Urban Congestion: Modelling Traffic Patterns, Delays and Optimal Tolls

Working Paper

This Paper provides an account of preliminary work on urban traffic congestion that forms part of the Bureau of Transport and Communications Economics project on Urban Transport Externalities. The project is concerned with a range of external impacts of urban transport. Congestion is just one of these impacts but, because it is so intimately related to the traffic patterns which give rise to the others, it has been made the focus of the initial work.

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Urban congestion:

modelling traffic patterns, delays and optimal tolls

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FOREWORD

This paper provides an account of preliminary work on urban traffic congestion that forms part of the Bureau of Transport and Communications Economics project on Urban Transport Externalities. The project is concerned with a range of external impacts of urban transport. Congestion is just one of these impacts but, because it is so intimately related to the traffic patterns which give rise to the others, it has been made the focus of the initial work.

The project is concerned with impacts in Melbourne, Sydney, Brisbane, Adelaide and Perth. However, mainly for reasons of immediate data availability, Melbourne is the subject of this paper. It is anticipated that the approach used here will be applied to the other cities as data become available.

Urban travel behaviour is very complex. Analysts have tried to capture its main features in models that provide estimates of the levels and patterns of traffic on the urban road network. While the models are complex, they are still radical simplifications of real urban systems, and their treatment of some aspects of travel behaviour can only be described as rudimentary. Nevertheless, they constitute the state of the art in quantitative urban transport analysis, and they provide a valuable framework for thinking about urban policy issues.

The paper provides an overview of the general features of urban transport models, together with estimates of the level and distribution of delay due to congestion on the urban road network, and of the level of optimal congestion tolls.

This work was undertaken by Dr Franzi Poldy and Brett Evill. The assistance of R. J. Nairn and Partners in the use and modification of the TRANSTEP model is gratefully acknowledged.

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Canberra
May, 1995

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CHAPTER 1 INTRODUCTION

BACKGROUND—URBAN TRANSPORT EXTERNALITIES

This paper provides an account of preliminary work on urban traffic congestion that forms part of the Bureau of Transport and Communications Economics (BTCE) project on Urban Transport Externalities.[1] The project is concerned with all external economic impacts of urban transport but has been divided into a number of stages. In the first stage, we are concerned with the externalities of urban transport *operations* (ignoring upstream externalities associated with vehicle manufacture, road building and fuel refining, and downstream externalities such as the disposal of scrapped vehicles and used oil, tyres and batteries) and, among these, the focus is on the

- noise,
- vehicle emissions,
- accidents, and
- congestion

associated primarily with road traffic. The project is intended to develop an understanding of the costs of these externalities as they are experienced in the larger Australian cities—Sydney, Melbourne, Brisbane, Adelaide and Perth.

The work is also directly relevant to the BTCE's assessment of measures for reducing greenhouse gas emissions, as urban traffic is the main transport source of these emissions. Greenhouse gas emissions constitute an externality in their own right but, because their impact is global rather than local, they are considered separately. However, measures for reducing greenhouse gas emissions would be expected to entail changes to some or all of the local externalities, and the assessment of these measures therefore needs to take account of changes in the costs of local external impacts.

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[1] For the economic theory of externalities see Baumol and Oates (1988). For the purposes of this paper, the essential point about external impacts is that they impose costs (or benefits) that are not taken into account by those who determine the levels of the activities that cause the impacts.

In forming an opinion on the relative merits of different solutions to urban problems, we need to understand how traffic fits in and interacts with the other components of the urban system. Where appropriate, we will be particularly interested in the scope for using economic instruments to address problems of urban transport externalities. However, it will clearly be up to State authorities to develop and implement those urban policies that seem appropriate to them.

It was fortunate that the start of this project coincided with that of the Victorian Transport Externalities Study (VTES), which addressed these issues in Melbourne. By participating in the VTES the BTCE gained experience that will be valuable in extending the work to other cities.

The report of the VTES was released in October 1994 (EPA 1994). Table 1.1 summarises the aggregate costs of urban transport externalities as estimated by the VTES for Melbourne. The table gives a brief indication of how the estimates were made, but the full study should be consulted for details. The focus in the table is on the *external* costs of the impacts, although the estimation procedures generally provide *total* costs. The distinction may not be important in the case of noise and vehicle emissions, for which most of the impact is certainly external. But it is important for accidents and congestion.

TABLE 1.1 EXTERNAL COSTS OF URBAN TRANSPORT–MELBOURNE

Impact	*Basis of estimate*	*Annual cost ($million)*	*Year*
Noise	Traffic volumes on arterial roads → noise exposure to adjacent property → property value depreciation → loss converted to annuity at 5%	40 to 90	1992
Vehicle emissions	EPA records/estimates of air pollution → health effects[a] (deaths, hospital admissions, etc.) → unit cost estimates (deaths, hospital days, etc.) → costs → 85% of air pollution (and associated costs) attributed to road traffic	< 60	1990
Accidents	Police and insurance accident records → unit cost estimates → costs	800[b] (30% of 2 600)	1988
Congestion	Transport model estimates of excess travel time	1 300[b] (66% of 2 000)	1991

a. The health effects taken into account were: morbidity and mortality associated with the impact of ozone on the respiratory system; and fatal and non-fatal cancers attributed to the carcinogenic components of vehicle emissions. The study did not take account of the association of particulate emissions with cardiopulmonary disease, which recent work (Dockery et al. 1993) suggests may be very significant.

b. The study estimated the total costs. The external component is the indicated percentage of the total cost. See text.

Source EPA (1994), vol. 2.

Little is known about the extent to which accident costs are external. The issue is conceptually complex, and is complicated by the workings of the insurance system. Following the practice of a number of OECD reports, a notional 30 per cent of accident costs has been assumed to be borne externally. Congestion costs are considered in this paper and are estimated to be about 66 per cent external.

Despite these uncertainties, it would seem from table 1.1 that the external costs of noise and vehicle emissions are much smaller than those of accidents and congestion. The main qualification on this conclusion is that the impact of particulate emissions on cardiopulmonary disease was not taken into account in costing the health effects of vehicle emissions. Recent work (Dockery et al. 1993) suggests that this may be very important.

CONGESTION—THE PRIMARY TRANSPORT EXTERNALITY

Traffic is the underlying cause of the impacts that are of concern. Figure 1.1 shows the relationships between traffic and its impacts. The arrows represent causal connections. Traffic gives rise to congestion, but the congestion feeds back directly to influence the traffic patterns. There is thus a very tight connection between traffic and congestion, and one cannot be understood without the other.

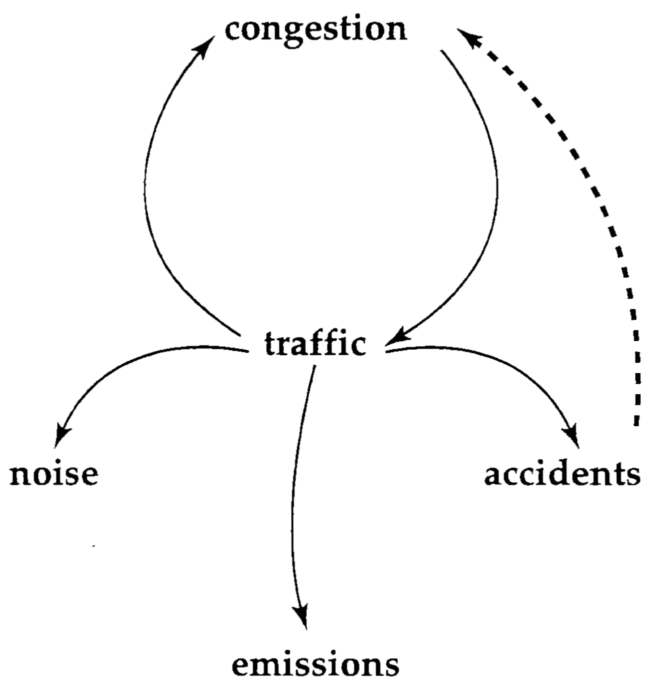

Figure 1.1 Relationships between urban traffic and its impacts

Traffic also gives rise to noise, vehicle emissions (and consequent air pollution), and accidents, but in these cases there is no direct feedback from the impacts to the traffic.[2]

The initial focus is therefore on traffic and congestion, and the aim is to understand how they are jointly determined by people's demand for travel and the capacity of the urban transport system to meet that demand. An understanding of the patterns of traffic and congestion will be essential in estimating the levels of noise and vehicle emissions.

An initial focus on congestion is also likely to be consistent with policy priorities because it appears to be the most costly[3] of the external impacts (see table 1.1), and the one for which economic instruments (such as congestion tolls) are most likely to be relevant. It is also likely that any 'solution' to the congestion problem (other than simply building more roads) will itself go some way to reducing the problems of noise and emissions.

UNDERSTANDING TRAFFIC AND CONGESTION—URBAN TRANSPORT MODELS

Urban systems are very complex. In the short term, travel in cities depends on the distributions of population, employment and facilities, on people's preferences for different transport modes, and on the way they choose their routes on the urban road network. In the longer term, the nature of the transport system and the ease of access to facilities are important factors in determining where people choose to live and work, and where new facilities are developed.

Urban transport models try to capture this complexity and provide a means for estimating travel and traffic patterns and their evolution under different policies. They have become a routine part of the armoury used in planning and investment analysis by State Departments of Transport, the various Road Authorities and consultants working on behalf of these and other clients.

While the models are complex and have a voracious appetite for data, they are still radical simplifications of real urban systems, and their treatment of some aspects of travel behaviour can only be described as rudimentary. Nevertheless, they constitute the state of the art in quantitative urban

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[2] There is, in fact, a linkage between accidents and congestion, but this is usually taken into account implicitly. The process whereby traffic gives rise to congestion is deemed to include a contribution from the expected number of accidents.

[3] Road accidents are also very costly to the community. However, a great deal is already being done to improve road safety, and it seems unlikely that further progress will depend on the use of economic instruments.

transport analysis, and provide a valuable framework for thinking about urban policy issues.

The results presented in this paper were obtained using the TRANSTEP urban transport model developed by R. J. Nairn and Partners. TRANSTEP is one of a number of urban models that the BTCE has been examining. While there are differences between the models, they are all based on broadly similar assumptions about how cities work, and the results presented here could, in principle, have been obtained with other models.

A STRATEGIC OVERVIEW OF URBAN TRAFFIC

Urban transport models are complex, they are not easy to use, and their results are often unintelligible. Yet they embody much of our knowledge and many of our assumptions about urban dynamics, and these should, ideally, be available to those involved in urban policy formulation. One of the goals of this project will be to try to extract from the modelling work an intelligible strategic overview of urban transport which will be of use at the policy level. Such a strategic overview would focus less on numerical results and more on the basic patterns of traffic and public transport use and on the way these patterns change under different policies.

As a first step towards a strategic overview, this paper

- outlines the general features of urban transport models. This will provide a qualitative understanding of the way cities are conceived in these models, and list the components and aspects of travel behaviour that are taken into account. It will not constitute a detailed technical description.
- shows how a readily intelligible overview of the state of urban traffic can be provided by graphical presentations of the distribution of traffic characteristics over the road network.
- estimates the level of a theoretically optimal congestion toll and its distribution over the road network. The net benefits of such a toll and the equity consequences of the transfers of welfare from and among road users are also considered.
- discusses the use of model results to provide estimates of environmental impacts from urban road traffic.

CHAPTER 2 URBAN TRANSPORT MODELS

The following outline of the general features of urban transport models aims to provide a qualitative understanding of what has been taken into account in reaching the results presented in later chapters.

The description is at a generic level and does not necessarily refer to the TRANSTEP model from which the results were obtained. For a detailed description of TRANSTEP see Nairn, Field and Parker (1977) or the current General Description (Nairn and Partners 1986) or User Manual (Nairn and Partners 1991). In fact, TRANSTEP differs in some respects from the commoner so-called traditional four-step transport models and, where this difference is significant, it will be noted. However, as has been mentioned, the results could, in principle, have been obtained with other models, and it is important for this work that detailed differences should not distract from the essential features of the models and the results.

MODEL COMPONENTS

Land use in the city is represented by a set of zones that cover the urban area. The transport system is described in terms of the road network and public transport routes.

Zones

The urban area is divided into zones, for each of which land use characteristics relevant to travel demand are recorded. The commonest characteristics, and the ones generally used in TRANSTEP, are:

- residential—represented by either population or number of households, usually with an indication of the income distribution;
- employment—represented by numbers of jobs, possibly with some disaggregation by industry type;
- retail activity—represented either by numbers of retail jobs or by area of retail floor space;
- educational facilities—represented by enrolments at schools, colleges and universities; and

- recreational—which may be represented in a variety of ways such as the areas of parkland or the spectator capacity of sporting facilities. This aspect of land use is less important for the analysis of peak hour commuting travel, which is the focus of most urban transport modelling work.

The number of zones varies with the size of the city, the availability of data and the aims of the analysis. The Melbourne model used in this paper has 542 zones, of which 17 are external zones representing travel origins or destinations outside the urban area.

The road network

The road network is represented by a set of nodes and links. Nodes are generally numbered and, for plotting purposes, their co-ordinates in the plane are given. Nodes represent junctions or intersections between roads, or in some cases serve to indicate the route of roads that are not straight. A subset of nodes, one for each zone, are known as zone centroids and represent the interface between the zone and the road network.

In some models, nodes have additional attributes representing the junction or intersection type (stop, give way, roundabout, traffic signals, etc) and its impact on travel time. TRANSTEP does not model intersection delay, but its consequences are implicitly incorporated in the speed–flow relationships on the road links adjacent to the intersections.

A link is a stretch of road joining two nodes, and is identified by the numbers of the pair of nodes it connects. Links are of a number of types corresponding to the different types of road in the network—freeways, divided or undivided arterials, collectors and distributors—with account taken of the number of lanes. For city-wide strategic modelling, the network would typically include only these larger road types. Streets within zones are represented in an approximate way by centroid connectors, which are particular types of links connecting zone centroids to nodes on the road network proper.

Each road type is characterised by a free speed and a traffic capacity. The free speed is the speed of vehicles at very low levels of traffic. The traffic capacity is a loose measure of the maximum traffic volume (in vehicles per hour) that the road can carry. These quantities are parameters in the speed–flow relationship, which describes how traffic speed falls off as the volume of traffic increases (see appendix II).

As with zones, the number of nodes and links in the road network depends on city size and the aims of the analysis. The Melbourne road network used here has 1853 nodes (including the 542 zone centroids) and 2712 links (including 925 centroid connectors). There are 10 different road types.

Public transport routes

There is a distinction between on-road and off-road modes. On-road modes such as buses and trams share the road network with private traffic; they thus contribute to and experience the effects of congestion. Off-road modes such as trains and ferries operate between nodes of the network on dedicated links that are not part of the road network. Routes for both on- and off-road modes are defined as consecutive sequences of links between nodes. Nodes on public transport routes can also be classified according to such features as whether passengers can board and alight or whether there are special facilities for transfer between routes.

