdel-Aty 2003). However, bias in sampling is quite likely to be an issue in these surveys and the field is as yet relatively unexplored.

4.6.4 Costs

Direct interview surveys are generally the most expensive, followed by questionnaire surveys (especially with regard to the number of valid completed questionnaires returned) and then telephone surveys. Observational surveys can be relatively inexpensive, at least in terms of elemental costs such as hourly wage rates or where automatic data loggers can be employed (as for automatic vehicle counts). However, large-scale observational surveys (such as vehicle number plate surveys that require a large number of observed vehicles) can prove very expensive and are sometimes not particularly efficient in terms of the collection of usable, quality data.

4.6.5 Revealed versus stated preferences

A further distinction in interview surveys should be drawn between the collection of revealed preference data (what people are seen to do or record that they have done) and stated preference data (what people say they would do in different circumstances, such as when faced with changes in transport fares, services or costs).

Generally, the household travel surveys concentrate on revealed preference data. They record historical data on travel behaviour, which then form a snapshot of travel activity in an area at one particular point in time. These data provide little information on how people might change their behaviour in response to new transport policies or to changing travel environments or to the availability of new modes or services. Stated preference data may be used for these purposes and stated preference experimental methods provide powerful tools in this regard. At the same time, there are considerable problems in ensuring that stated preference information is valid and reliable. Louviere, Hensher and Swait (2000) provide a full coverage of this survey methodology and its use. It should be noted that stated preference methods are a rich source of information for the development of discrete choice models of travel behaviour.

For further reading on transport survey methods see Taylor, Bonsall and Young (2000), Louviere, Hensher and Swait (2000) and Richardson, Ampt and Meyburg (1995).

4.7 Sample size estimation

As indicated in Section 4.17, most transport data surveys are sample surveys. Sampling is usually necessary because it is too expensive to survey all members of the population (for example, to obtain travel diaries from all inhabitants of a metropolitan area) or it is physically impossible to do so (such as testing the roadworthiness of all vehicles) or because the survey testing process would be destructive (such as determining the strength of railway sleepers).

Almost all transport surveys involve observing some members of a target population to infer something about the characteristics of that population. In this sense they are statistical sampling surveys. As the effectiveness of the survey is dependent upon choosing an appropriate sample, sample design is a fundamental part of the overall survey process.

Sample design includes the following elements:

- Definition of target population
- Definition of sampling unit
- Selection of sampling frame
- Choice of sample method
- Consideration of likely sampling errors and biases
- Determination of sample size.

Two main methods exist for selecting samples from a target population: judgement sampling and random sampling. In random sampling, all members of the target population have a chance of being selected in the sample, whereas judgement sampling uses personal knowledge, expertise and opinion to identify sample members.

Judgement samples have a certain convenience. They may have a particular role, such as 'case studies' of particular phenomena or behaviours. The difficulty is that because judgement samples have no statistical meaning, they cannot represent the target population. Statistical techniques cannot be applied to these samples to produce useful results as they are almost certainly biased.

There is a particular role for judgment sampling in exploratory or pilot surveys where the intention is to examine the possible extremes of outcomes with minimal resources. However, to go beyond such an exploration, the investigator cannot attempt to select 'typical' members or exclude 'atypical' members of a population, or to seek sampling by convenience or desire (choosing sample members on the basis of ease or pleasure of observation). Rather, a random sampling scheme should be adopted, to ensure the sample taken is statistically representative.

Random samples may be taken by one of four basic methods (Cochran 1977): simple random sampling, systematic sampling, stratified random sampling and cluster sampling. Taylor, Bonsall and Young (2000 pp. 155–58) describe each of these sampling methods and their applications, as do Richardson, Ampt and Meyburg (1995).

Simple random sampling allows each possible sample to have an equal probability of being chosen, and each unit in the target population has an equal probability of being included in any one sample. Sampling may be either 'with replacement' (any member may be selected more than once in any sample draw) or 'without replacement' (after selection in one sample, that unit is removed from the sampling frame for the remainder of the draw for that sample). Selection of the sample is by way of computerised randomisation techniques such as random number generation. The methods of statistical inferences applied to sample data analysis are predicated on the basis that a sample is chosen by simple random sampling. Data collected using other sampling methods need to be analysed using known techniques that include corrections to approximate simple random samples.

There is always a possibility that a sample may not adequately reflect the nature of the parent population. Random fluctuations ('errors'), which are inherent in the sampling process, are not serious because they can be quantified and allow for using statistical methods.⁶ However, if due to poor experimental design or survey execution there is a systematic pattern to the errors, this will introduce bias into the data and, unless it can be detected, it will distort the analysis. A principal objective of statistical theory is to infer valid conclusions about a population from unbiased sample data, bearing in mind the inherent variability introduced by sampling. Bias and sampling errors are two, quite different, sources of error in experimental observations. As described in Richardson, Ampt and Meyburg (1995, pp. 96–101), bias (or systematic error) needs to be removed from sample data before statistical analysis can be attempted, for statistical theory treats all errors as sampling errors.

A distribution of all the possible means of samples drawn from a target population is known as a sampling distribution. It can be partially described by its mean and standard deviation. The standard deviation of the sampling distribution is known as the standard error. It takes account of the anticipated amount of random variation inherent in the sampling process and can therefore be used to determine the precision of a given estimate of a population parameter from the sample.

⁶ Noting that minimisation of experimental errors is of course important in improving the precision of parameter estimates based on survey data.

Surveys for specific investigations usually attempt to provide data for the estimation of particular population parameters or to test statistical hypotheses about a population. In either case, the size of the sample selected will be an important element and the reliability of the estimate will increase as sample size increases. However, the cost of gathering the data will also increase with increased sample size – an important consideration in sample design. A trade-off may have to occur and the additional returns from an increase in sample size will need to be evaluated against the additional costs incurred. If the target population may be taken as infinite, then the standard error (s_x) of variable X is given by

$$S_{\bar{X}} = \frac{s}{\sqrt{n}}$$

[EQ 4.1]

where s is the estimated standard deviation of the population and n is the sample size, assuming that the sampling distribution is normal. Even when the sampling distribution is not normal, this method may still apply because to the Central Limit Theorem which states that the mean of n random variables form the same distribution will, in the limit as n approaches infinity, have a normal distribution even if the parent distribution is not normal. The standard deviation of the mean is inversely proportional to \sqrt{n} . The implication of equation 4.1 is that as sample size increases, standard error decreases in proportion to the square root of n . Here is an important result. The extra precision of a larger sample should be traded off against the cost of collecting that amount of data. To double the precision of an estimate will require the collection of four times as much data.

Similar results are found for other statistical parameters. For instance, the standard error (s_p) of a proportion p (e.g. a measure such as ‘the proportion of households owning one vehicle’) is given by:

$$S_p = \sqrt{\frac{p(1-p)}{n}}$$

[EQ 4.2]

The practical application of these results requires some prior knowledge of the population, such as a prior estimate of the sample standard deviation (s) in the case of the mean value of variable X or an initial estimate of the proportion p . The results of previous surveys, or the pilot survey, may be used to provide this knowledge.

5. Model development

5.1 Estimation techniques

Frequently, analysts may wish to identify relationships between the factors contained in their data. These relationships are investigated through the application of statistical models that provide a useful, but simplified, view of the process being studied. This simplicity is limited by the need to provide a reasonable representation of the process. Statistical models use sample data to develop mathematical relationships between factors.

In the process of deriving relationships in the trip generation step, a multivariate linear model is often used. It has the form:

$$Y_i = b_0 + b_1X_{i1} + b_2X_{i2} + \cdots + b_mX_{im} + \varepsilon_i$$

where the Y is the dependent variable (trip productions and attractions) and X_{ij} represents the m independent variables (typically demographic variables) for $1 \leq j \leq m$. The subscript i represents the i^{th} observation, the b_0, b_1, \dots, b_m terms represent the model parameters, and the ε_i is an error term.

Multivariate linear regression is a general statistical tool through which the analyst can investigate the relationship between dependent and independent variables. While multivariate linear regression is a straightforward, powerful and widely-used model estimation technique, care is needed in the development of any multivariate regression model intended for practical application. **The advice of a statistician is recommended.**

The computational ease with which such models can be estimated can mask the fact that such models are based upon assumptions that the inexperienced user typically does not validate, or even understand. These assumptions are based upon the absence of:

- Multicollinearity
- Heteroskedasticity
- Autocorrelation.