Each public transport route is characterised by its scheduled speed, frequency of service and capacity (persons per vehicle). In addition, for on-road modes, the contribution of the vehicles to congestion is recorded in terms of passenger car equivalent units[1], and the actual speed is limited by the traffic speed, which may be less than the scheduled speed in congested conditions.

In this TRANSTEP model of Melbourne, there are 71 bus routes, 19 tram routes, and 23 train routes.

MODELLING URBAN TRAVEL

Transport models try to describe people's use of the urban transport system to meet their needs for access to all the facilities of the city, and the consequences of this use for traffic on the road and public transport networks. People's travel behaviour is extremely complex and depends on (among other factors): where they live; where they work; where they shop or go to school; the number and types of vehicles they own; their access to and the cost and convenience of public transport; when they choose to travel and whether they have any choice in the matter; and so on. Many of these factors are, themselves, dependent on transport conditions in the city; so there are important feedback effects on different time scales that need to be taken into account. In the short term, congestion, travel time and transport costs influence people's choice of mode and where to shop. In the longer term, these factors influence where people live and work, and where developers locate new facilities. And the location of population, employment and other facilities influences the roads and transport services provided by governments and the private sector. In principle, the models try to capture all of this.

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1 For example, if a bus were equivalent to 3 cars for congestion purposes, a traffic flow of 1000 vehicles per hour made up of 980 cars and 20 buses would be represented as a flow of 1040 passenger car units per hour.

In practice, the representation of these complexities, in all models, is very uneven. The academic literature describes a great deal of research into urban travel but, until very recently, it has not been feasible to implement many of the findings of this research in models suitable for routine use.

A body of practical understanding and feasible techniques has evolved over the last 30 years, and forms the basis for almost all urban transport models in common use. The standard approach has become know as the 'traditional four-step modelling process'. The following paragraphs provide a brief overview of this process. The TRANSTEP model does not, in fact, fall quite within the four-step tradition. However, for the purposes of this paper, it is the general principles and limitations that are important, and these are common to all models.

The four steps of the traditional process are:

1. trip generation—estimating the total number of trips *to* and *from* each zone, on the basis of people's needs to be elsewhere and of the power of urban facilities such as job locations, schools and shopping centres to attract people;

2. trip distribution—determining the origin and destination zones of the trips actually made;

3. mode split—estimating on the basis of the travel time, cost and convenience of the trips to be made the proportion of trips between each pair of zones that will be made by public transport or by private car;

4. trip assignment—estimating the paths taken by traffic on the road network and the public transport routes used to accomplish the required trips.

Trip generation and distribution and the origin–destination matrix (steps 1 and 2)

The aim of the first two steps of the traditional process is to produce a zone to zone origin–destination (O–D) matrix of person trips to represent the demand for travel about the city. The O–D matrix is a square matrix, of order equal to the number of zones, in which the entry in row i and column j records the number of trips from zone i to zone j. Clearly, the sum of all the entries in row i is the total number of trips originating in zone i, and depends, in part, on the number of people in the zone who are likely to want to make trips. Similarly, the sum of the entries in column j is the total number of trips that end in zone j, and depends, in part, on the extent of the facilities in the zone that are likely to attract people.

The first step, trip generation, is concerned essentially with generating the row and column totals (whose grand totals must, of course, be equal—the total number of trips *from* all zones must equal the total number of trips *to* all zones). The second step, trip distribution, is concerned with filling in the body of the O–D matrix in a way that is consistent with the row and column totals *and* with some measure of people's perceptions of the generalised cost[2] of trips between each pair of zones.

Clearly, this procedure is *not* the way individuals make their travel decisions, but it can produce an acceptable description of aggregate trip making.

TRANSTEP departs somewhat from the traditional four-step process by combining the first two steps. The result, however, is still a zone to zone O–D matrix of person trips which is the input to the mode split routines in the third step. The details are described in Nairn and Partners (1986).

It is worth noting, in passing, that the costs of trips between pairs of zones are stored in a cost matrix of the same order as the O–D matrix (for technical reasons, the cost matrix is often called a 'skim' matrix). The entry in row i and column j of the skim matrix records a measure of the cost of trips from zone i to zone j. Different cost measures are used for different purposes and at different stages of the calculations. For example, a skim matrix might record the distance (on the shortest route through the network) between each pair of zones, or the travel time (at free speed or in congested conditions), or a weighted average of the costs by private car and public transport.

Mode split (step 3)

In the third (mode split) step, the number of trips between each pair of zones (the entries in the O–D matrix) is allocated among the available modes. The modelling in this step is closer to the way individuals make their travel decisions in real life, and attempts to take account explicitly of the main factors thought to govern choice of transport mode: access time; frequency of service; need to transfer between routes; in-vehicle time; comfort; fares, overall travel time and vehicle operating costs.

The principal split sought at this stage is that between private car and public transport, but different choice structures can be accommodated. In this work, the person trip O–D matrix is first split into motorised and non-motorised trips. The proportion of non-motorised trips, representing walking and cycling, naturally falls off rapidly with trip distance. These trips are, therefore, primarily intra-zonal. The motorised trip matrix is then split

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2 The notion of generalised cost is used widely in transport economics, not always very precisely. Its main use is to provide an aggregate measure of all the cost components (including non-monetary costs) relevant to a particular analysis. In this work, the focus is on the costs taken into account in making travel decisions (whether to travel, where to travel, by what mode and by what route). The generalised cost includes vehicle operating costs, public transport fares and travel time.

between car and public transport trips. The entries in the car trip matrix may be divided by an average vehicle occupancy (which may be a function of trip length) so as to represent vehicle trips as required in the traffic assignment step. The public transport trip matrix continues to represent person trips.

Trip assignment (step 4)

The final step is to determine how all these trips will be accommodated by the road network and the public transport system. The routes of trips by both public transport and private car are selected to minimise some measure of generalised cost that can include fares, vehicle operating costs and tolls on particular routes, but is often dominated by travel time. In low traffic volumes, the preferred route for a trip is close to the shortest path through the network between origin and destination. But, as traffic volumes increase and congestion reduces speeds on preferred routes, trips may be diverted to routes of greater distance but shorter travel time.

The outcome of this fourth step, the so-called equilibrium assignment, is a pattern of traffic on the road network (and patronage of public transport services) such that all trips are made at minimum generalised cost. The assignment is said to be in equilibrium because no trip could be made by an alternative route at a lower generalised cost.

These patterns of traffic and public transport patronage are the principal outputs of urban transport models. Depending on requirements, it is possible to determine traffic volumes, speeds and the state of congestion on every link of the road network. These are the results considered in the next chapter.

Computation, feedback and iteration

Nothing has been said above about the details of the calculations. For the most part they are not necessary for an overview. However, one aspect of the calculations does need to be noted.

Traffic gives rise to congestion and delay. But we have also seen that delay (acting through travel time and the generalised cost of trips) is one of the factors that influence trip demand and mode choice, which together determine traffic volumes. The extent of this feedback is not known at the start of the model calculations, and it is therefore necessary to iterate through the whole process a number of times until consistent results are obtained.

In the first iteration, travel demand (as represented by the O–D matrix of person trips) and mode choice are determined on the assumption that trips will be made in traffic flowing at its free speed. Traffic assignment on this basis takes no account of congestion and, as a result, unreasonably high traffic volumes are assigned to some links. These high volumes imply very large delays. This reduces the demand for travel on these links in the second iteration, at the end of which improved estimates of traffic volumes and travel times are obtained. It is *not* obvious that this procedure must necessarily converge, and it is therefore common to use weighted averages of the travel times from the last two iterations as input to the next.

DATA AND CALIBRATION

Urban transport models contain large numbers of parameters. The basic behavioural parameters describing the propensity to travel and mode preferences are estimated from data obtained from detailed household travel surveys. Such surveys are expensive and are conducted only at infrequent intervals.

Land use information is obtained primarily from census data, supplemented from a variety of other sources.

Information on the road network and public transport services is usually obtained from the relevant State authorities, which are also the source of most of the data required for calibration.

A number of technical parameters are obtained from the academic and applied literature on traffic engineering and management. These include such items as: road capacities and free speeds on different types of road; speed-flow relationships, which describe the impact of congestion; and equivalence factors relating trucks and public transport vehicles to cars for the purpose of estimating congestion. There is considerable uncertainty about some of these parameters.

The models are calibrated by adjusting the parameters that specify travel behaviour until the model descriptions of urban travel patterns match reality as closely as possible. Calibration data are often difficult to obtain. Home interview surveys provide information on trip length distributions and mode splits. Traffic counts on the main arterial roads are generally available, although care is required to ensure that the period to which the data refer corresponds to the period modelled. In some cases, screen line data are available. Screen line data record the number of vehicles on all roads crossing a specified line during a specified period. Public transport authorities can provide additional mode split information, although again it is important to ensure that it refers to the period modelled.

Economic interpretations of the model results are often dominated by the value attributed to changes in travel time. Model predictions of traffic flow speeds would therefore seem to be important items for calibration. Unfortunately, reliable speed data for this purpose are rarely available.

LIMITATIONS OF URBAN TRANSPORT MODELS

There are three main weaknesses in the current generation of urban transport models.

Inadequate treatment of travel demand

The models possess all the obvious weaknesses associated with trying to construct useable simplifications of very complex systems. Broadly speaking, the treatment of travel demand (the first two of the four steps of the traditional process) is weak, while the treatment of mode split and traffic assignment is better. While there are simplifications and possibly errors in all the steps, the treatment of travel demand in the first two steps is just too aggregate to capture the behavioural richness of individual choice that governs urban travel patterns in real life.

Moreover, the treatment of demand is not in a form that lends itself to economic analysis. While the costs of travel on the road network can be consistently obtained by summing the costs incurred on individual links, the benefits of travel are inherently associated with travel (by whatever route) between particular origins and destinations. Strictly speaking, they cannot be obtained by summing the benefits of travel on individual links. The consequence is that analyses of transport model results that focus on costs incurred on links are theoretically sound (within the limits of the model assumptions), and can be used to derive congestion tolls as is done in chapter 4. On the other hand, the examination, in that chapter, of the equity effects of congestion tolls uses the notion of consumer surplus on each link, and is less soundly based.

This limitation of traditional transport models is being addressed in another BTCE project in which the Institute of Transport Studies at the University of Sydney is developing, under contract, a much more sophisticated model of urban passenger travel demand (BTCE–ITS 1993). Based on a new household travel survey in all the major Australian capital cities, the model will include an explicit treatment of the choice of: residential location; dwelling type; workplace location; work patterns (as they affect commuting); number and type of vehicles per household; vehicle use for different purposes; mode for the journey to work; and commuting departure time.

This represents a very substantial improvement in the treatment of urban travel demand. Pending its incorporation in routine urban transport models, the emphasis in this work is on those aspects of the current models that depend most strongly on step 4, the traffic assignment step.

Omission of freight transport

The current generation of urban transport models deal only with passenger travel. This is clearly an important limitation, and a variety of tactics have been adopted to get round it—if only partially. The simplest procedure is to calibrate the models against actual traffic volumes on the assumption that some fixed proportion (typically 5 to 15 per cent) is composed of freight vehicles. The further, usually implicit, assumption here is that freight and passenger traffic follow the same patterns. This is clearly wrong.

A slightly better procedure, if some information about freight traffic flows is available, is to pre-load the freight traffic onto the road network, and to conduct the analysis of passenger traffic flows against a constant background level of freight traffic. In this way, freight contributes to congestion and the other impacts of traffic, although it does not respond endogenously to changes within the model. The impact of freight policies can, however, be assessed by varying the freight traffic flows exogenously.

There appears to be no prospect, for the foreseeable future, of including a treatment of freight transport decision making in the models in the way that is done for passengers.

Focus on peak hour commuting travel

Urban transport models arose to meet the need for analysis to support investment decisions relating to urban transport capacity. As the demands on that capacity were greatest during peak hour commuting travel, it was natural that modelling should focus on this period and on the journey to work. With further growth in the demand for urban travel the inter-peak periods have filled in to some extent (though with different patterns of traffic flow) and, as a result, the peaks are not now so clearly distinguishable, nor is the journey to work so dominant a proportion of overall travel.

It is possible and, indeed, fairly common to set up the models to represent all-day travel. The problem with this is that the parameters are required to represent averages over even wider ranges of behaviour than is the case with peak hour modelling. Congestion phenomena, in particular, occur on a short time scale (where even the typical one hour-modelling period may be too long) and cannot be treated adequately in an all-day model.

When there is a requirement for estimates of aggregate costs or impacts on a whole-day or annual basis it would, in principle, be necessary to set up models specifically for each of the characteristic time periods and traffic patterns. Analytical resources and data usually do not permit this. The alternative is to scale the results from peak hour analyses, taking account of their special features so far as possible. There are obvious limits to the accuracy of such procedures.

CHAPTER 3 MELBOURNE TRAFFIC PATTERNS

The value for policy work of results from urban transport models is considerably enhanced if they can be presented in a way that is easy to understand and that brings out the essential features of urban traffic patterns. This chapter attempts to provide such a presentation.

The results are based on data provided for the TRANSTEP model by R. J. Nairn and Partners for the weekday morning peak hour (8 to 9 am) for Melbourne in 1988. The information on land use and the road and public transport networks dates from that year, but the information on household travel behaviour goes back to a survey in 1978. The overall data set has been re-calibrated for 1988, and should, therefore, adequately reflect travel and traffic patterns in that year.

On the other hand, model predictions based on substantial departures from the situation in 1988 (such as the introduction of a congestion toll) may be less well founded. However, it is a moot point whether the main limitation would be the deficiencies of this particular data set or the basic treatment of some aspects of travel behaviour in the model.

The figures in this chapter provide basic information about the roads, travel, travel time and delay on the Melbourne road network. The same presentation is used in later chapters in the discussions of congestion tolls and environmental impacts.

FORMAT OF THE FIGURES

The results are presented in a series of figures that are intended to bring out the variations in the spatial distribution of features of the traffic. A grid of 3 km by 3 km cells is overlaid on the Melbourne road network. In each cell, quantities representing characteristics of the traffic on roads passing through that cell are plotted vertically. The figures provide perspective views of the three-dimensional plots as seen from the south-west—looking towards the city from a position roughly over Geelong.