Multicollinearity occurs when (as is often the case) some of the ‘independent’ variables are highly correlated with each other – the statistical theory on which multiple regression is based assumes them to be independent of each other. Care is needed in selecting a subset of the independent variables for inclusion in the multiple regression relationship. The usual approach is to enter or delete independent variables one-by-one in some pre-established manner. Some of the approaches used are forward inclusion, backward elimination and stepwise solution. With *forward inclusion*, independent variables are entered one-by-one only if they meet certain statistical criteria. The order of inclusion is determined by the respect contribution of each variable to the explained variance. In *backward elimination*, variables eliminated one-by-one form a regression equation that initially contains all variables. With a *stepwise solution*, forward inclusion is combined with the deletion of variables that no longer meet the pre-established criteria at each successive step.

Heteroskedasticity is also a common phenomenon. It relates to the variation of the absolute errors in measurement of an independent variable with the actual magnitude of that variable. Statistical theory for regression analysis assumes that the variance of the error term is the same for all values of the independent variable. This is called *homoskedasticity*. There are many instances where this may not be the case. For instance, in considering the masses of consignment loads to be transported, an error in measurement of 1 kg would be insignificant for an item of machinery of mass (say) 400 kg, but would be very significant for a parcel of mass 5 kg. For standard regression analysis, the consequences of heteroskedasticity in an independent variable are to underestimate the standard error of the estimated (dependent) variable (Y) and to falsely raise the apparent significance of independent variables (X_i). It does not affect the estimated values of the model coefficients, but does reduce the efficiency of the model as an estimating tool. One solution is to use weighted least squares analysis, in which each observation of an independent variable is adjusted for the expected size of its error term. Another possibility is to transform an independent variable (for example, by using its logarithm, $\log(X)$). This approach is useful for variables where there is a great range of sizes in the observations (such as the distribution of household incomes in a region).

Autocorrelation occurs when successive observations of a given variable are highly correlated. This phenomenon frequently arises in data observations taken over time. Here again, the problem for multiple regression analysis is the underlying assumption that observed values of the independent variables are independent of each other. In fact, autocorrelation is most important in its own right and there is a special field of statistical analysis devoted to 'time series' analysis. Autocorrelation reflects cyclical behaviour in a variable over time, such as seasonal variations in agricultural production, travel demand or road crashes in a region. Knowledge of these cycles is important in understanding the patterns of demand for transport services, among other things.

There are a number of statistical tests and procedures to identify and cope with these potential problems in regression modelling. Chapter 17 of Taylor, Bonsall and Young (2000, pp. 392–410) provides a more detailed discussion of regression modelling techniques. See also Fahrmeir and Tutz (1994).

Multivariate linear regression is not the only technique available to estimate model parameters. It is recommended that statistical advice is sought to identify the most appropriate statistical, or other estimation technique to apply in estimating model parameters.

Fit for purpose techniques exist to determine the coefficients in logit models of discrete choice processes. (e.g. see Louviere, Hensher & Swait 2000). A further method for model parameter estimation is 'entropy maximisation' or the use of the mathematical theory of information (Shannon 1948; Van Zuylen & Willumsen 1980). This method is used, for instance, in the estimation of origin-destination matrices from observed link counts – see Taylor, Bonsall and Young (2000, pp. 116–20).

5.2 Network checking

Model networks are a critical component of the 'supply' side of transport models. It is therefore essential that the model network is appropriate for its purpose. Inaccuracies in the alignment, connectivity or element components of the model network can lead to erroneous assignment of traffic to routes or inaccurate estimations of congestion and travel times.

Despite increases in geographic data and computer power, there is still a necessity for all three levels of transport models to simplify real world networks into usable representations. For example, strategic transport model road networks will often exclude local roads and road classification may be limited to link class, lane number and posted speed. Similarly, microsimulation networks may simplify the gradient or road surface characteristics of a link.

In many cases the attributes of a network will have a degree of subjectivity. For example, strategic transport model networks will group roads into a fixed number of link classes or link types. Classifying a new or existing road into one of these groups will often involve the transport modeller making a judgement based on available information and a comparison to similar links in the network. In cases where subjective classifications directly affect a project being modelled, the details of the classification should be documented.

The degree of a network audit will often be constrained by time or budgetary constraints. At a minimum, the network should be checked in detail for any project links or elements as well as links or elements that are directly influenced by the project. The audit should include checks on internal consistencies as well as checks against reality.

It is desirable that checks be carried out across the entire modelled network. However, the detail of these checks will often be limited to 'broad brush' audits or automated investigations.

Strategic transport model network auditing

The auditing of a strategic model network has two roles

1. Ensure that the network has appropriate connectivity and
2. Ensure that the link and node attributes are appropriate for the model.

Some general techniques that can be used to check transport network models are:

- Visual checking of the network in the study area against aerial and 'streetview', photography (GoogleMaps or equivalent). The modeller should endeavour to align the date of the photography with the base model year.
- Compare the model network to reputable maps (street directories, public transport maps etc.)

It is increasingly common for network data to be processed directly from electronic sources (road networks maintained for satellite navigation tools, and public transport timetables). In these cases, particular emphasis needs to be placed on the interpretation of these data, in particular the connectivity represented at junctions and stops. Some techniques that can be used to check the connectivity transport network models are:

- Use the model to build paths to or from selected zones (on the basis of minimum distance, time or generalised cost) – this is one of the best ways of checking the network coding; the path building process will ensure the paths built by the model are logical and any errors in the coding are identified and corrected, eliminating any illogical paths during the assignment step.
- Checking connection points of centroid connectors by visual inspection or assigning the demand to the network and confirming that all demand has been assigned (excepting intrazonal trips)

Some techniques that can be used to check the link and node attributes are:

- Use the model or other GIS to display or map link and node attributes. This will assist the modeller or others who are familiar with the network to identify errors.
- Create link attribute frequency data for each link class. For example, a tabulation of posted speed for a freeway link class can be useful for identify links with erroneously low posted speeds
- Use the model to assign a peak period demand. Examine the results for links with zero volume or unexpected results such as high volume over capacity ratios or low speeds to identify outliers. Results such as these can indicate errors in coding.

- Plot observed traffic volumes against link capacity. Examine links where observed volumes exceed capacity.
- Comparing actual travel times along key links with those from the network model
- Comparing link distances from the model with actual distances

Some techniques that can be used to check Public transport networks are:

- Checking the frequency and stopping patterns of public transport routes. GIS can be used to display headways, speeds, number of services, capacity, etc.
- Use the model to assign Public Transport trips. Examine the results for links with zero volume or unexpected results.
- Compare model travel times to Public Transport timetables or Automatic Vehicle Location (AVL) data. In some instances, modellers have analysed time stamped smart card ticketing data to assess vehicle running time intervals between stops.

Mesoscopic transport model network auditing

The techniques described above for strategic models are also applicable for mesoscopic transport models.

In addition, the following checks should be conducted for mesoscopic models

- Intersection coding (e.g. lane and queueing configurations)
- Signal phasing and timing data

Microscopic transport model network auditing

Microsimulation models can be more sensitive to network errors than larger scale models. It is essential that the modeller ensures that the model network is an accurate representation of the true network.

Some network checks and recommendations include:

- It is recommended that networks are built from site layout drawings and supplemented by Aerial photographs where required
- The modeller should ensure all drawings and aerial photographs are up to date. Accuracy should be checked via site visits where possible.
- Model link and connector overlap should be avoided or minimised
- Node structure should be logical and consistent throughout the model.
- Reduced speed areas should be present on all links where horizontal road geometry is expected to cause driver deceleration
- All conflict points should be managed with appropriate priority treatments or signals
- Signal operations should be checked against operations sheets, or during site visits, to ensure accuracy
- Any model error files should be checked and justifications provided

For more details on microsimulation networks see Traffic Modelling Guidelines (Transport Roads and Maritime Services, NSW, 2013).

5.3 Calibration and validation

Estimation involves the use of statistical methods to estimate the parameters of the equations of the various components of the transport modelling system (trip generation, distribution, mode choice). Calibration of transport models involves manual and automated procedures to adjust model parameters so the modelled travel patterns, traffic volumes and patronage estimates replicate observed survey data. Estimation of transport models is predicated partly on the availability of large-scale origin–destination (O–D) survey data, which – due to the high costs involved – is becoming scarce. Household travel surveys (see Section 4.1.7) and census journey-to-work data can provide detailed information for model estimation.

The validation process attempts to quantify how accurately a transport model reproduces a set of Reference (Base) Year conditions (such as traffic volumes or patronage estimates) and is used, together with dynamic indicators of the responsiveness of the model to changes in inputs, to define the transport model's degree of 'fit-for-purpose'.