Source R. J. Nairn and Partners TRANSTEP data

Figure 3.1 TRANSTEP Melbourne road network

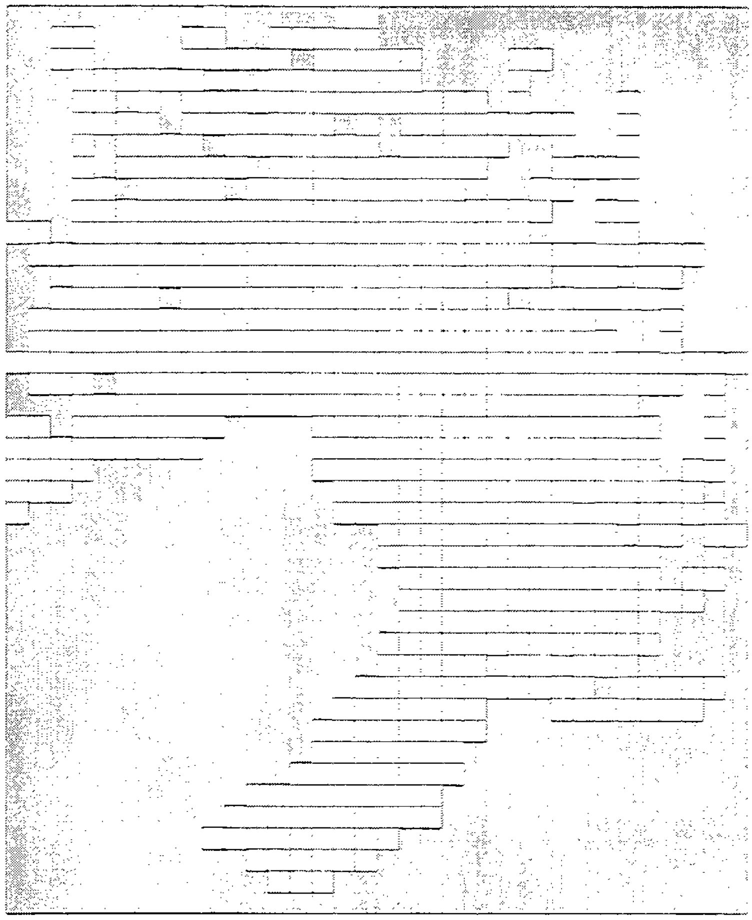


Figure 3.2a **3kmx3km grid over the Melbourne urban network**

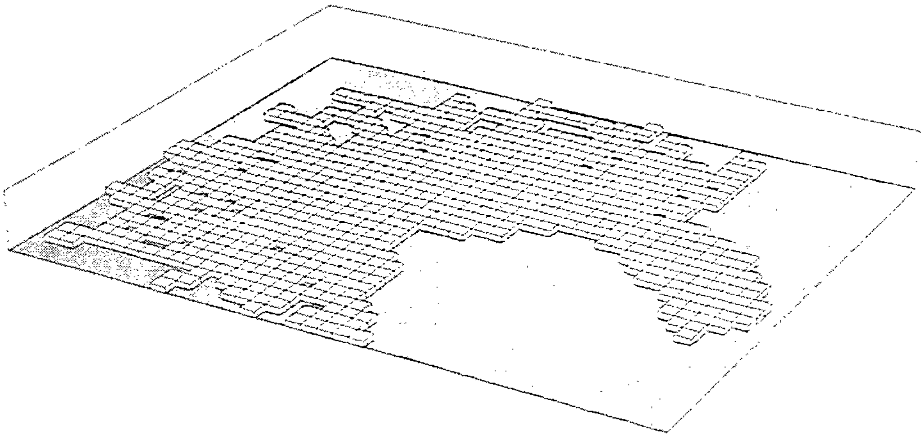


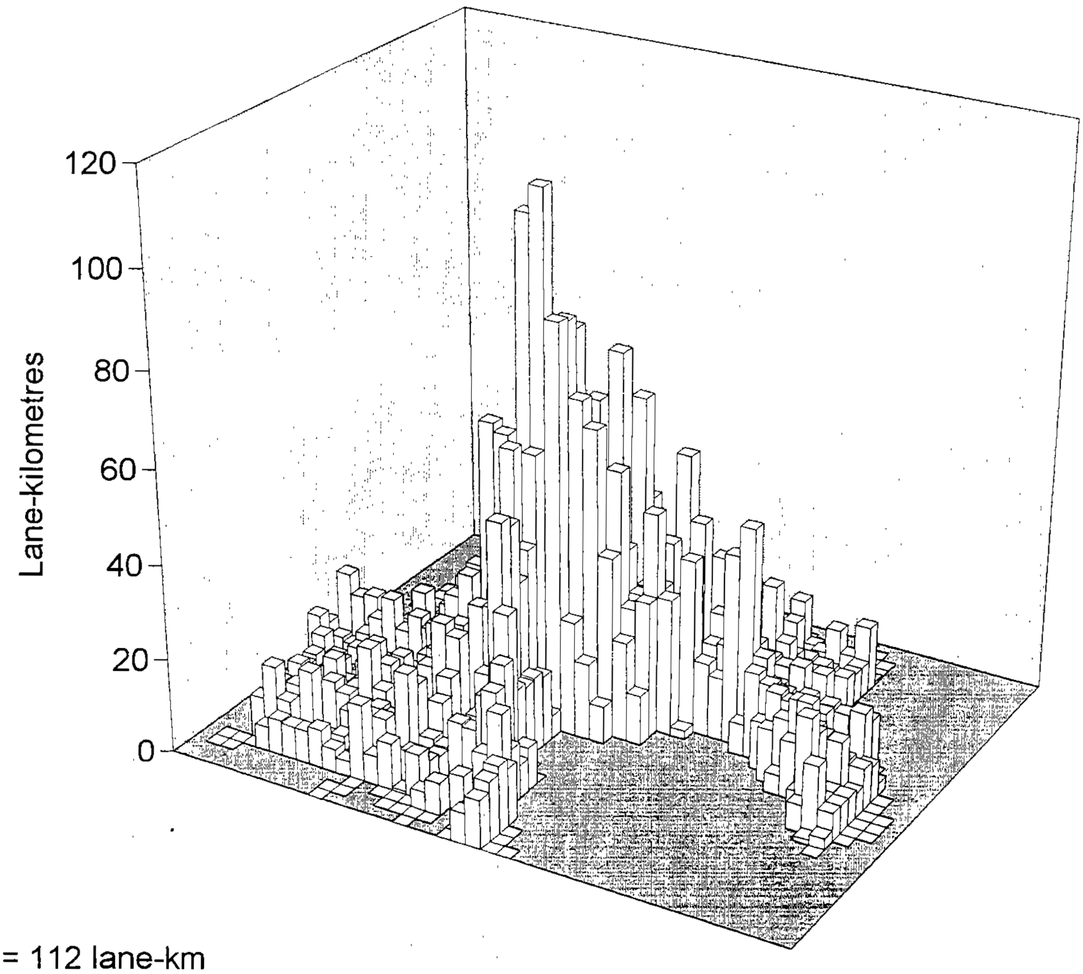
Figure 3.2b **View of Melbourne grid from south-west**

Figure 3.1 shows the road network, and figure 3.2 is an aid to interpreting subsequent figures. Figure 3.2 shows (a) the grid on which traffic characteristics are plotted; and (b) the perspective view from the south-west.

BASIC TRAFFIC CHARACTERISTICS

Figures 3.3, 3.4 and 3.5 show the distributions of roads, travel and travel time as calculated by TRANSTEP for the Melbourne weekday morning peak hour in 1988.

Figure 3.3 shows the distribution of roads in the network in terms of lane-kilometres in each grid cell. The maximum is 112 lane–km (per 9 km^2 cell); the total for the whole network is 9 304 lane–km.

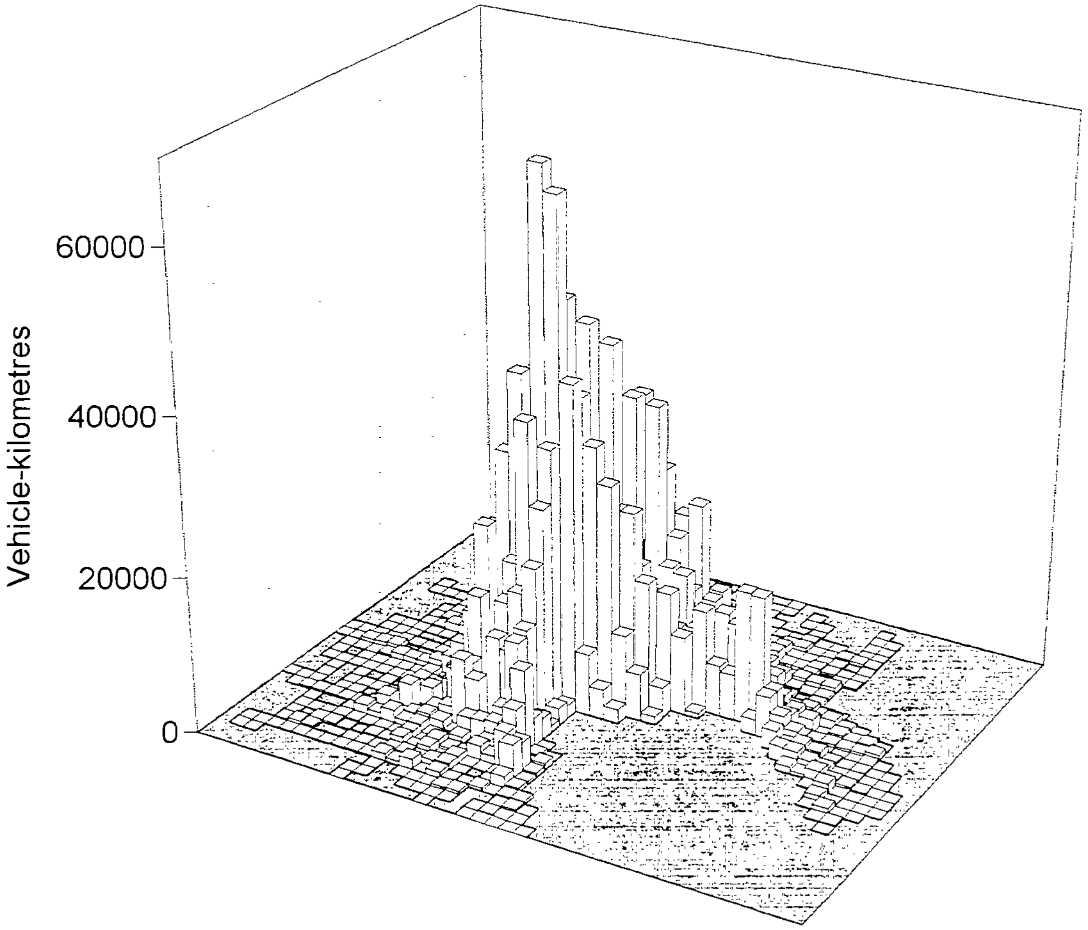


Max = 112 lane-km
Total = 9304 lane-km

Source BTCE estimates.

Figure 3.3 Distribution of roads

Figure 3.4 shows the distribution of travel during the weekday morning peak hour. Travel density reaches a maximum of 67 090 veh–km per cell; total travel on the network during the hour is 3 160 020 veh–km.

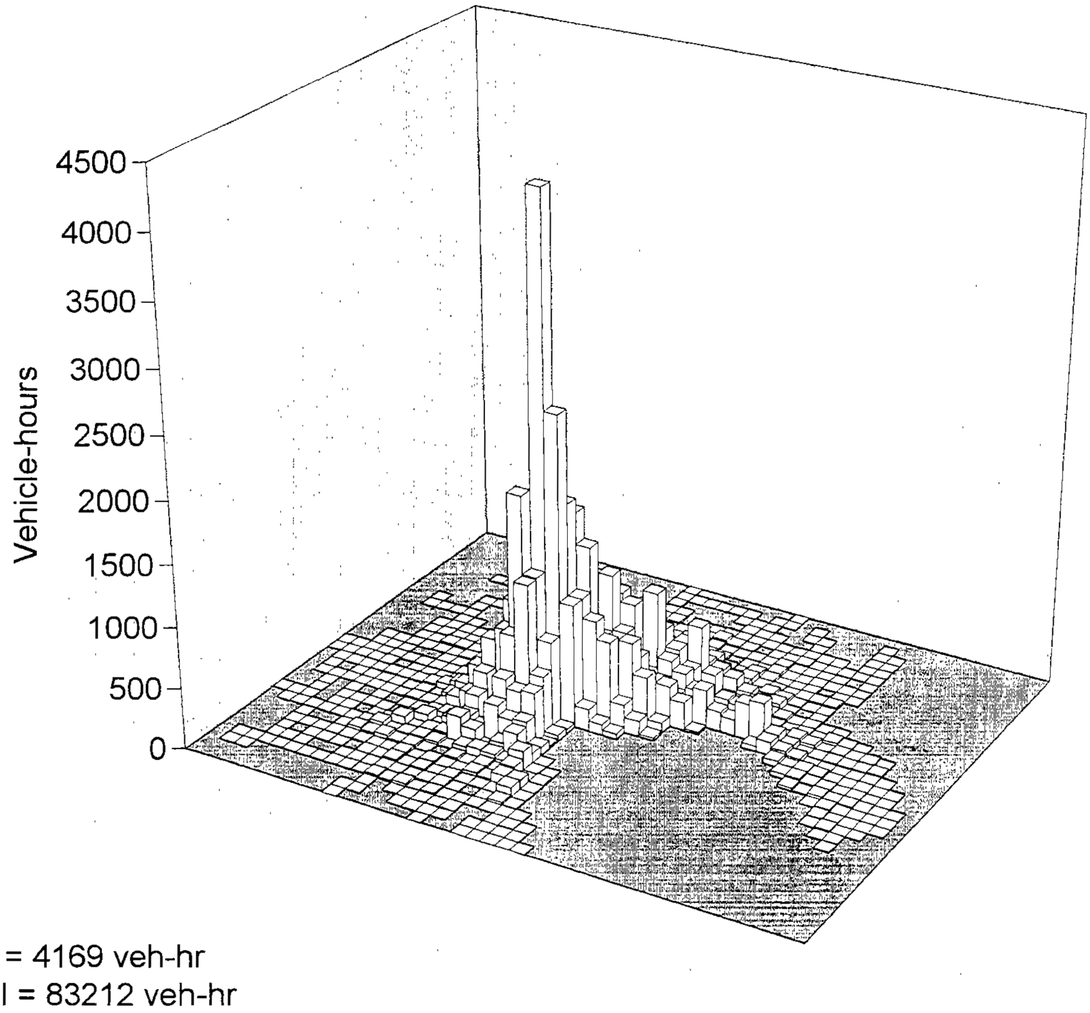


Max = 67090 veh-km
Total = 3160020 veh-km

Source BTCE estimates.

Figure 3.4 Distribution of travel

Figure 3.5 shows the distribution of travel time in vehicle–hours per cell. The concentration near the centre (half the total travel time is spent in 34 cells) reflects the lower speeds due to congestion. The maximum in any cell is 4169 veh–hr; and the total travel time 83 212 veh–hr.



Source BTCE estimates.

Figure 3.5 Distribution of travel time

MEASURES OF CONGESTION

Not all travel time is avoidable. If the unavoidable time associated with travel at the free speed in uncongested conditions is subtracted from total travel time, the remainder can be considered as delay due to congestion.

The total delay suffered by all travel during the morning peak hour is 29 872 veh–hr. At $15 per vehicle–hour (see chapter 4), this would represent a congestion cost of about $0.45 million for travel during the hour. As noted at the end of chapter 2, this figure can be scaled to give an indication of the daily and annual congestion costs.

Edwards (1994) reports preliminary results of the Victorian Activity and Travel Survey (conducted by the Transport Research Centre at the University of Melbourne), which show the distribution of traffic throughout the day. Peak periods are not easy to distinguish as, with the exception of a small dip in the early afternoon, traffic is fairly constant throughout the working day (7 am to 6 pm), with about 7.5 per cent of daily trips made in each hour. If we assume that congestion costs are constant and limited to this 11–hour period, we obtain an estimate of about $5 million per weekday.

The daily cost can be converted to an annual cost by using a further scaling factor of 260. This procedure suggests that congestion costs in Melbourne are of the order of $1300 million per year. This is somewhat lower than the estimates of Miles (1992) and Luk (1994) which are discussed in chapter 4. The difference is most likely to be due to the omission, in this estimate, of the effect of congestion on vehicle operating costs, and to the restriction to weekdays.

Figure 3.6 shows the distribution of delay due to congestion. The comparison between figures 3.5 and 3.6 shows that most of the broad 'skirt' in the travel time distribution is associated with unavoidable running time, and that almost all the delay is experienced close to the city centre. In fact, just 18 cells account for half the total delay.

Table 3.1 summarises the peak hour traffic conditions.

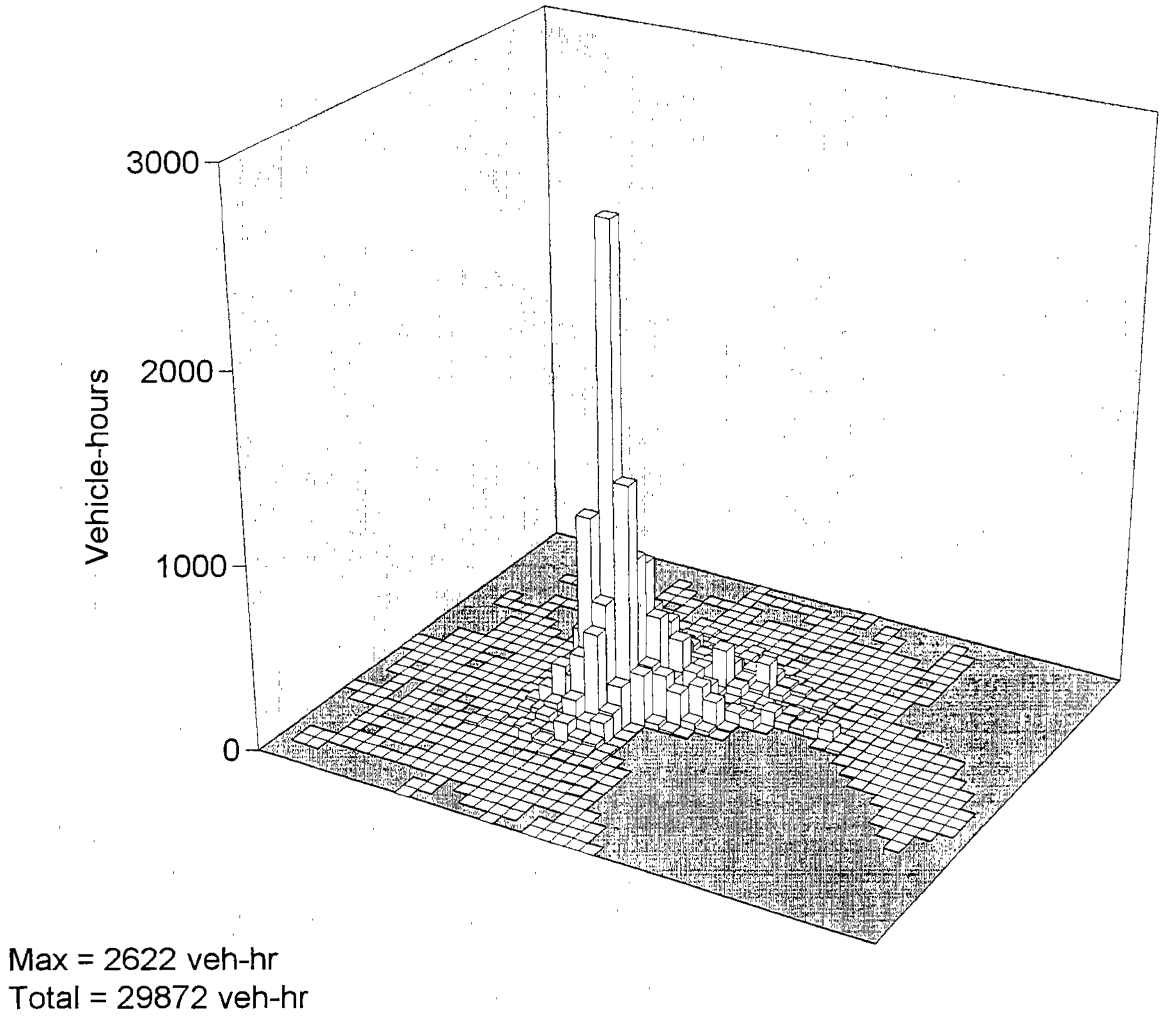
TABLE 3.1 SUMMARY OF MODEL ESTIMATES OF PEAK HOUR ROAD AND TRAFFIC CONDITIONS—MELBOURNE 1988

	Network[a]	*Extreme value*[b]
Road (lane–km)	9 304	112
Travel (veh–km)	3 160 020	67 090
Travel time (veh–hr)	83 212	4 169
Delay (veh–hr)	29 872	2 622
Average speed (km/hr)	38.0	16.1

a.Totals (or, for speed, the average) for the whole network, excluding centroid connectors.

b.The extreme value in any ($9km^2$) cell; generally the maximum but, for speed, the minimum.

Source BTCE modelling results.



Source BTCE estimates.

Figure 3.6 Distribution of congestion delay

CHAPTER 4 THE ECONOMICS OF CONGESTION

THE VALUE OF TRAVEL TIME

Figure 3.6 provides a measure of the impact of congestion in terms of delay or lost time in Melbourne. In highly congested conditions, delay accounts for the greater part of the cost of congestion. But it is not the only cost; and, in order to reach the conclusion that it *is* the greater part, it is necessary to be able to compare the time losses with other impacts of congestion such as increased vehicle operating costs and air pollution.

This comparison is based on monetary valuations of the various impacts and requires a value of time.

Determining the value of time is a complex and controversial exercise on which there is a vast literature. It will be necessary, in the course of this project, to make a considered determination of the value of time, but this has not yet been done. For the purposes of this paper, an illustrative value has been chosen, close to that recommended by the NSW RTA (1993) for the economic analysis of peak hour traffic conditions.

The value of time chosen is $15 per vehicle–hour.

THE COST OF CONGESTION

Table 4.1 shows some recent estimates of the costs of congestion in Australian cities.

All these estimates are based on the difference between the total costs of the travel actually undertaken in congested conditions and the costs estimated for

TABLE 4.1 THE COST OF CONGESTION IN AUSTRALIAN CITIES

City	Annual cost of congestion ($ millions)	Value of time: Private car ($/veh–hr)	Value of time: Business car ($/veh–hr)	Value of time: Light truck ($/veh–hr)	Value of time: Heavy truck ($/veh–hr)	Source
Sydney	2 000	7[a]	43	17	–	Commeignes
Melbourne	2 000	6	36	17	13	Miles
Sydney	2 080	7	41	–	–	Luk
Melbourne	1 820	7	41	–	–	"
Brisbane	400	7	41	–	–	"
Perth	368	7	41	–	–	"
Adelaide	275	7	41	–	–	"
Canberra	105	7	41	–	–	"
Hobart	42	7	41	–	–	"
Darwin	24	7	41	–	–	"

a. Commeignes gives value of time for private travel in $ per person–hour

– not applicable

Sources Commeignes (1992); Miles (1992); Luk (1994).

hypothetical uncongested conditions.[1] This definition is the same as that used in chapter 3 to obtain the estimate of $1300 million per year for the cost of congestion in Melbourne (scaled from $0.45 million for the cost of congestion during weekday morning peak hour travel).

The definition has the merit of having as its reference point a relatively well–defined state of zero congestion. However, it is important to note that there is no implication that zero congestion is a possible or desirable goal for policy. In this respect, the 'cost of congestion' must be carefully distinguished from the 'cost of doing nothing about congestion'–a quite different notion, which is discussed later in this chapter.

The hypothetical state of zero congestion is only *relatively* well defined. Appendix I discusses alternative assumptions that can be made about what the traffic patterns would be like if there were no congestion. The alternative assumptions lead to different estimates of the cost of congestion; though, in view of the other uncertainties in these estimates, the differences are unlikely to be of great importance.

MARGINAL DELAY AND CONGESTION TOLLS

A definition of the cost of congestion based on the difference between current and hypothetical uncongested conditions is easy to understand, and appears to be a natural measure of the scale of the problem. Unfortunately, from the point of view of policy, it is a dead end. Eliminating congestion is not possible, and the cost of congestion, estimated in this way, provides no pointers to an improved use of the road network. Moreover, it is a measure of *total* cost. The proportion of this cost that represents an economic *externality* (that is, the proportion not taken into account in travel decision making) is rarely considered.

The standard economic analysis of congestion provides an alternative measure of the scale of the problem. The theory is well known (see, for example, Small (1992)), though attempts to quantify the relevant supply (cost) and demand (benefit) curves are rare. Part of the problem has to do with the differences between individual road links and networks. The theory can be clearly stated for individual links where traffic response parameters and the 'commodity' in demand (passage along the link) are well defined. Both are less well defined on networks. In particular, it becomes difficult to specify the 'commodity' in demand on a network when routes, origins and destinations may all change in response to congestion costs.

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[1] The components of total travel costs considered are usually limited to travel time and vehicle operating costs because these are assumed to be the only ones affected by congestion.

Urban transport models deal with these network complexities and provide results at the individual link level. The theory can therefore be applied rigorously using the individual link results and, at least for costs, the relevant economic quantities aggregated as required for whole network considerations. However, as noted in chapter 2, benefits cannot strictly be aggregated in this way. Nevertheless, some indicative results can be obtained.

Marginal delay under current congestion

Figure 4.1 is the diagram typically used to present the theory. It describes the supply and demand for travel on a single link. A similar diagram could be drawn for each link of the network. In principle, the ordinate is some measure of generalised cost that includes operating and other costs as well as time. However, it simplifies the presentation to focus on time.

Figure 4.1 is a schematic diagram, and the shape of the supply or cost curves represents only the fact that the costs increase with traffic and (consequently) the marginal cost curve is above the average. The detailed shape of the curves depends on road type. Appendix II lists the road types and discusses the effect on the shape of these curves of the different mechanisms of speed reduction due to congestion. By way of illustration, figure 4.2 shows the average and marginal travel time curves for freeways and for streets in the CBD.

The average travel time curve is given by equation II.1 in appendix II. Because it gives the (expected) travel time for individual vehicles, it represents the *private* cost, and is the basis for decision making—in this case, whether to use this particular link. This accords with its use for traffic assignment and the calculation of trip times in the model.

At any given level of traffic, a vehicle joining the traffic stream contributes its own travel time to the total for all vehicles. However, by joining the stream it also exacerbates the congestion and imposes additional delay on other vehicles. The marginal vehicle's contribution to total travel time (the marginal *social* cost) may therefore be very much greater than the average or expected travel time (the marginal *private* cost) which was the basis of the travel decision. The marginal travel time curve in figure 4.1 is the derivative, with respect to traffic, of total travel time. It is given by equation II.2 of appendix II.

Demand for travel on the link is, of course, a much more complicated matter. It depends on the basic demand for travel, on mode choice, and on the availability of (and congestion on) other links. While the models deal with all these issues, it is not possible to plot out the demand curve as a simple function of traffic on the link. But the models *do* tell us the equilibrium traffic