The validation process should use data separate to that used in the model calibration. Calibration and estimation data are critical for establishing the parameters and equations used in the transport modelling system. Validation data are critical to testing the overall validity of the model against a set of criteria. Appendix C sets out criteria to be used in assessing the ability of a transport model to reproduce a set of Reference (Base) Year conditions. There are constraints on the quantity of data available for model development that cause tensions in holding data aside for independent validation. Statistical techniques, such as 'bootstrapping' can assist to maximise the value of sample data.

In general, transport model validation reporting should cover the following:

- Description of the data used in estimating, calibrating and validating the model
- Reporting on the 'fit' achieved to the estimation and calibration data
- Reporting on the validation outcomes for a Reference (Base) Year.

5.4 Vehicle operating costs and the value of time

Part PV2 of the Guidelines provide estimates of various road use unit costs (such as value of time, crash costs and vehicle operating costs) for Australia. These are suitable for using in appraisal and may be interpreted as input parameter values of behavioural time and vehicle operating costs in the transport modelling process. Part PV1 of the Guidelines provides a detailed coverage of parameter values for public transport appraisal.

5.5 Generalised cost weightings

When calculating the generalised cost of public transport travel, it is usual practice to weight the different components of public transport travel to reflect the passengers' utility (or perception of utility) for each component. Part 1 of NGTSM06 Volume 4 provides a detailed discussion of these weights.

5.6 Matrix estimation

Matrix Estimation is a process in which numerical methods are used to find an 'optimal' solution to an Origin-Destination (O-D) trip matrix that when assigned to a network will replicate screenline traffic counts. The mathematics behind matrix estimation has undergone a number of developments since it came into use in the 1970's. Works by Willumsen (1978), Van Zuylen (1980), Cascetta (1984) and Speiss (1987) set the foundations on which most modern matrix estimation software are based. A good summary of this work and an introduction to the mathematics of matrix estimation can be found in Ortúzar, J. d. D. and Willumsen, L. G. (2011).

Generally, the matrix estimation is considered acceptable as a legitimate technique that could be used to improve the representation of an O-D trip matrix for a strategic, mesoscopic or microsimulation model. However, the user needs to pay special care when applying the technique to ensure the estimated matrix representing the true pattern and not be distorted by the process.

Input data into the matrix estimation process can include trip ends, travel costs, a prior matrix together with traffic counts. Confidence weights are used to constrain the solution best to reflect these inputs.

Matrix Estimation can be thought of as a search for a matrix that fits the data while staying consistent with other available inputs or assumptions. It can be a powerful low cost method to estimate an O-D matrix when direct observation is not feasible.

However, care needs to be taken to avoid finding a spurious result that fits traffic count data at the expense of reason or is contrary to other reliable sources of data. In all but the simplest of matrices, there will not be a unique O-D matrix that when assigned to a network will reproduce the traffic counts.

The misuse of Matrix Estimation can result in apparently well validated traffic models that have origin-destination patterns that greatly differ to actual trip patterns and are consequently unsuitable for forecasting. This potential for misuse has often led agencies model end users to specifically require that Matrix Estimation is **not** used when requesting transport modelling work.

The following sections provide information on common pitfalls as well as guidance which should assist the modeller in the appropriate use of Matrix Estimation.

The modeller should always acknowledge when Matrix Estimation has been used in the calibration of a transport model. The acknowledgement will assist reviewers and users of the model to make a more informed assessment of the model validation and to the method of forecasting. It is important that the provenance of the matrix should be fully documented and repeated sequential use of matrix estimation as models are refined should in most cases be avoided.

5.6.1 Input Data

Traffic counts

The traffic counts should be grouped into short screenlines by direction covering corridors of traffic movement. The use of individual counts (single count screenlines) should be avoided where possible unless they represent a distinguishable transport corridor.

The modeller should also ensure that the set of traffic counts being used in the matrix estimation are internally consistent, that is, they 'add up' along a route. Inconsistency can result in overestimating or underestimating localized trip ends in an attempt to match the incompatible traffic counts.

It is recommended that a selection of traffic count data is withheld from the matrix estimation to allow for 'out of sample' testing. These counts may be spot counts or screenline counts. In doing so, the modeller will provide some evidence that the linkage to the base model has not been broken.

Trip Ends

Trip Ends may be sourced from models or observed data.

Prior Matrix

A prior matrix can be input into the matrix estimation. Typically, the prior matrix will be the output of a four step model or obtained through surveys.

For many models, observed trip matrices are very sparse with many empty cells. The Matrix Estimation process can only adjust non-zero cells.

If the modeller has reason to believe a cell is empty due to the limitations of the survey and are not justified (for example conflicts with the trip end inputs), the modeller can 'seed' these cells with small non-zero values. The seeding will increase the flexibility of the process without significantly changing the total size of the prior matrix.

If the modeller has reason to believe a substantial proportion of cells are empty due to the limitations of the survey matrix estimation should not be applied; consideration may be given to constraining synthetic matrices at a sector level, or similar techniques applied to develop a suitably structured prior matrix.

If the modeller finds that the matrix estimation is making large changes to either the trip ends or trip length distribution it may be necessary to growth factor the prior matrix before its use in matrix estimation. Matrix estimation should not be applied in itself to make significant adjustments to matrices.

The UK WebTag guidelines Unit M3.1 Highway Assignment modelling – Jan 2014 provides prescriptive steps for the use of matrix estimation. The reader will find that WebTag proscribes a strict minimalist implementation of matrix estimation to avoid all but the smallest changes to the prior matrix. Such strictness is arguably less appropriate in the Australian context where confidence in the prior matrix is typically lower than in UK, therefore if required matrix estimation could be used to improve the OD matrix with quality traffic counts and trip ends.

5.6.2 Confidence levels

In most cases, the confidence in the input data is proportional to the accuracy of the data. Data errors arise from sources including measurement error, sampling error and synthesis of modelling error.

A common result is:

Traffic count confidence > Trip End confidence > Trip Cost confidence > Trip pattern confidence

Typically, a relatively high confidence will be assigned to screenline traffic counts. This is a reasonable approach if the counts are recent and are of good quality. However, the modeller may need to reduce the confidence to some of the traffic counts in consideration of the traffic survey methodology. For example, a manual traffic count taken on a single day would be expected to be less accurate than an automatic tube count taken over two weeks, and counts of heavy vehicles may be less accurate than counts of all vehicles.

The trip end input data to matrix estimation is typically obtained through observation (surveys) and/or through reliable demographic data and a trip generation model. The modeller may wish to apply a higher confidence to the observed trip ends compared to those derived from a trip end model.

The confidence on Trip Cost can be relatively high if the cost is equal to distance. However, in most cases the trip cost will include elements of time and/or toll. The inclusion of time, tolls or other penalties into the trip cost will necessarily reduce the confidence in the accuracy of the data, although it will almost certainly improve the correlation between the cost estimates and travel patterns.

5.6.3 Recommended Matrix Estimation Checks

The following is a list of four checks that a modeller should always conduct when using Matrix Estimation. They will help both the modeller and reviewer understand the size and nature of changes to the prior matrix.

1. Assign both the prior and post matrices to the network and view a plot of network differences. This plot will help show where large changes have occurred.
2. Prepare a scatter plot of prior and post trip ends showing line of best fit and R2 (which should be considered with and without large external zones).
3. Prepare a scatter plot of prior and post matrix cells showing line of best fit and R2. (It will usually also be helpful to aggregate the matrices using a sectoring that reflects the broad patterns of movements that may be affected by interventions the model is intended to assess)
4. Compare trip length distributions of the prior and post matrices with and without intrazonals.

The results of checks should be investigated to explain the causes and reported.

In addition to the four tests listed above, the modeller may find value in conducting a select link analysis of one or more of the traffic screenlines to assess the changes that have occurred due to the matrix estimation. By conducting the select link first using the prior matrix followed by the post Matrix Estimation matrix, the modeller is able to use bandwidth plots to examine the location and nature of the changes that have occurred.

Interpreting the results

The optimum result of Matrix Estimation occurs when the process results in a good fit to traffic counts whilst making only minimal changes to the prior matrix. However, if the modeller finds that the process is in fact only making minimal changes to the prior matrix the modeller should reassess the need for using matrix estimation. The 'cost' to the model in terms of future year matrix adjustments, reporting requirements and perhaps reputation may exceed the benefits coming from the of improved validation to traffic counts.

In practice, the modeller needs to make a trade-off between the level of fit to traffic counts and the size and nature of the changes to the prior matrix.

The changes to the prior matrix should always be interpreted in comparison to the quality of the prior input data.