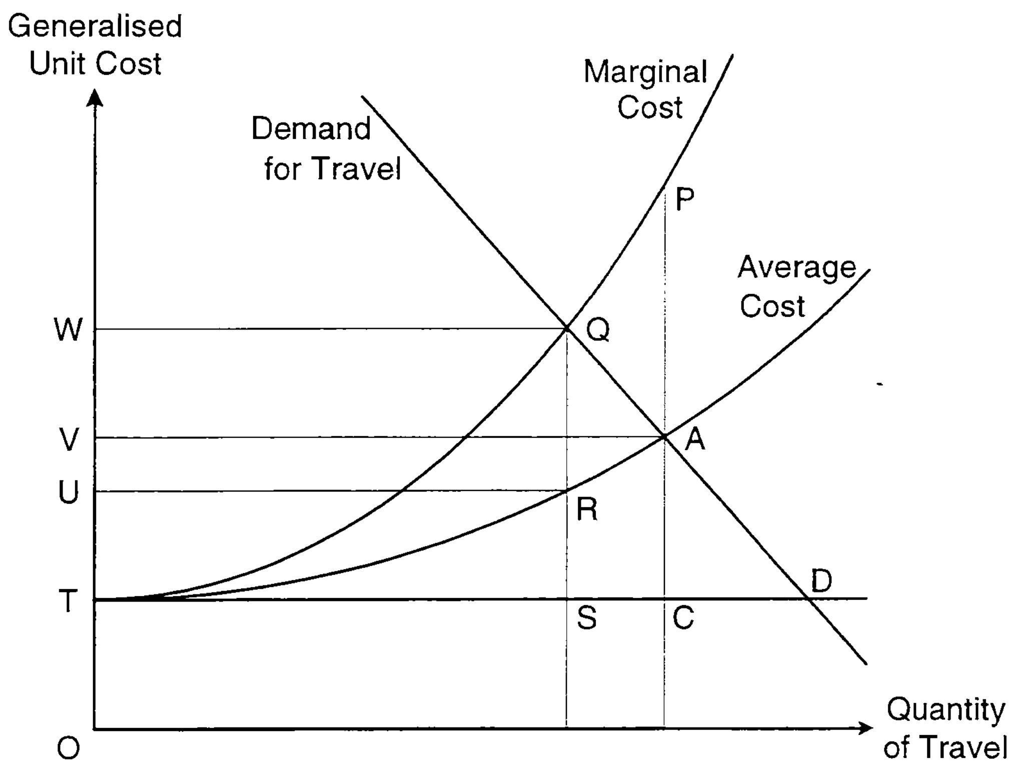
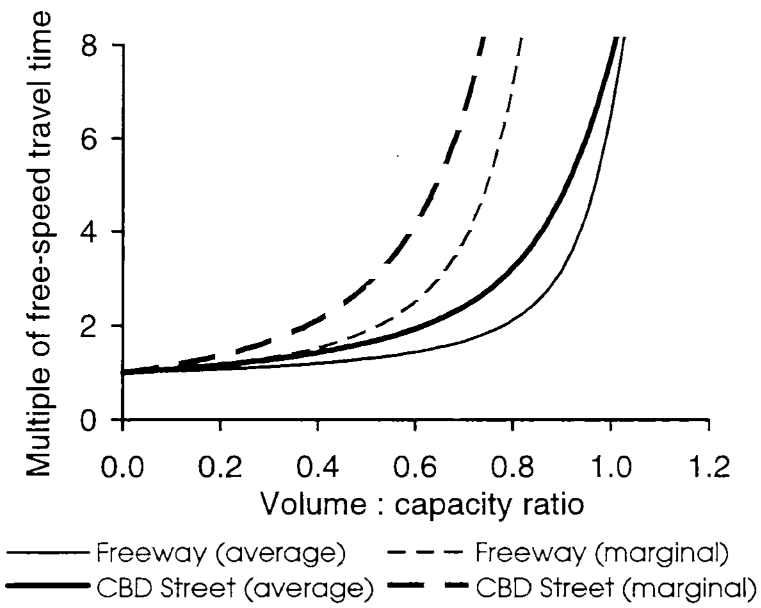
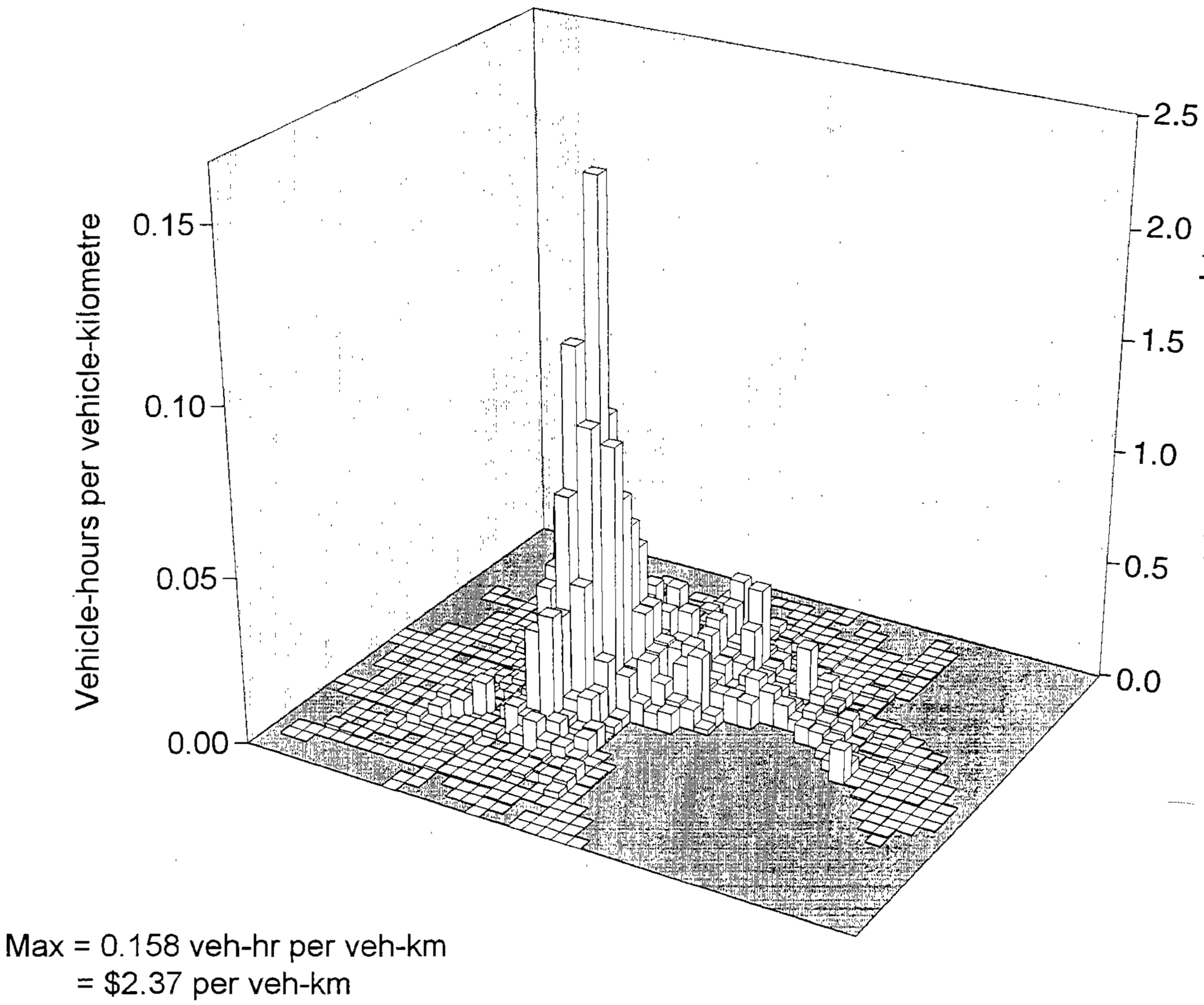


Figure 4.1 Economic analysis of congestion



Source BTCE estimates

Figure 4.2 Average and marginal travel time curves for different road types



Source BTCE estimates.

Figure 4.3 Distribution of marginal external delay

flow on each link, in other words, where the demand and supply (or average travel time) curves cross—at the point A in figure 4.1.

Given the volume of traffic on each link, the marginal travel time (the social cost) can be determined from equation 2 of appendix II–the point P in figure 4.1. The quantity AP might be called the *marginal external delay* and represents the external cost (per veh–km) that the marginal road user imposes on others.

Figure 4.3 shows the distribution of marginal external delay for Melbourne. Note that, unlike the previous figures where the quantity plotted was the *total* for the cell in question, in this figure the quantity is the marginal external delay *averaged* over the travel in the cell. High marginal external delays are concentrated near the city centre and, in the most congested cell, rise to over

9 veh–min per veh–km (0.158 veh–hr per veh–km). [2] If this is converted into monetary units using a value of travel time of $15 per veh–hr (RTA 1993), it corresponds to a component of travel cost (at the margin) of $2.37 per veh–km that is entirely ignored by individuals making travel decisions. This value is a cost under current traffic conditions—*but it is not the recommended level for a congestion toll.*

The external component of the cost of congestion

The cost of congestion discussed previously is the value of the *total* delay due to congestion. However, not all of this cost is borne externally. Travel time is, after all, assumed to be a major influence on travel decisions, and so some component of this cost must be borne internally.

Appendix III discusses the degree to which congestion delay is borne externally.

The *external* component of congestion delay is represented by the area between the marginal and average travel time curves (the area TQPAR in figure 4.1). This quantity can be determined for each link and summed to give the external component of congestion delay for the whole network. As compared with the estimate of the total delay during the morning peak hour of 29 872 veh–hr, the external component amounts to 19 844 veh–hr, or about 66 per cent.

Modelling traffic flows under an 'optimal' congestion toll

The rationale for congestion tolls is that they would ensure that the only travel undertaken would be that for which the benefits exceeded the costs—including the costs of additional delay imposed on other road users. Such travel, and the associated traffic flows, could be said to be 'socially optimal' in the sense of welfare economics.

Urban transport models, of course, have been designed to simulate actual travel behaviour as closely as possible. At the level of traffic assignment and route choice, it is generally assumed that travellers try to minimise their expected travel times under the prevailing conditions—that is, they make their decisions on the basis of the average travel time curve in figure 4.1. This is probably one of the more robust of the assumptions in the models.

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[2] In other words, an additional vehicle joining this traffic stream imposed extra delay on other vehicles amounting to 9 veh-min on for every kilometre it travels. The extra delay may be only a few seconds for each vehicle but, summed over all the affected traffic, it amounts to 9 veh-min.

It is, however, possible to simulate the traffic flows that would result if travellers' decisions also took account of the delay imposed on other travellers. All that is required is that, in the traffic assignment step of the modelling process, the calculation of the travel time associated with each link should be based on the *marginal* rather than the *average* travel time curve in figure 4.1.

The resulting traffic flows are those that would be obtained if travel decisions *did* take account of congestion costs imposed on others. In terms of a single link as represented in figure 4.1, this amounts to determining where the demand curve crosses the marginal travel time curve—that is, to establishing the point Q. *This* is the 'optimal' volume of traffic for the link (taking account of the demand for travel and traffic volumes on all other links), and the theory suggests that traffic could be limited to this level if a congestion toll equal to the value of the difference, QR, between the average and marginal travel time curves were levied on the link.

Figure 4.4 shows the distribution of this theoretical congestion toll with the assumed value of time of $15 per veh–hr (averaged over all the travel in each cell, as in figure 4.3). It rises to a maximum of about $0.50 per veh–km (0.032 veh–hr per veh–km) in the most congested cell. The 28 most congested cells, in which the toll is above $0.15 per veh–km, account for over half the total toll revenue. The revenue from this toll for the whole network during the peak hour is about $290 000 (19 474 veh–hr).

Table 4.2 summarises the impact of the 'optimal' congestion toll.

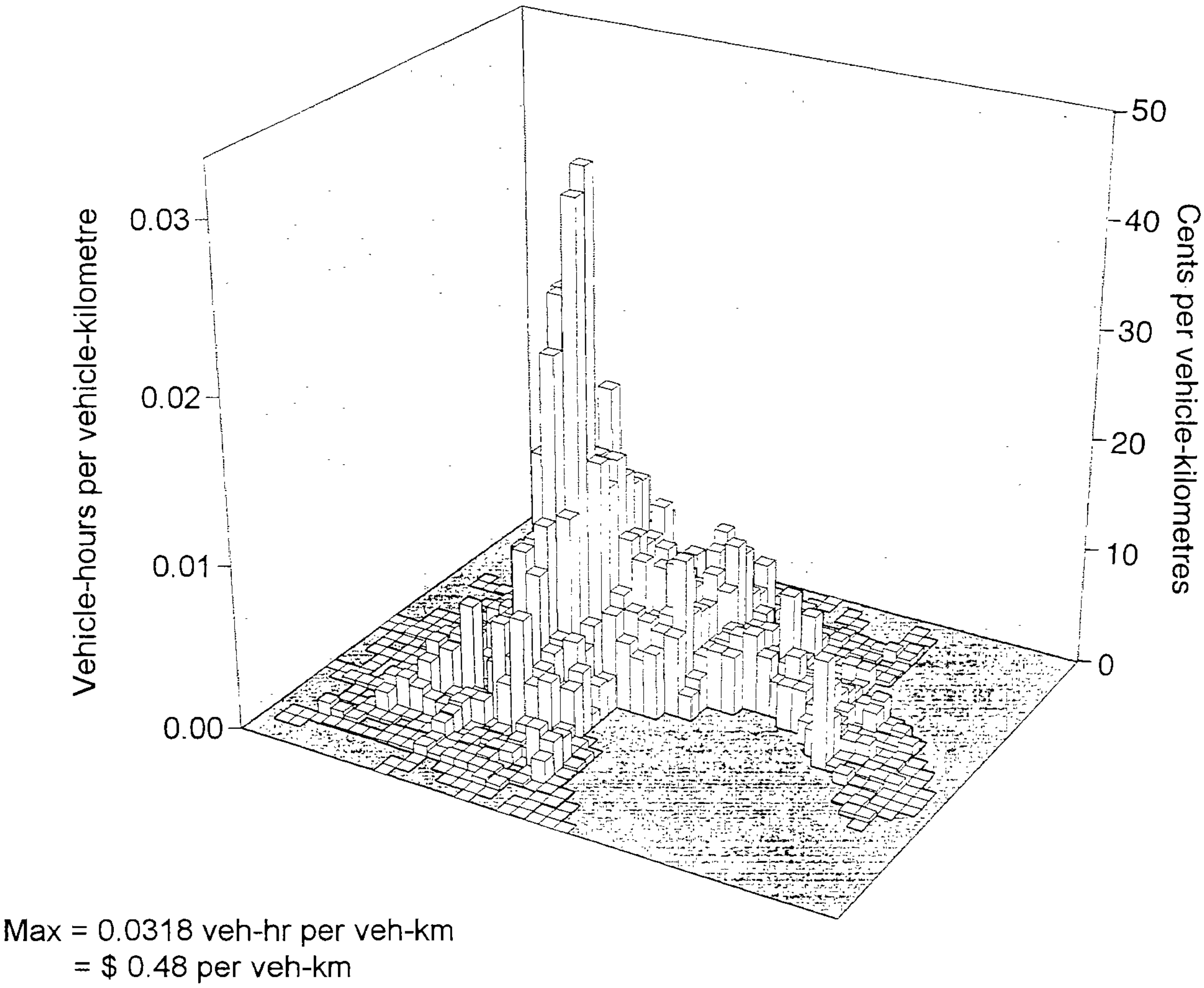
TABLE 4.2 IMPACT ON AGGREGATE TRAFFIC CHARACTERISTICS OF 'OPTIMAL' PEAK HOUR CONGESTION TOLL

Traffic characteristic	*No toll*	*'Optimal' toll*	*Change (per cent)*
Travel (veh–km)	3 160 020	2 451 746	– 22
Travel Time (veh–hr)	83 212	52 085	– 37
Delay (veh–hr)	29 872	10 804	– 64
Speed (network average) (km/hr)	38.0	47.1	+ 24
Speed (slowest cell) (km/hr)	16.1	27.3	+ 70
Toll revenue ($)[a]	0	292 110	–

a. Assuming a value of time of $15 per veh–hour.

— not applicable

Source BTCE modelling results.



Source BTCE estimates.

Figure 4.4 Distribution of theoretical congestion toll

CONGESTION TOLLS AND EQUITY

One of the principal objections to congestion tolls is that the overall net benefit is obtained at the expense of a transfer of welfare *away* from those who bear the costs of congestion. The strength of this objection depends primarily on the relative magnitudes of the transfer and the net benefit. Other important factors are the homogeneity of the traffic (in terms of value of time and contribution to congestion), and how it is proposed that the toll revenue should be employed.

Evans (1992) has considered this question. His treatment has been criticised (Hills 1993; see also Evans 1993) for reasons that included the deficiencies in the treatment of travel demand that were mentioned in chapter 2. The problem is the ambiguity in the choice of vehicle–kilometres or number of trips as the measure of the quantity of travel. Vehicle–kilometres are convenient at the link level when considering how travel and congestion costs are incurred, but people's demand is for trips, and even the nature of the trips in demand may change with the level of congestion. These problems are bypassed in Evans's work, which is restricted to travel with a fixed origin destination pattern.

Our work is not restricted in the same way, but there are still difficulties in relating demand for travel on individual links to the more basic demand for trips. The essential problem is that the demand function for travel on an individual link depends on the traffic levels on all other links. The models correctly (within the limitations of their assumptions) estimate the traffic levels on each link, and therefore identify the points A and Q in figure 4.1. Each of these points is the intersection of a demand curve with the average (at A) or marginal (at Q) travel time curve. But the demand curve passing through A is not the same as the one passing through Q, and estimates of consumer surplus based on the assumption that it is are not strictly valid. Nevertheless, pending the incorporation of a more sophisticated treatment of demand in urban travel models, Evans's approach probably provides an acceptable indication of the scale of the equity consequences of congestion tolls.

Evans regards the total benefit (B) of the road network as being composed of the consumer surplus of users (S) and the revenue from any congestion tolls (R). Starting from the current situation with no tolls (B = S; R = 0), introduction of the toll leads to a benefit gain (ΔB) which is the sum of the changes in consumer surplus (negative) and revenue (positive).

$$\Delta B = \Delta S + \Delta R$$

The approach can be applied to individual links and the results summed to provide network-wide measures. Referring to figure 4.1:

- the loss in consumer surplus, ΔS, is given by the area WQAV;
- the gain in revenue, ΔR, is given by the area WQRU; and
- the benefit gain, ΔB, is the difference between these two areas and can be shown to be equal to the area APQ (which is where economists would normally look for a net change in welfare).