For example, a modeller should be concerned if the Matrix Estimation results in large changes to prior trip ends that are the result of a well calibrated trip generation model. In some cases, Matrix estimation may help 'uncover' previously overlooked special generators, but this will be the exception.

Conversely, larger changes to the prior trip ends may be expected if the prior trip ends are based on sparse observations or an unsophisticated trip end model.

If changes due to matrix estimation are excessive, the modeller should examine the nature of the changes and review the input data and the prior matrix before rerunning the matrix estimation.

Particular care needs to be taken in examining changes in average trip length and the shape of the trip length distribution as a result of Matrix Estimation.

Large increases or decreases in average trip length are usually a sign that significant changes have been made to the prior matrix.

It is important to compare the prior and post trip length distributions both with and without internals as it will help show if the matrix estimation is increasing the number of short trips to match underestimated traffic counts.

5.6.4 Application to future year matrices

If matrix estimation is used in the calibration of the base year, the changes due to the matrix estimation must be applied to the future year matrices.

There are several approaches to applying the changes. One common method is to find the difference matrix between the post and prior matrices and apply this difference to each of the future year matrices. A shortfall of this approach is that it may underestimate the size of adjustments required in growth areas. Care also needs to be taken to avoid negative values in future year matrices once the adjustment has been made.

A second common method is to apply a factor matrix of the ratio between the post and prior matrices to each of the future years. A shortfall of this approach occurs when the ratio deviates excessively from one. Large ratios can result in unrealistically high cell values in future year matrices once the adjustments have been made.

An alternative approach is to use a combination of difference and factor matrices where the choice to use either approach is dependent on the size of the factor and the future year matrix cell before the adjustment has been made. A good description of the problem is given by Daly, A., Fox, J., Patrui, B., & Milthorpe, F. (2011). In which they describe an eight case method to pivoting.

5.7 Transport network validation

In general terms, transport network validation will usually include:

- Comparing modelled travel times with observed travel times
- Comparing modelled screenline volumes with observed screenline volumes
- Comparing modelled service patronage volumes with observed service patronage volumes
- Checking that paths through the network are realistic
- Comparing distances between specified O–D pairs derived from the model with actual distances
- Comparing modelled public transport travel times with timetables
- Checking public transport routes in terms of stopping patterns, timetables and frequency.

5.8 Assignment validation

The assignment of vehicles or passengers onto a network is typically the final step in the modelling process. To get to this point usually involves the culmination of several sub models and processes. For this reason and perhaps the importance of volumes to project outcomes, the level of assignment validation is of great interest to modellers and model users. Care must be taken not to give undue weight to this aspect of the model validation, which would risk prejudicing the integrity or performance of other models and degrading the forecasting capability of the whole model system.

Assignment validation is traditionally the comparison of measurable model outputs with sets of observations. However, given that transport models are used to forecast how a change in inputs may lead to a change in modelled conditions, some practitioners include assignment sensitivity tests or 'dynamic validation' as a component of the assignment validation. While these tests rarely have observed data for comparison, they are relatively easy to perform and can provide useful insights into the nature and reasonableness of the model. Where interventions have occurred within the model and recent changes have been observed it is beneficial to undertake 'back casting' to demonstrate how well the model reproduces these observed changes.

5.8.1 Purpose of Model Validation and validation criteria

The purpose of model validation is to give confidence in the ability of the model to replicate a set of observations given a set of base data and consequently have confidence in the fitness of the model to forecast traffic using a set of forecast data.

Model Validation criteria give a benchmark to facilitate both discussion and critical analysis of a model's performance. In particular, the criteria can assist a transport modeller to identify the strengths and weaknesses of a model and they can contribute to evidence that the model is accurate enough for the desired purpose of the forecasts.

The ability or inability of a model to meet a set of validation criteria against a set of observations is not sufficient to conclude the model's suitability for forecasting. Within Australia and New Zealand there has been a growing appreciation in the industry, as discussed by Clark (2015), about the value of intelligent use of model guidelines rather than the strict adherence to target values. A similar shift is apparent in the language used in the "Model checking and reasonableness guidelines" by FHWA (2010) compared to earlier versions, and in the reference to 'acceptability guidelines' in UK guidance.

The intelligent use of model guidelines could include:

- avoiding over calibrating the model to meet target values
- using targets that are appropriate for the model type and intended purpose (i.e. context specific)
- making a spatial distinction between areas or links of importance to a project
- understanding the limitations and variability of the observed data
- Understanding the stability of the observed data and the influence of new developments on demographics and traffic counts.

The modeller should also be aware of and preferably document in a model validation report the quality and characteristics of

- The model input data (demographics, networks, economic parameters etc.)

- The model functions (demand model, the use of matrix estimation etc.)
- The model validation data

To be able to have confidence in model forecasts, it is of primary importance that the modeller can demonstrate that the model is built on sound foundations. A model validation that relies on unreasonable parameters or unexplained factors is unlikely to be fit for forecasting future conditions.

5.8.2 Agreement of validation criteria

A number of validation statistics are used by modellers to assess and critically compare the differences between modelled values and observed data. Model validation criteria for the different levels of transport modelling have been published by a number of agencies (VicRoads, RMS, NZTA, DRMB) to provide a standardised system of validation reporting for their respective jurisdictions. See for example VicRoads (2010), RMS (2013), NZTA (2010) and DRMB (2010). Each of these sets of criteria differs in both their requirements and strictness.

It is recommended that an agreement is made prior to the commencement of the model validation to a set of appropriate validation criteria that is both suitable for the project and the scale of the model. This may include predetermining the importance of specific criteria for specific locations. For example, it could be agreed that a GEH of less than 5 is achieved for 90% traffic counts within project study area while it is necessary for only 75% of traffic counts outside of project study area.

5.8.3 Validation criteria for traffic volumes

Modelled traffic volumes are used at either the link level or screenline level. Link data are generally concerned with the ability of the model to represent routeing and screenline data with the pattern of regional movements.

Link volume plots

For each time period, a map should be produced of the transport network showing modelled and observed link flows and the differences between them. The totals should be summarised for available screenlines. These plots are used to check modelled and observed flows by geographic area and level of flow.

Scatter plot of modelled and observed flows

For each time period, XY scatter plots of modelled versus observed flows should be produced for:

- all individual links
- freeway links
- screenlines

Each plot should include the $y=x$ line. Report on the R^2 and slope for each plot.

XY Scatter plots give the modeller a quick and easy visual of the match between the model and traffic counts. These plots are included in most validation guidelines including VicRoads, RMS and NZTA.

The modeller should aim for a slope close to one, a high R^2 and an intercept close to zero. Outliers and points with zero model volume should be investigated.

Screenline percent differences versus screenline volumes

For each time period, the modeller should produce a scatter plot showing the total for each screenline by direction versus the percentage difference compared to counts.

The VicRoads modelling guidelines require comparing each point in these plots to criteria curves that decrease in magnitude as the screenline volume increases. These curves were originally derived by FHWA and are based on both an expectation of the error inherent in traffic counts as well as a judgement on the importance of accuracy for a given traffic volume.

GEH statistic

The GEH statistic, a form of Chi-squared statistic, is designed to be tolerant of larger errors in low flows. It is computed for hourly link flows and also for hourly screenline flows. It is generally not applicable to aggregate period or daily flows. The GEH statistic has the following formulation:

$$GEH = \sqrt{\frac{(v_2 - v_1)^2}{0.5(v_1 + v_2)}}$$

Where:

v_1 = modelled flow (in vehicles/hour) and

v_2 = observed flow (in vehicles/hour).

GEH targets are present in modelling guidelines in NZ, UK and US, although they are not as widely used in Australia. These targets are usually in the form of the desired percentage of links with a $GEH < x$.

Percentage root mean square error (RMSE)

The RMSE applies to the entire network (as opposed to GEH which is calculated for each link or screenline) and has the following formulation:

$$RMSE = \sqrt{\frac{\sum \frac{(v_1 - v_2)^2}{C - 1}}{\frac{\sum v_2}{C}}} \times 100$$

where:

v_1 = modelled flow (in vehicles/hour)

v_2 = observed flow (in vehicles/hour)

C = number of count locations in set.

The RMSE statistic is present in the modelling guidelines of Australia, NZ, UK and US.

Mean Absolute Deviation (MAD)

The MAD expressed as percentage is calculated as the sum of the absolute differences between each observed count and modelled volume divided by the number of observed counts. The MAD statistic is not commonly found in transport modelling guidelines. Due to using the absolute difference, the MAD statistic cannot provide information on whether the model is under or overestimating.

It is perhaps most useful for providing a quick single value comparison between models or validation attempts.

Mean Absolute Weighted Deviation (MAWD)

The MAWD expressed as percentage is calculated as the weighted sum of the absolute differences between each observed count and modelled volume divided by the number of observed counts. In the modelling context, the applied weights are determined by the modeller and are usually linked to the importance or confidence of the count. The MAWD statistic is not commonly found in transport modelling guidelines. Like the MAD statistic it is most useful as use as a comparator.

The following table provides examples of target model validation criteria.

Table 6 Examples of Target Model Validation Criteria

Model Type	R2	Slope	Screenline	GEH	RMSE
Strategic four step – Daily	>0.85	0.9-1.1	+/-10%	N/A	<30%
Strategic – peak period	>0.85	0.9-1.1	+/-10%	60% individual links GEH<5 95% individual links GEH<10 100% individual links GEH<15 GEH<5 for each directional screenline	<30%
Mesoscopic	>0.88	0.9-1.1	+/-10%	85% individual links GEH<5 GEH<4 for each directional screenline	<25%
Microscopic	>0.90 (network wide) >0.95 (core area)	0.9-1.1(network wide) 0.95-1.05 (core area)	+/-5%	85% individual links GEH<5 GEH<3 for each directional screenline	<20%

5.8.4 Criteria for travel times

Travel time validation of a model assignment is an essential component of assignment validation, especially where the purpose of the model is to assess the impacts of a project on route choice, or to provide economic appraisal. Validation of travel times usually consists of the two following checks.

Comparison of Total observed and modelled journey times

The percentage difference is calculated between the average total observed and total modelled journey times for each route by direction for each time period. Modelling guidelines typically set a desired minimum difference or use confidence intervals of the observations to assess the differences.

The comparison of total journey time differences presents some challenges. Firstly, the difference in totals does not provide information on whether the error is systematic or localised. And secondly, the measure does not standardise for the journey length, therefore, all else being equal, longer routes will tend to validate total travel times better than short routes.

The following table provides an example of travel time validation target criteria.

Model Type	% of Travel time routes within the greater of 15% or 1 minute
Strategic	85%

Mesosopic	90%
Microscopic	90%

Comparison plot of observed and modelled journey times by distance

A comparison plot using cumulative time-distance graphs are a good method of assessing the nature of the differences between modelled and observed journey times. Plots should be shown for each route by direction and by time period.

Some modelling guidelines include the recommendation that 95% confidence intervals for the observed travels are included in the plots.

5.8.5 Sensitivity testing and dynamic validation

In addition to checks of the model against observed data the assignment validation should include some testing of the sensitivity of the model to changes in inputs and assumptions.

These tests may include:

- Modifying volume delay functions for different highway classes to identify whether the changes in assigned traffic are logical
- Modifying public transport fares (for example, increasing fares by 10% and noting the change in forecast patronage and corresponding change in road traffic volumes)
- Modifying the value of time used in the generalised cost and path building formulations, and noting the changes in mode share
- Modifying public transport frequencies and noting the change in forecast public transport patronage and traffic volumes
- Modifying the zonal trip generation (employment and population levels) and noting the change in vehicle-kilometres of travel on the highway network.
- Modifying toll levels and noting the change in toll users.
- Modifying demand matrices and noting the changes in congestion and operation.

5.9 Model convergence

It is necessary to assess the stability of the trip assignment process referred to in Section 3 before the results of the assignment process are used to influence decisions or for input to economic appraisal, or both.

The iterative⁷ nature of the assignment process leads to the issue of defining an appropriate level of assignment convergence. In practical terms, an assignment process may be deemed to have reached convergence when the iteration-to-iteration flow and cost differences on the modelled network are within predetermined criteria.

The recommended indicator for assessing the convergence of urban transport models is the delta (δ) indicator. This indicator is the difference between the costs along the chosen routes and those along the minimum cost routes, summed across the whole network and expressed as a percentage of the minimum costs. An urban transport model is deemed to have reached convergence when δ is less than one per cent (see Table 7).

Table 7 Example of model convergence output

Summary of convergence for 2031 Base Case two-hr am peak.

ITERATION	DELTA		AAD	RAAD	% FLOW	
41	1.03119	%	4.53441	0.0029626	0.18298	%
42	0.68327	%	9.86224	0.0080850	2.70688	%
43	0.93032	%	6.95290	0.0047448	0.63728	%

Source: Melbourne Integrated Transport Model

Generally, the number of iterations required to reach convergence increases:

- The more trips are in the demand tables
- The more zones that are in the model
- The more links in the network.

Consideration of the time required for the model to converge should be made during specification of the model.

5.10 Transport model documentation

Transport model documentation is a step towards improving the understanding and usefulness of travel demand models. If the model documentation is too brief, or it is not updated with changes to the model, then it will not be useful to transport modellers.

Model documentation may contain a variety of information. The following is a list of suggested topics:

- Description of the modelled area and transport network coverage
- Land use and demographic data for all years modelled, by transport zone or the level of geography adopted for the modelling and analysis
- Description and summaries of all variables in the networks
- Source and coverage of traffic counts used in the model development process

⁷ Feedback of generalised travel costs derived from the trip assignment process to the trip generation and mode split sub-models within an urban transport model, until a pre-defined level of convergence is achieved.

- Description of the trip generation model and any core assumptions
- Identification of special generator and external trips input to trip generation
- Summary of trip generation results
- Description of the trip distribution model and any core assumptions
- Description of the impedance measures used in trip distribution, including intra-zonal and terminal times
- Summary of trip distribution results
- Description of the mode choice model by trip purpose
- Description of the variables used in the mode choice model
- Summary of the mode choice results
- Identification of the source and value of inter-regional trips
- Description, if applicable, of the time period models and any core assumptions
- Description of the trip assignment models and any core assumptions
- Description of the impedance measures used in the trip assignment models
- Identification of the volume–delay and path-building algorithms applied in trip assignment
- Summary of the trip assignment results, for traffic (vehicle-kilometres of travel, vehicle-hours of travel, passenger kilometres travelled, delay and average speed), and for public transport (passenger-km by mode, passenger boardings, interchange, passenger travel time)
- Summary of model parameters and statistics obtained during the estimation of model components
- Identification of model validation tests and results for each model step.

5.11 Auditing

In common with many other activities, transport modelling quality is defined by process. This means that a forecast traffic volume or patronage level cannot be determined as being ‘good’ simply by looking at the forecasts. Instead, confidence in the processes used to derive the forecasts should be sought via the structure of the transport model and its calibration and validation. It should be stressed that forecasts are only as good as the input assumptions.

Generally, using transport modelling in the appraisal of initiatives and impact assessment involves four broad processes:

- Data collection
- Model specification
- Model estimation and calibration
- Model application to the scheme appraisal.

Each of these processes should either follow accepted guidelines or accord with good practice. The following is a suggested list of information that should provide a suitable basis for the evaluation of transport models in the context of the stated objectives of users:

- A statement of the modelling objectives and the elements of the model specification that serve to meet them

- a specification of the base data:
 - description of travel surveys
 - sample sizes
 - bias assessments and validation, where available
- description of transport networks
 - structure
 - sources of network data (such as inventory surveys, timetables)
- description of demographic and employment data (such as sources, summary statistics)
- A document reporting on model specification and model estimation:
 - model structures, variables and coefficients
 - outputs of statistical estimation procedures
 - model fit to data
- Evidence of validation:
 - fit to independent data
 - comparison with other models
 - sensitivity tests and elasticities
- Description of the forecast year inputs (such as networks, demographic data, economic assumptions):
 - sources of data
 - statistics describing the main features of the data
- Documented validation of the forecasts, paying attention to the types of model runs and types of output most vulnerable to error (e.g. tests of small changes, economic benefit estimates):
 - comparison with other forecasts, where available
 - comparison with historic trends, if relevant
 - reasoned explanations of the forecasts (such as the sources of the diverted traffic, the reasons for diversion – size of time saving)
- A record of model applications.

Appendix D provides a Model Audit Checklist.