While the theoretical benefit gain is always positive, Evans notes that it is unlikely to be politically acceptable to strain after a small benefit gain at the expense of a large transfer of welfare away from road users. His initial analysis considers the case of homogeneous traffic (in which all vehicles have the same value of time and contribute equally to congestion) and uses the relative magnitudes of ΔB, ΔS and ΔR to examine the circumstances under which congestion tolls are likely to be acceptable.

Public acceptance of congestion tolls is likely to be enhanced if a substantial benefit gain (ΔB) can be obtained for a relatively modest loss of consumer surplus (ΔS). High values of the ratio $\Delta B/\Delta S$ might therefore provide an indication of acceptability. For the network as a whole during the peak hour, the net benefit from the congestion toll is made up of the toll revenue of \$292 110 (19 474 veh–hr), less the loss in consumer surplus of \$145 680 (9712 veh–hr). The net benefit is therefore \$146 415 (9761 veh–hr), about equal to the consumer surplus loss. Whether this ratio of net benefit to welfare transfer is acceptable is not, of course, an economic question.

Mixed traffic and the use of toll revenue

Evans (1992) also considers the case of mixed traffic, in which vehicles have different ratios of value of time to their contribution to congestion. He shows that vehicles whose value of this ratio is (sufficiently) above the average can, in fact, benefit from congestion tolls. The obvious examples are public transport vehicles such as buses, whose contribution to congestion might be 3 to 5 times that of a private car, but whose value of time (when full) might be 20 or more times that of a car.

This observation is independent of the use made of the toll revenue, but it fits in well with the view that toll revenues that exceed infrastructure provision costs should be seen as a signal of the need for additional capacity—and be used for that purpose. The capacity in question, of course, is that of the urban transport system *seen as an integrated whole*, and consisting of *both* the road *and* public transport networks.

The use of toll revenues will, of course, be an important consideration for the political acceptability of congestion tolls—but these questions are beyond the scope of this paper.

THE COST OF DOING NOTHING ABOUT CONGESTION

The net benefit discussed above provides an alternative measure of the scale of the congestion problem.

According to the theory, society would obtain the maximum possible benefit from the road network if the volume of traffic on each link were limited to that which corresponds to the point Q in figure 4.1—and this could be achieved by introducing a congestion toll corresponding to the value of the time difference QR. The benefit gain in this situation (as compared with the current situation in which the traffic volumes correspond to the point A) is represented by the area APQ in the figure.

Unlike the 'cost of congestion' discussed earlier, this measure of the scale of the problem is of considerable policy relevance because there is a serious possibility of obtaining these benefits. Not to attempt to do so is an opportunity forgone, and can be described as the 'cost of doing nothing about congestion'.

The relationship between the two measures is shown in figure 4.5. The 'cost of congestion' (the value of the losses as compared with a hypothetical situation of zero congestion) is represented by the area VACT. It will be recalled from chapter 3, that the aggregate cost for the whole network (that is, the sum for all links), measured in this way, was found to be $0.45 million.

The 'cost of doing nothing about congestion' is represented by the area APQ. The corresponding aggregate cost for the whole network is $0.15 million.

The two 'costs' provide alternative measures of the scale of the congestion problem. It is likely that the 'cost of doing nothing about congestion' would be a larger proportion of the 'cost of congestion' if the estimates were made only for the congested central areas (which could be serious candidates for congestion tolls) rather than for the whole network.

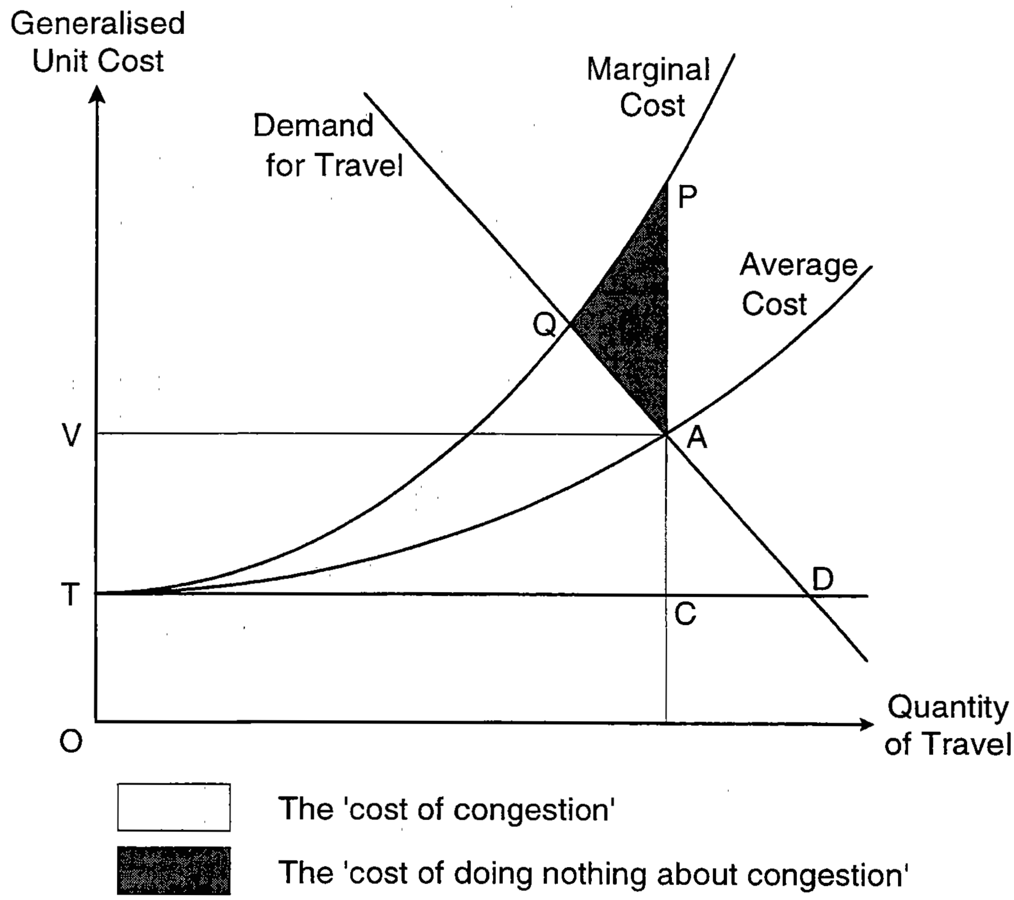


Figure 4.5 The 'cost of congestion' and the 'cost of doing nothing about congestion'.

CHAPTER 5 ENVIRONMENTAL STRESS AND IMPACTS

Traffic was described, in chapter 1, as the underlying cause of all the main external impacts of urban transport. Figure 1.1 showed the causal connections. Chapters 3 and 4 showed how urban transport models can be used to estimate traffic flows and congestion, taking into account the feedback between them.

These traffic flow estimates can, in turn, be used as the basis for estimating environmental stress and, in some cases, impact.

The distinction between stress and impact is not always clear, but it is important as it can have consequences for mitigation policies. It is best illustrated by example.

Road vehicles emit a variety of substances to the atmosphere. These substances have a wide range of effects, but we can focus on the consequences for human health as one of the main concerns. The causal chain between vehicle emissions and health effects is a long and complicated one involving

- atmospheric chemistry—primary emissions may be converted to other substances by reactions in the atmosphere;
- meteorology—primary emissions and their secondary products may diffuse or be blown around the city, causing air pollution at sites remote from their sources—or they may be washed from the atmosphere by rain (possibly causing water pollution at some other site);
- human customs and behaviour—people's exposure to air pollution depends on time spent indoors, outdoors and in vehicles, and on their level of physical activity; and
- physiology—this governs the health effects of exposure to different levels of pollutants.

In this example, the primary vehicle emissions constitute the *stress,* which is mediated by the environment, eventually giving rise to an *impact* on human health. While there certainly is a relationship between stress and its impact, it may be a very complicated one. Simplifying assumptions may sometimes be made, but for the purposes of this paper it would not be appropriate to describe the emission estimates as a measure of environmental impact.[1]

In the case of noise, however, the relationship between the stress and its impact is more immediate and the distinction between the two less important. Estimates of traffic noise can therefore be used as a measure of the environmental impact.

The basic assumption, in all cases, is that the environmental stress or impact can be expressed as a function of the traffic characteristics estimated by the urban transport model. These are, for each link of the road network,

- traffic volume;
- traffic speed;
- volume-capacity ratio, which can be interpreted as a measure of driving smoothness; and
- information about the mix of vehicle types.

Quantities that can be given as functions of these traffic characteristics include

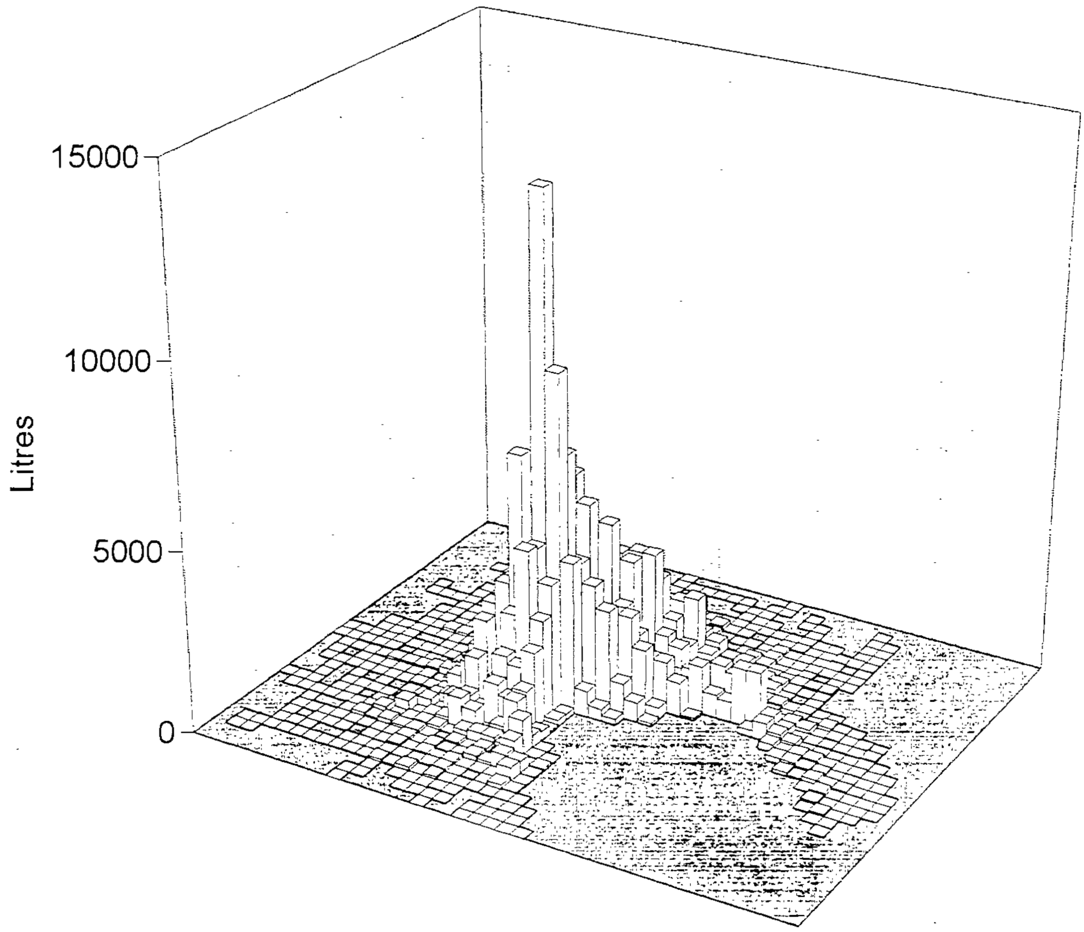
- fuel consumption (and associated carbon dioxide emissions);
- noise; and
- noxious vehicle emissions, in particular hydrocarbons and nitrogen oxides which are ozone precursors, and particulate emissions primarily from diesel engines.

By way of example, fuel consumption can be considered with the aid of a function derived from the NSW Road and Traffic Authority VEHOP program. Consumption (c, in litres per kilometre) is given as a function of speed (v) and volume-capacity ratio (x) by

$$c = (26.67 + 1433.8/v + 0.000508.v^2)(1 + x)/1000$$

Figure 5.1 shows the distribution of fuel consumption. Carbon dioxide emissions would be roughly proportional to the fuel consumed. There is, of course, little interest in the *distribution* over the network of fuel consumption and carbon dioxide emissions, for which the *totals* are the relevant quantities. However, the distribution would be important for the presentation of noise results, and for the adequate consideration of noxious vehicle emissions.

[1] It should be noted, in passing, that the 3 km by 3 km grid used here for displaying traffic characteristics and consequences is compatible with the air-shed models used in a number of Australian cities. These models provide estimates, at this resolution, of the consequences for air quality of mobile (traffic) and stationary (industry, power stations) sources of emissions.



Max = 13800 litres
Total = 344989 litres

Source BTCE estimates.

Figure 5.1 Distribution of fuel consumption

CHAPTER 6 CONCLUDING REMARKS

THE CONTEXT FOR CONGESTION TOLLS

The theoretically 'optimal' congestion toll and its variation over an urban road network, which were estimated in chapter 4, serve to illustrate the application of urban transport models to the analysis of congestion. It is important to emphasise the preliminary nature of this work, and the limited accuracy that can be expected from even the best available models.

This work does not constitute a presentation of the case for congestion tolls. The theoretical case is well known, but the practical implementation would require a more extensive analysis than has been presented here. In particular, the analysis would need to cover both peak and off-peak periods; the urban transport system would need to be treated as an integrated whole[1] consisting of both the road and public transport networks; and the use to be made of toll revenues would have to be considered.

Mayo (1989) discusses the pricing of congestible facilities. Although he is concerned with pricing policy for government trading enterprises, some of the principles are relevant to urban transport (including road) pricing. The main points are that

- pricing should take account of demand variations between peak and off-peak periods and should be based on full marginal social cost. (In the urban transport situation, this would include the external costs of delay imposed on others);
- peak period revenues may be used to subsidise off-peak use, the price differential between peak and off-peak periods serving as an incentive to users to reschedule their demand; and
- if revenue from pricing determined in this way exceeds the cost of providing and maintaining the facility, the excess serves as a signal of the need for additional capacity.

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[1] Our analysis *does* treat the urban transport system as an integrated whole. Indeed, that is the main advantage of using urban transport models. However, the presentation in this paper has not drawn on the public transport results.

It is in relation to the last two points that the need to take an integrated view of the urban transport system is most important. There is a long history of attempts to solve urban congestion problems by providing additional road capacity—although almost never associated with appropriate pricing policies. Additional road capacity *will* sometimes be appropriate. However, if the urban transport system is considered as a whole, it becomes apparent that additional capacity may sometimes be provided more effectively through public transport.