6. Forecasting and appraisal

6.1 Projection of demand growth

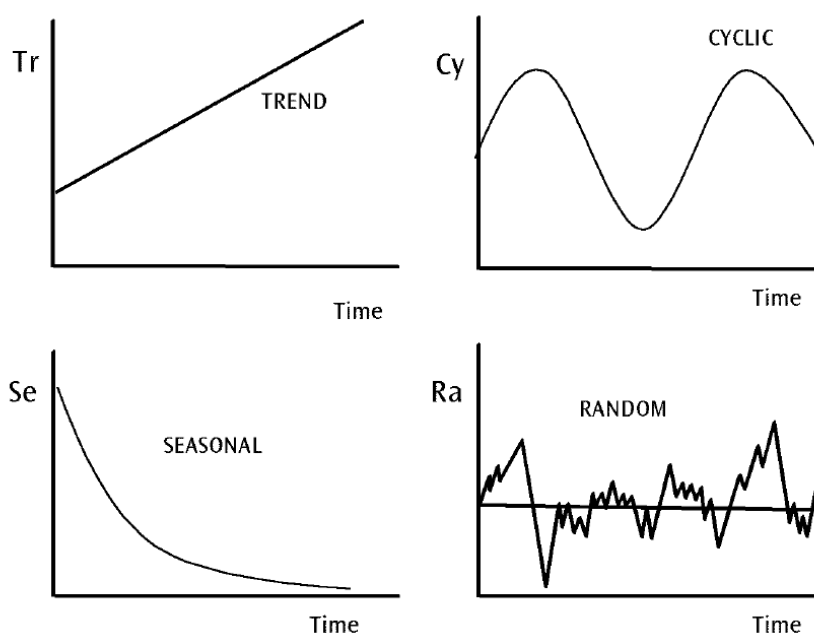
Many transport problems are a combination of deterministic and stochastic processes that may vary over time. Time series analysis is the statistical technique used to study such problems. From a stochastic point of view, traffic flow on a particular link of a network could be regarded as consisting of four components: trend (*Tr*), seasonal (*Se*), cyclic (*Cy*), and random (*Ra*) components. The trend component may result from long-term growth in traffic. Seasonal variation may result from different flows at different times of the year. Cyclic components can result from long-term economic changes. The random component may result from short-term variations in traffic flow. When there is an additive relationship between the components, they can be combined as in equation EQ 6.1 and Figure 10 below.

$$X(t) = Tr(t) + Se(t) + Cy(t) + Ra$$

[EQ 6.1]

The loads on a transport network reflect the time-dependent variations in social, economic, industrial, agricultural and recreational activities in the area it serves, as well as long-term trends in the levels of those activities. For instance, traffic data – such as hourly or daily traffic volumes – that are indicative of these loads, must be recorded as time dependent data. The distinguishing feature of time-dependent data is that they come from processes that are undergoing continual change. If we are to understand the data, we must extract the components of change that are involved and separate the random effects from the trends and cycles that influence the data. Stationary processes (those whose parameters are stable over time) offer the possibility of repeating observations in order to uncover the degree of variability existing in the data. Time series data do not permit repetition of observations as data collected at one point in time will, of necessity, differ from those collected at other times.

Figure 9 Components of a time series



Methods for the analysis of time series data, including the use of moving averages and autocorrelation coefficients, are outlined in Taylor, Bonsall and Young (2000, pp 416–22) and described more fully in textbooks such as Chatfield (1984).

Time series data are important information sources for transport analysis. They include data on system performance and impacts over time, such as passenger movements or road fatalities, as well as economic performance and activity data (such as quarterly GNP statistics and fuel sales) and socio-economic data (such as population and employment data sets). Gargett and Perry (1998), Amoako (2002) and Sutfcliffe (2002) provide recent examples of the use of time series data in analysis of freight movements in Australia.

6.2 Forecast horizon

In the past, the practice has been to develop a forecast for one year, usually the year of opening of the initiative. Given that demographic projections are usually available for a number of forecast years, it is recommended that at least two forecast years are used – one for the opening year and the other 10 years after opening.

Using the second forecast year enables issues such as fare level changes, value of time and vehicle operating cost increases, and land use changes to be explicitly input into the model and may result in a more robust forecast and appraisal outcome.

6.3 Network options

The ‘do-minimum’ network should be based on the validated Reference (Base) Year network and should include all the supply-side proposals (such as committed highway and public transport infrastructure) and operational proposals that are expected to be implemented by the forecast year.

The ‘do-something’ network should be based on the ‘do-minimum’ network with the difference between the two networks being the project being appraised and any other changes, such as a service scenario, that are different to that in the ‘do-minimum’ network.

6.4 Sensitivity tests

Sensitivity tests around a ‘do-minimum’ case should be undertaken in order to identify the robustness of the forecasts to changes in assumptions. Some examples of sensitivity tests that could be undertaken are:

- Different unit rates for travel time, vehicle operating costs, public transport wait times and transfer penalties
- Changes in public transport fare levels, parking charges, road pricing
- Changes in the demographic assumptions (i.e. population and employment levels)
- Ranges of growth in travel demand
- Changes in model parameter values (ie affecting routeing, distribution and mode choice responses)
- Different economic growth assumptions
- An assessment of complementary schemes.

Appendix A Transport modelling process

The following is provided as a guide to assist in defining and implementing the transport modelling process.

Consolidate the transport modelling task

This step involves discussing the transport modelling requirements to determine the scale and scope of the transport modelling.

- Review the purpose, goals and objectives of the task or study
- Review the timeline for the task or study
- Identify how transport modelling can contribute to informing the study goals and objectives within the specified timeline
- Identify and confirm the scale and scope of transport modelling required:
 - strategic level
 - regional level
 - corridor level
 - microsimulation
- Confirm the time period to be modelled:
 - peak (am, inter-peak and pm)
 - 24-hour
- Confirm the transport network and land use options to be modelled. These options need to be defined early in the process to determine the resources required to undertake the modelling
- Confirm the calibration and validation criteria for the modelling task:
 - root mean square error (RMSE)
 - GEH
 - travel time reporting
- Confirm the timelines for the modelling task
- Confirm the outputs from the modelling task. Examples of transport modelling outputs are:
 - highway link volumes
 - public transport patronage
 - transport network performance indicators e.g. vehicle-hours, vehicle-distance, passenger-kilometres, levels of congestion, average speeds and travel times.

Data collection

Identify and source the data required for the transport modelling task:

- Revealed preference data
- Origin–destination
- Traffic counts (mid-block, intersection)
- Route (link) travel times
- Demographic (population, employment)
- Land use (quantum of industrial, residential, commercial land)
- Stated preference data
- Public transport boarding and alighting data.

Model calibration and validation

Undertake the Reference (Base) Case transport model calibration and validation according to the criteria presented in Appendix C.

Develop options

Forecasts are used to determine the performance of alternative scenarios of future land use and transportation systems. Options development would normally include different land use and transport systems and mixtures of highway and transit services and facilities. Since land use affects travel and travel affects land use, both must be considered.

Options modelling

Undertake the modelling of the various options and produce the demand and assignment outputs and network performance indicators such as:

- Mode shares
- Total vehicle-kilometres, vehicle-hours of travel and passenger kilometres travelled
- Total network travel time
- Vehicle operating and travel time costs
- Emissions – CO₂, CO, NO_x, CH₄, HC, PM₁₀, PM_{2.5}.
 - The modelled options should be compared to the calibrated and validated Base Case model on the basis of:
 - traffic volumes
 - public transport patronages
 - network performance indicators.
- Accessibility

Sensitivity analysis

Sensitivity analysis is usually undertaken to assess the response of the forecasts to a range of assumptions around an agreed transport network and demand scenario, usually the 'Do-Minimum' Case. The sensitivity testing may include:

- An allowance for generated / induced travel
- Ranges of growth in travel demand
- Changes in model parameter values
- Public transport fare changes
- Different planning or economic growth assumptions
- An assessment of complementary schemes such as travel behaviour change initiatives.

Economic appraisal

Economic appraisal is undertaken to assess the economic benefits of preferred options. Transport user benefits are derived by comparing the effects of the scheme against a 'Do-Minimum' Case, discounted over the assumed life of the scheme, and compared with scheme cost estimates and revenue implications.

Modelling Report

A Modelling Report demonstrates that the transport model appropriately reproduces an existing situation and summarises the accuracy of the base from which the forecasts are produced.

The Modelling Report should also include the aims and objectives of the modelling task, document the assignment validation and output, document the details of any model calibration and report on the economic appraisal.

The Modelling Report should include:

- A description of the modelling task, aims and objectives
- A description of the data used in calibrating and validating the model
- The model calibration outcome
- Documentation of the modelling assumptions
- Documentation of the model validation
- Documentation of the economic appraisal.

Appendix B Discrete choice models

Discrete choice models have been employed widely in travel demand analysis since the 1970s, with the most common application being in the choice of travel mode. Modal split is the relative proportion of travellers or shippers using one particular mode compared with the other available modes. Most models of modal choice use a 'utility' function representation of the attributes of the different modes and of the travellers or shippers as a main set of independent (explanatory) variables. The utility function is usually a weighted sum of the modal and personal attributes considered (such as travel time and reliability, travel cost, service frequency and socio-economic characteristics). The simplest choice models consider only two alternatives (for example, Mode A and Mode B) and are known as binary choice models. In general terms, a binary model can be expressed as:

$$\frac{p_A}{p_B} = F(U_A, U_B)$$

where p_A and p_B are the probabilities of choosing modes A and B, U_A and U_B are the utility functions for modes A and B, and $F(U_A, U_B)$ is some suitable function. The models are often expressed for one of the modes only, for example, as:

$$p_A = f(U_A, U_B)$$

and they can be extended to include more than two alternatives in the choice set. The discrete choice models are often termed 'behavioural' because they can represent causality in that they can be derived from a theory that explicitly maps out the decision-making processes of the individual taking the decision. The theoretical basis is usually that of utility maximisation. It assumes the utility an individual ascribes to an alternative is defined by a utility function in which the attributes of the alternative and characteristics of the individual are determining factors. The choice of a particular alternative is made on the basis of comparing the levels of utility derivable from each of the available alternatives.

Of necessity, the models estimate the probability that n_A individual, in a given situation, will choose a particular alternative rather than the definite selection of a preferred alternative. Assume that an individual can choose one alternative r from a set of K available alternatives and that the utility of alternative r is for that individual is given by U_{ri} . Alternative r will then be chosen if:

$$U_{ri} \geq U_{ki} \text{ for all } r \neq k \in K$$

Given that there will almost always be some uncertainty concerning the specification of the utility function – because of measurement errors, omission of unobservable attributes and other specification errors – utility functions have a random component. Thus it is only possible to determine the probability that a given alternative will be chosen. We can represent the utility function U_{ri} as:

$$U_{ri} = V_{ri} + \varepsilon_{ri}$$

where V_{ri} is the deterministic part of the utility function and ε_{ri} is the random part. Then the probability that an individual will select alternative r can be written as:

$$p_{ri} = Pr\{U_{ri} \geq U_{ki}\} = Pr\{V_{ri} + \varepsilon_{ri} \geq V_{ki} + \varepsilon_{ki}\} = Pr\{V_{ri} - V_{ki} \geq \varepsilon_{ki} - \varepsilon_{ri}\} \text{ for all } k \in K \mid k \neq r$$

Specific mathematical forms of the choice model then emerge depending on the assumptions adopted about the form of the joint distribution of the random errors $\varepsilon_{ki} - \varepsilon_{ri}$. If this distribution is assumed to be the normal distribution, then the choice probability model is the probit model. Unfortunately, this model is mathematically intractable. As a result, the practice is to assume that the distribution follows Weibull distribution, which approximates the normal distribution to some degree. The advantage of this assumption is that the resultant choice model is the multinomial logit model, which is mathematically tractable. The function form of the multinomial logit model is:

$$p_{ri} = \frac{\exp(U_{ri})}{\sum_{k \in K} \exp(U_{ki})}$$

The binomial form of this model – using the earlier notation of alternatives A and B – is:

$$p_A = \frac{\exp(U_A)}{\exp(U_A) + \exp(U_B)} = \frac{1}{1 + \exp(U_B - U_A)}$$

This function is such that if U_A and U_B are equal, then the probability of choosing each of the two alternatives is 0.5, while if $U_A > U_B$, then the probability of choosing A is greater than choosing B. The utility functions are generally weighted linear functions of the attributes. For example:

$$U_{ri} = \alpha_r + \sum_{j=1}^J \beta_{rj} X_{rji} + \sum_{l=1}^L \gamma_l Y_{li}$$

Where α_r is an alternative-specific constant, the $\{\beta_{rj}, j = 1, \dots, J\}$ are constant coefficients for the attributes (e.g. service variables) $\{X_j\}$ of the alternative and the $\{\gamma_l, l = 1, \dots, L\}$ are constant coefficients for the attributes (e.g. socio-economic characteristics) of the individual decision-maker i .

The coefficients of the utility function may be used to provide further information. For example, if a utility function takes the form:

$$U = \alpha + \beta_1 \times \text{price} + \beta_2 \times \text{time} + \beta_3 \times \text{reliability}$$

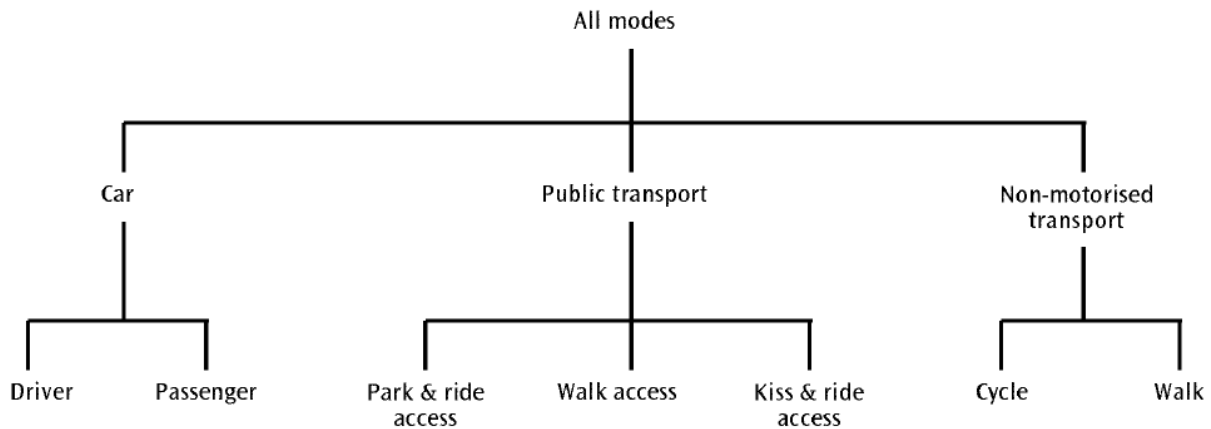
then by dividing both sides of equation (7.3) by B_1 , yields the money value of time (B_2/B_1) and the money value of reliability (B_3/B_1).

Coefficients in the utility functions are generally estimated from observed data sets using maximum likelihood techniques implemented in software packages such as LIMDEP.

While the multinomial logit model is a powerful tool for understanding travel choices, it has some significant limitations. The most important of these is its reliance on the ‘Axiom of the Independence of Irrelevant Alternatives (IIA)’ (Luce 1959) which states that “if a set of alternative choices exists, then the relative probability of choice among any two alternatives is unaffected by the removal (or addition) of any set of other alternatives”. This means that the ratio p_A/p_B is independent of the other alternatives available in the choice set. This property is the basis of the multinomial logit model. Unfortunately, while the model is attractive and easy to use, it really applies only in rather special circumstances and its use in practice can lead to certain anomalies (for example, the ‘red bus-blue bus’ anomaly⁸). The general solution is to use nested logit models that present a hierarchy of choices in which the decision-maker usually has to choose between no more than two alternatives at any point in the nested structure. Multinomial logit models are generally used at each of the decision points. An example of a nested logit model for mode choice is displayed in Figure 10.

⁸ Consider the case where travellers can choose between two modes – say car and bus – to make a given trip and further assume that the utility values for both of these modes are equal. Then there are probabilities of 0.5 for the use of both modes. Now assume the public transport operator paints half of the buses red and the other half blue. There are now three modes apparent: car, red bus and blue bus. All modes still have the same utility values, so the ratio between any pair of modes is unity and the overall modal split is (according to the multinomial logit model) one third car, one third blue bus and one third red bus. The proportion of travellers using cars has then decreased from 0.5 to 0.33, but nothing has actually changed except the colours of the buses. This is an illogical result and is due to the fact that the two bus modes are actually variations of the same choice alternative for the travellers – they are not truly independent alternatives.

Figure 10 Structure of a nested logit modal choice model



This model incorporates three broad modes of travel: car, public transport and no-motorised transport. The car mode is split into car driver and car passenger. Public transport is split into three separate elemental modes, depending on the mode of access taken to use the transit services (note that this model does not distinguish between rail or bus services). Non-motorised transport is split into bicycle and pedestrian modes. Douglas, Franzmann and Frost (2003) describe the development of similar discrete choice modes for modal choice in Brisbane.

The use of multinomial logit models in freight transport studies is illustrated in Wigan, Rockliffe, Thoresen and Tsolakis (1998). This study used the models to estimate the value of time spent in transit and reliability of arrival time for both long-haul and metropolitan freight.