It needs to be emphasised that the rationale for using congestion toll revenue to provide capacity or to support the operations of public transport is analogous to that for using peak hour tolls to subsidise off-peak use. The object is to make the most efficient use of the *whole* of the urban transport system. In particular, the rationale is *not* based on any notion of compensating those who experience congestion delay. As has been pointed out by Baumol and Oates (1988), the optimal internalisation of externalities involves ensuring that those who cause the externalities pay their full social cost (in this case, the congestion tolls), but explicitly excludes the compensation of victims.

Urban transport models provide the only analytical means at the necessary level of detail for considering the urban transport system as a whole. The main limitation is the availability of data.

CONFIDENCE IN RESULTS

Confidence in the results presented in this paper is limited by the inherent weaknesses of urban transport modelling, which were outlined in chapter 2. Work is in progress to improve the treatment of the complex range of choices that determine urban travel demand. In the meantime, the analysis has focussed on aspects of urban travel that depend primarily on the traffic assignment assumptions. These are likely to be among the more robust assumptions in the models.

Data availability is always a problem. As noted previously, the results are based on a data set calibrated for 1988 but relying, in part, on survey data from 1978. The results suggest that, in Melbourne, congestion delay is very strongly concentrated near the city centre—or that it was in 1988. More recent information suggests that, with the shift of the distribution of employment towards the suburbs, congestion may no longer be restricted so strongly to the city centre.

The principal technical limitation on confidence in the results is the weak empirical basis for the road capacities, free speeds and speed–flow relationships. Sensitivity testing (not reported here) shows that the levels of marginal delay and congestion tolls are very sensitive to the values assumed for these quantities. On the other hand, the location of the areas of greatest congestion (the central peak in figure 3.6) are much less sensitive to these assumptions. This is convenient for the policy relevance of results of this kind. Any implementation of congestion tolls would need to ensure that they were applied in the right areas, but the actual level of tolls would take account of many more factors than are included in analyses of this kind.

Nevertheless, further work is this area is required. Akçelik (1991) recently provided values for the parameters of the Kimber and Hollis function used in this work (see appendix II), and Rose, Taylor and Tisato (1989) have called for empirical estimation of these functions.

SUMMARY AND CONCLUSIONS

The outline of the general features of urban transport models provided in chapter 2 should provide a qualitative understanding of the types of issues in urban transport that can reasonably be addressed by these models.

The graphical presentation of model results, showing the distribution over the urban transport network of the important characteristics of traffic and congestion, provides a strategic overview that should be of value to those attempting to formulate urban transport policy.

The 'cost of congestion' during the morning commuting peak-hour in Melbourne in 1988 was estimated as $0.45 million per hour. This corresponds to an annual cost of about $1300 million.

The 'cost of doing nothing about this congestion' was estimated as $0.15 million for the peak hour—or about $430 million annually. This cost could, in theory, be avoided by introducing a congestion toll that, in the most congested central area, would be of the order of $0.50 per veh-km. The revenue from such a toll would be about $835 million per year. However, it is unlikely to be feasible, in practice, to implement such a theoretically 'optimal' toll. Moreover, congestion tolls have equity consequences that would need to be considered carefully. Urban transport models can provide additional measures or indicators to support such considerations.

All these results are preliminary and are subject to review.

APPENDIX I COMPONENTS OF THE COST OF CONGESTION

The cost of congestion is commonly estimated by comparing the cost of travel in congested conditions with the cost in a hypothetical state of zero congestion.[1] This has the merit of referring to a relatively well-defined base state in which costs would be zero. It is certainly better than attempting to define an arbitrary 'acceptable' level of congestion.

However, the hypothetical state of zero congestion is only *relatively* well defined. It depends on what is assumed about traffic patterns if there were no congestion.

The commonest assumption is that *road users would make the same trips and follow the same routes* as they do now. With this definition, the delay due to congestion can be calculated from transport modelling results as the difference between the congested and free speed travel times multiplied by the traffic volumes on each link.

Clearly, alternative assumptions can be made about what the traffic patterns would be like if there were no congestion.

Even if road users made the same trips as they do now, one would expect them to choose alternative routes. Current routes are chosen at least partly to avoid congestion and, if this were not an issue, one would expect more direct routes to be chosen. As a result, the estimate of congestion delay based on *preferred routes* would be greater than the one above because, in addition to travelling at a higher speed, travellers would cover a shorter distance. Traffic volumes on links, under these circumstances, can be estimated in the urban transport models by retaining the O–D trip matrix for congested conditions and repeating the assignment step with the speed–flow relationship specifying free speed for all traffic volumes.

In fact, congestion limits not only speed and route choice, but also the choice of trips. Some trips are avoided altogether, and others are made to

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[1] Time and vehicle operations are the items generally costed. For the purposes of this appendix, nothing is lost by focussing on time.

destinations chosen, in part, to avoid congestion. Traffic patterns corresponding to the choice of both *preferred trips and routes* can be estimated from complete model runs with all travel decisions based on free speed traffic flow. Under these circumstances, it is no longer adequate simply to use the difference in travel time as the measure of congestion cost. Preferred trips might well be longer than current trips, and the estimate of congestion cost based on preferred trips and routes should contain a component representing the consumer surplus lost when low value trips are suppressed or diverted to other destinations by congestion.

These alternative congestion scenarios are illustrated in figure I.1. While this figure is closely related to figure 4.1, it refers to travel on the whole network. It can therefore only be schematic, because there is an ambiguity, in the definition of the quantity of travel, between number of trips and distance to be covered.

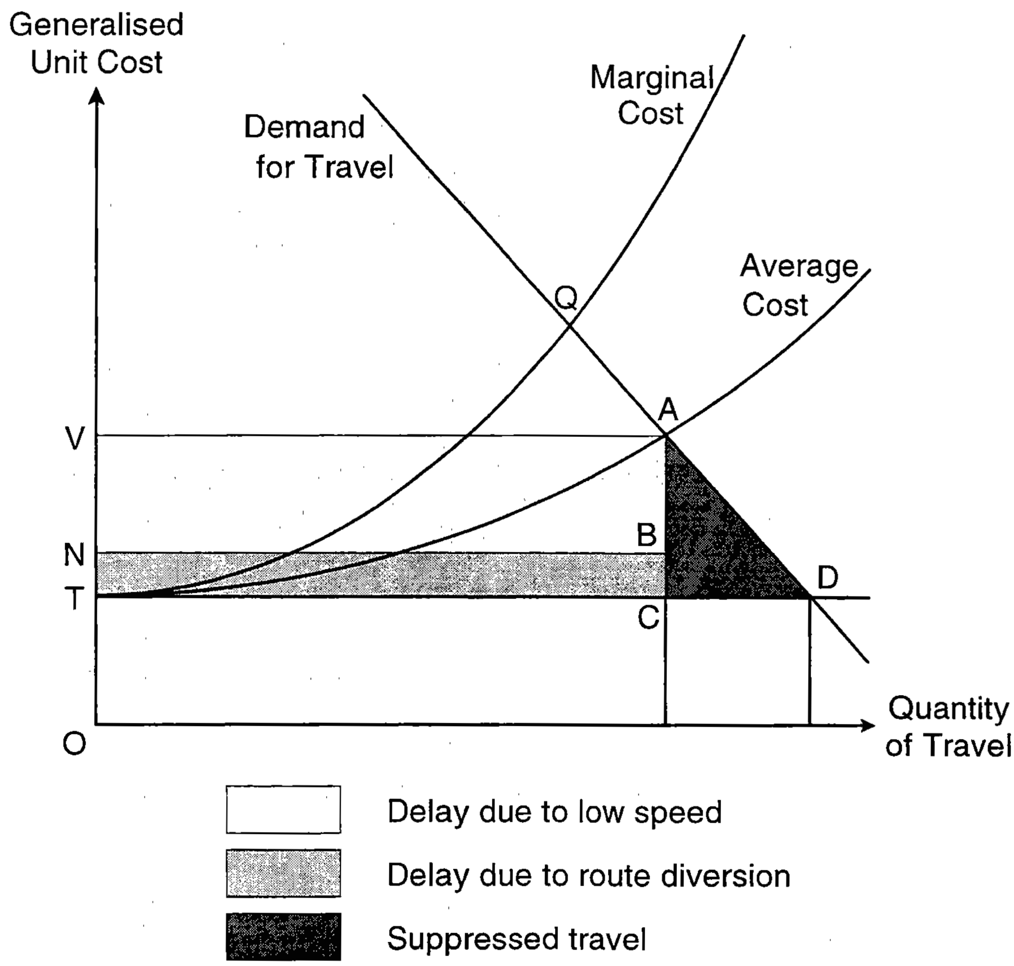

Figure I.1 Components of the cost of congestion.

With this qualification[2], scenario A, the current congested situation, corresponds to the intersection of the travel demand curve and the average private cost curve.

Scenario B is the zero congestion case in which travellers make their current trips by the same routes as they use now. Scenario C is the zero congestion case in which travellers make their current trips by preferred routes. Scenarios B and C refer to the same number of trips as A, although in C the distance covered is less and the time and cost correspondingly lower. Scenarios B and C do not correspond to any actually observable equilibrium situations (they are not on the demand curve), but they do represent the hypothetical uncongested situations against which estimates of congestion costs are made.

The estimates of congestion cost made in chapter 3 and those by Commeignes and Luk cited in table 4.1 are of type B, and represent the costs of time lost due to reduced speed. They correspond to the area VABN in figure I.1.

Although it is not entirely clear from the text, Miles's estimate (table 4.1) appears to be of type C, and to include the cost of time lost due to route diversion as well as reduced speed. It corresponds to the area VACT.

Figure I.1 can be interpreted entirely consistently for scenarios A, B and C if it is assumed that the quantity of travel, (that is, the commodity in demand) is the number of trips.

Scenario D is the zero congestion case in which travellers choose their preferred trips and routes. D is represented at the intersection of the travel demand curve with the fixed cost line for zero congestion. As compared with scenarios A, B and C, the quantity of travel is greater; and the cost of congestion, represented by the area VADT, includes the consumer surplus associated with the travel which was suppressed by congestion. This is represented by the area ADC.

However, there is now an ambiguity in the figure. If demand is considered to be for trips (as before) then, as congestion costs decline, people would be expected not only to make more trips, but also to make longer trips to different destinations. These trips would not have the same cost as the trips made under scenario C, and the difference would not be due to the state of congestion, but to the fact that the nature of the travel product had changed. This is not easily represented in a simple figure of this type.

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[2] Other qualifications may also be required. See Evans (1992) and the comment (Hills 1993) and rejoinder (Evans 1993) for a discussion of the difficulties in correctly specifying diagrams of the supply and demand for urban travel.

The ambiguity is not resolved by considering demand to be for vehicle–kilometres of travel, because scenario B would then have to be considered to be meeting a higher level of demand than C. In fact, in the analysis of travel on the network, vehicle–kilometres of travel (and the operating costs and travel time they give rise to) are not the items in demand but costs which people incur in meeting their needs to be elsewhere. This ambiguity does not arise when we consider travel on a particular link of the network. The commodity in demand is then simply passage along the link, which is then clearly defined, and is not affected by congestion or the level of demand.

Despite these ambiguities, the schematic representation in figure I.1 is useful because it allows the components of the cost of congestion to be related, at least conceptually, to the standard economic measures of supply and demand.

Table I.1 summarises the aggregate measures of travel from the TRANSTEP analysis of the Melbourne morning peak hour.

TABLE I.1 TRAFFIC MEASURES UNDER CURRENT CONGESTED CONDITIONS AND UNDER HYPOTHETICAL UNCONGESTED CONDITIONS

Scenario[a]	*Traffic situation*	*Number of vehicle trips*	*Total travel (veh–km)*	*Total travel time (veh–hr)*	*Mean speed (km/hr)*	*Mean trip length (km)*	*Mean trip time (min)*
A	Current congested conditions	248 989	3 160 020	83 212	38.0	12.7	20.1
B	No congestion; current trips and routes	248 989	3 160 020	53 343 (–36%)	59.2 (+56%)	12.7 (0%)	12.9 (–36%)
C	No congestion; current trips, preferred routes	248 986	3 084 756 (–2%)	51 905 (–38%)	59.4 (+56%)	12.4 (–2%)	12.5 (–38%)
D	No congestion; preferred trips and routes	288 631 (+16%)	4 345 874 (+38%)	91 611 (+10%)	47.4 (+25%)	15.1 (+19%)	19.0 (–5%)
Q	With 'optimal' congestion toll	212 491 (–15%)	2 451 746 (–22%)	52 085 (–37%)	47.1 (+24%)	11.5 (–9%)	14.7 (–27%)

a. Scenario identifiers correspond to the letters used in figure I.1.

Note Percentage changes (where indicated) are with respect to scenario A.

Source TRANSTEP modelling results (see text)

APPENDIX II THE EFFECT OF TRAFFIC VOLUME ON SPEED

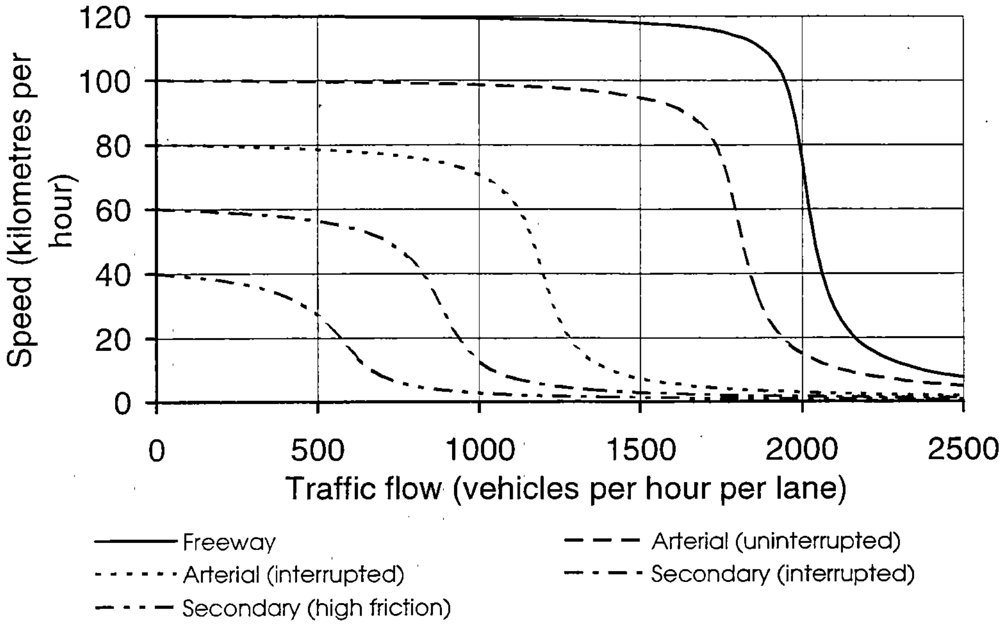
The essential feature of congestion is that, as traffic volumes increase, speeds decrease. The details of the relationship between speed and traffic flow are important for estimates of the costs of congestion, and even more so for estimates of marginal delay and congestion tolls. Unfortunately, the empirical basis for the relationship is weak.

Akçelik (1991) has provided illustrative functions (shown in figure II.1) which describe the speed–flow relationship for a number of broadly defined urban road types.