More complicated, but more generally applicable, choice models are also available, such as the mixed logit models (see Louviere, Hensher & Swait 2000; Train, Revelt & Ruud 2004). While the standard logit model assumes the utility function coefficients are the same for the entire population (everyone has the same values of time and of other quality attributes), the mixed logit model allows the analyst to make the more realistic assumption that the coefficients vary across the population according to some distribution (such as uniform, normal, log normal). The mixed logit model relaxes the assumption of IIA and allows correlation in the unobserved components of utility between alternatives. The model is, however, much more data intensive and computationally exhaustive.

It must be noted the reliance on the ‘independence of irrelevant alternatives’ axiom does not invalidate the multinomial logit model. It is a perfectly acceptable model as long as care is taken to ensure its basic assumptions are not violated in a given application.

One advantage of the multinomial logit model is that it is possible to derive point elasticity values from it. Considering the choice model defined by equations EQ 3.1 and EQ 3.2, it can be shown that the elasticity of the probability of choosing mode A for an individual with respect to changes in X_{rj} (the j^{th} independent variable of alternative r) is given by:

$$\eta_{Aji}^r = [\delta_{Ar} - p_{ri}] \beta_{rj} X_{rji}$$

where δ_{Ar} is a delta function defined as:

$$\delta_{Ar} = 0 \text{ if } A \neq r \text{ (cross elasticity)}$$

$$\delta_{Ar} = 1 \text{ if } A = r \text{ (direct elasticity)}$$

This result indicates that the direct elasticity for alternative A depends only on the attributes of that alternative, while for the cross elasticities only, the attributes of the other alternative r enter the equation.

Properly established discrete choice models are powerful decision-support tools for policy analysis and project evaluation. At a basic level, the models can be used to estimate changes in market shares across modes, or for alternative routes if a project is undertaken that will reduce the price or improve one or more of the service quality attributes for one mode or route. The models may also be used to help a transport operator determine the price to charge that will maximise profits. At a more complex level, the models can be used to estimate the welfare gains to customers from an improvement in a service quality attribute, which is important for inclusion in benefit-cost analysis.

For further information on the development, estimation and application of discrete choice models, the determination of elasticity values from discrete choice models and the application of the models in project evaluation, see: Ortuzar and Willumsen (2011); Taplin, Hensher and Smith (1999); Hensher and Button (2000); and Louviere, Hensher and Swait (2000).

Appendix C Reference (Base) model validation criteria

A review of reference (base) model validation techniques will be undertaken during subsequent Stage of the NGTSM update. This will include the recommendation of fit-for-purpose statistics to use for model validation. This review will include investigation of the MAD% and MAWD% statistics amongst others.

In the meantime, the following criteria should be used to validate the Reference (Base) model to ensure that modelled results are consistent with observed data (i.e. traffic counts and travel times). If the criteria are met (or if not met, and there is sufficient confidence that the transport model is still fit-for-purpose), the Reference (Base) model is considered adequate for predicting the present and is fit-for-purpose for forecasting.

Ideally, the observed data should be the most recently available traffic counts and travel times.

Link flows

- **Link volume plots**
 - For each time period, produce a map of the transport network showing modelled and observed link flows and the differences between them. The totals should be summarised for available screenlines. These plots are used to check modelled and observed flows by geographic area and level of flow.
 - As a guide, a reasonable error tolerance for hourly flows on individual links is approximately ± 20 per cent. A major link is considered to be one that carries at least 15 000 vehicles per day in one direction. In the case of screenlines, an acceptable error tolerance is ± 10 per cent.
- **Scatter plot of modelled and observed flows**
 - Produce an XY scatter plot of modelled versus observed flows for:
 - all individual links
 - freeway links
 - screenlines
 - Superimpose the $y=x$ line on each plot. Report on the R^2 for each plot.
- **GEH statistic**
 - The GEH statistic, a form of Chi-squared statistic, is designed to be tolerant of larger errors in low flows. It is computed for hourly link flows and also for hourly screenline flows. The GEH statistic is intended for validating simulation models only, and should not be used with daily traffic volumes for the purpose of validating strategic transport models. The GEH statistic has the following formulation:

$$GEH = \sqrt{\frac{(v_2 - v_1)^2}{0.5(v_1 + v_2)}}$$

where V_1 = modelled flow (in vehicles/hour) and V_2 = observed flow (in vehicles/hour).

- **Percentage root mean square error (RMSE)**

- The RMSE applies to the entire network and has the following formulation:

$$RMSE = \frac{\sqrt{\frac{(v_1 - v_2)^2}{C - 1}}}{\frac{\sum v_2}{C}} \times 100$$

where:

V_1 = modelled flow (in vehicles/hour)

V_2 = observed flow (in vehicles/hour)

C = number of count locations in set.

Travel times

Provide a comparison of modelled and observed travel times as an XY scatter plot for each time period modelled. The scatter plot should also include the 95 per cent confidence limits for the modelled data. More specifically, modelled versus observed distance against time can be plotted for individual travel time routes.

Assignment convergence

Provide evidence of assignment convergence by detailing the:

- Type of assignment (equilibrium, volume averaging, incremental)
- Convergence achieved at the final iteration and the number of iterations required in achieving convergence
- Percentage change in total generalised user cost in the final iteration
- Proportion of links with flows changing <5%
- Normalised gap δ : this is the flow-weighted difference between current total costs and the costs incurred if all traffic could use the minimum cost routes – should be less than 1%.

Appendix D Model audit checklist

General information

Check if a model specification and detail is available for:

- The type of model used
- Geographic area covered by the model and the level of zonal disaggregation
- Tabulation of land use assumptions for all modelled years
- The transport networks (active, public transport, highway, freight) included and their details
- The time periods modelled
- The vehicle types modelled
- How the external trips are modelled.

Data sources

Check if a data source description and the source's reliability are available for:

- Transport network data (link lengths, link types, free flow speeds, capacities, number of lanes)
- Travel data and collection methods (traffic counts, origin–destination surveys)
- Source and coverage of travel data and collection methods (household travel surveys, origin-destination surveys, stated preference surveys)
- Other.

Matrices

Check for details on:

- The description of each step in the development of the Reference (Base) Year and forecast trip matrices, including methods, assumptions, parameters and factors applied – include details of any matrix estimation procedures that have been used
- Evidence of matrix fit to observed data (screenlines, comparison with independent origin–destination flows)
- Evidence of sensitivity testing of input parameters or elasticities
- Detail on the matrix methods or techniques used – if variable matrix methods or growth constraint techniques have been used, provide details on the method and parameters adopted and the justification for the approach
 - Description of the trip generation, trip distribution and mode choice modules by trip purpose, including a listing of all variables.
 - Description of special trip generators (airports, ports).
- The basis for the development of a commercial vehicle matrix.

Assignment

Check for details on the:

- Description of how the transport network was developed
- Assignment method used (incremental, equilibrium, volume-averaging, other)
- Generalised cost formulations used for route choice to include the methodology for incorporating tolls on route choice
- Volume delay functions adopted (equations, coefficients, calibration, validation)
- Any intersection modelling being undertaken and the basis it is being undertaken on.
- Outcomes of the model validation tests for each step of the 4-step modelling system.

Forecasting

Check for details on:

- Comparison of forecast year growth rates with historical trends (land use, household size, car ownership, traffic volumes, commercial vehicle volumes)
- Average growth across screenlines to ensure local growth is reasonable
- Comparisons with other forecasts (if any).

Appendix E Abbreviations

AAD	Average Absolute Volume Difference
ABS	Australian Bureau of Statistics
ANPR	Automatic number plate recognition
ASGS	Australian Statistical Geography
BITRE	Bureau of Infrastructure, Transport and Regional Economics
CATI	Computer Aided Telephone Interview surveys
DOT	Victoria Department of Transport
FHWA	Federal Highway Association (USA)
FTM	Fixed Trip Matrix methodology
GEH	GEH formula
ITS	Intelligent Transport System
LRT	Light Rail Transit
LUTI	Land use transport interaction
MAD	Mean Absolute Deviation
MAWD	Mean Absolute Weighted Deviation
NGTSM	National Guidelines for Transport System Management
NZTA	New Zealand Transport Agency
O–D	Origin–destination
PT	Public Transport
RAAD	Relative AAD
RMS	NSW Roads & Maritime Services,
RMSE	Root mean square error
SA1	Statistical Area Level 1
TAG	Transport Analysis Guidance
VATS	The Victorian Activity and Travel Survey

VKT	Vehicle Kilometre Travelled
VTM	Variable Trip Matrix methodology

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