For each of the road types in figure II.1, a free speed and a traffic flow capacity are defined. The interrupted arterial, for example, has a free speed of 80 kilometres per hour and a capacity of about 1200 vehicles per hour per lane. In addition, the shape of each curve is important. This is brought out more clearly by plotting the speed–flow relationship in *normalised* form, with speed measured as a fraction of the free speed, and traffic represented by the volume–capacity ratio. Figure II.2 shows the speed–flow relationships of figure II.1 in normalised form, together with an area speed–flow relationship for a dense urban network.

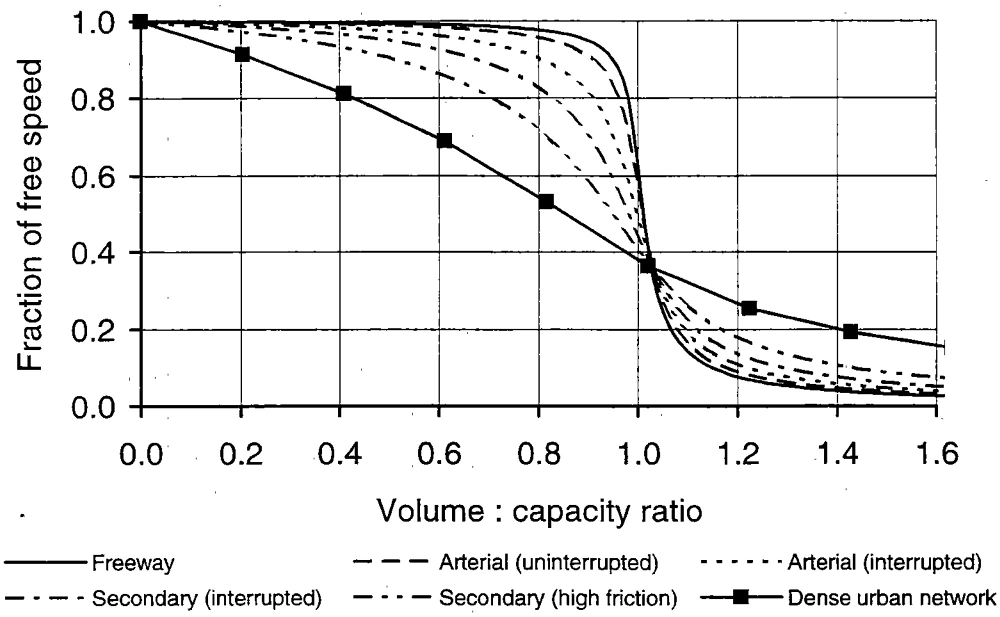
The shape of the curves in figure II.2 changes progressively with road type. This is because there is a progressive change in the mechanism by which high traffic volumes reduce speed. At one extreme, on freeways, which are designed to provide minimal interference to traffic flow, the mechanism is mainly the interaction between vehicles within the traffic stream. Speed falls very little until traffic flow approaches capacity, after which it falls off very rapidly.

At the other extreme, roads forming part of a dense urban network are continually interrupted by intersections and other discontinuities. On these roads, speeds are reduced primarily because of the time spent in queues at intersections and discontinuities. Speeds start to fall at low traffic volumes and fall continuously to low values. There is no very obvious critical value at which speeds fall rapidly, and it is hard, therefore, to identify capacity.



Source Akçelik (1991).

Figure II.1 Speed–flow rleationships for selected road types



Source Akçelik (1991) and BTCE estimates.

Figure II.2 Normalised speed–flow relationships for selected road types

The curve for the dense urban network is included to illustrate the limiting case of this progression of road types, though it is not strictly part of the same series as the other curves in figure II.2. The dense urban network curve is a semi-empirical result derived from modelling work in Hong Kong (Harrison et al. 1986). It differs from the other curves because it describes the average speed of traffic in an area rather than on a single link. There is also a normalisation problem associated with the difficulty in identifying capacity. The scale of the normalised curve in the horizontal direction in figure II.2 is, therefore, uncertain. It has been chosen so that the curve passes close to the point of intersection[1] of Akçelik's curves, in order to highlight the progressive change in shape.

The analysis of congested traffic flow and attempts to derive mathematical expressions for the form of these curves (Davidson 1978, Akçelik 1978, Taylor 1984, Tisato 1991) have, in fact, focussed on travel time, the inverse of speed. The most thorough treatment appears to be due to Kimber and Hollis (1979), who derived a function which correctly describes travel time and intersection delay on a road link for values of traffic flow both above and below capacity. Their function takes into account random fluctuations in traffic flow below capacity, the effect of overcapacity traffic flows of finite duration, and provides a smooth transition between the two regimes.

Kimber and Hollis's function has the form

$$t_a = t_o\left[1 + a\left\{(x-1) + \sqrt{(x-1)^2 + bx}\right\}\right] \qquad \text{(II.1)}$$

where

t_a = average travel time per kilometre;

t_o = free speed travel time per kilometre;

x = volume–capacity ratio; and

a and b are parameters.

[1] There does not appear to be any special significance to the fact that Akçelik's normalised curves all intersect near a common point, close to capacity. However, the capacity of a road is sometimes defined as equal to the traffic volume at which speed falls to a given fraction of the free speed.

Akçelik's normalised speed–flow curves plotted in figure II.2 are obtained from this equation by plotting $\frac{t_o}{t_a}$ against x for the following values of a and b:

freeway	$a = 30;$	$b = 0.00040$
arterial (uninterrupted)	$a = 25;$	$b = 0.00089$
arterial (interrupted)	$a = 20;$	$b = 0.00267$
secondary (interrupted)	$a = 15;$	$b = 0.00711$
secondary (high friction)	$a = 10;$	$b = 0.02133$

The curve for the dense urban network can be closely approximated by $a = 4$; $b = 0.17$.

It is possible to interpret the parameters a and b in terms of the traffic engineering quantities as discussed by Kimber and Hollis (1979) and by Akçelik (1991). However, for this work, it is sufficient that the function is simple, differentiable and defined for all positive x.

The choice of parameters appropriate for this work is complex and has not yet been entirely resolved. Because of the limited empirical basis, it has been necessary to experiment with ranges of parameter values. And because some of the results depend strongly on these values, it has been necessary to test the sensitivity to alternative choices. Fortunately, the choice is not unconstrained. For example, attempts to calibrate the model with parameter values close to those of figure II.1 lead to implausibly high average speeds.

TABLE II.1 PARAMETERS OF THE TRAVEL TIME FUNCTION ASSUMED FOR THE MELBOURNE ROAD NETWORK

Road type	*Road capacity* (veh/hr/lane)	*Free speed* (km/hr)	*Parameters of normalised speed–flow relationship* a	b
Freeway (no toll)	2 000	81.0	52.3	0.0112
Freeway (with toll)	2 000	81.0	49.6	0.0131
Rural highway	1 700	69.0	43.5	0.0195
Arterial divided	1 550	60.0	40.4	0.0243
Arterial undivided (no trams)	1 300	54.0	36.9	0.0318
Arterial undivided (with trams)	1 150	50.4	36.2	0.0339
Sub-arterial	1 100	50.4	35.8	0.0350
Local or CBD street	1 000	30.0	35.4	0.0362

Sources R. J. Nairn and Partners and this work.

This can be rectified by reducing free speeds or capacities or changing the speed–flow relationships. However, the tradeoffs among these, and the implications for the results, are still being explored.

Table II.1 gives the parameter values on which the results reported here are based, and figure II.3 shows the normalised speed–flow relationships for the different road types (excluding centroid connectors).

The economic analysis also requires the marginal travel time function. This is the derivative, with respect to traffic, of the total travel time. If

T = total travel time

q = traffic volume

Q = capacity of the link ($x = q/Q$)

then

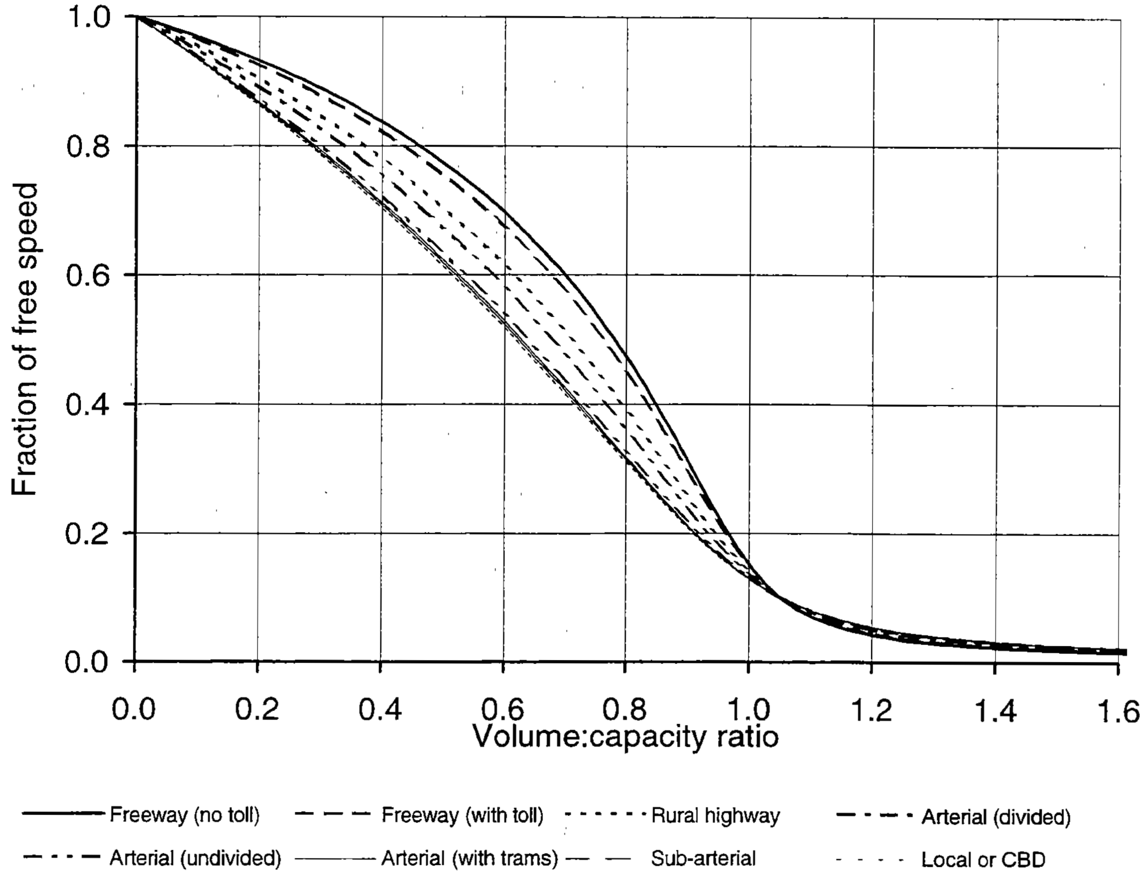
$$T = q t_a$$

and the marginal travel time function has the form

$$t_m = \frac{dT}{dq} = q\frac{dt_a}{dq} + t_a \qquad \text{(II.2)}$$

where

$$\frac{dt_a}{dq} = t_o a\left[1 + \frac{(x-1) + b/2}{\sqrt{(x-1)^2 + bx}}\right]$$



Source BTCE estimates.

Figure II.3 Normalised speed–flow releationships assumed for the Melbourne road network

APPENDIX III THE EXTERNAL COMPONENT OF CONGESTION DELAY

Figure III.1 identifies (for a single link) the important components of travel time and delay in relation to the average and marginal travel times which are functions of the volume of traffic. The horizontal line indicates the travel time at free speed.

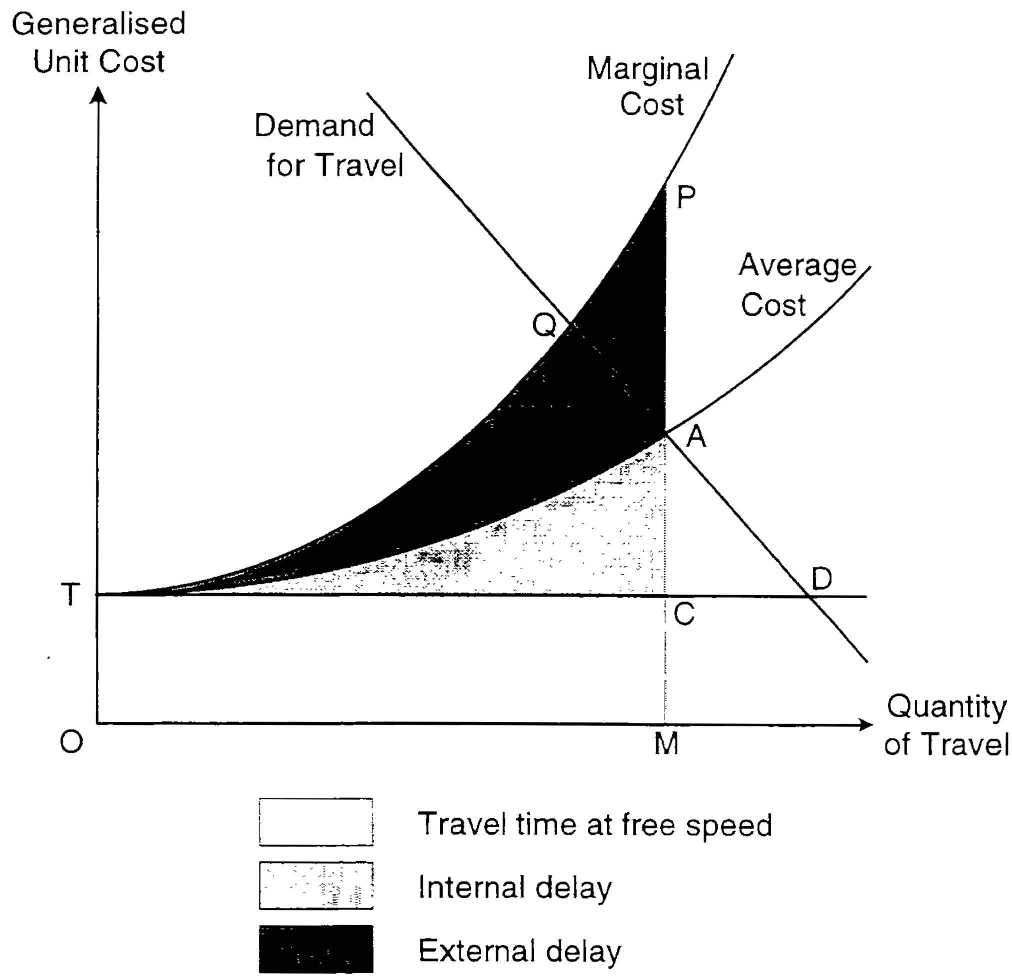


Figure III.1 External and internal components of congestion delay

The total travel time (for all vehicles) is the integral of the marginal travel time from zero up to the volume of travel in question. It is represented by the area between the marginal travel time curve and the traffic axis.

The lower, rectangular part of this area represents the minimum time for this travel if all vehicles could have travelled at the free speed.

The difference between the total and the free speed travel time can be considered to be the delay due to congestion. This total delay is represented by the area between the marginal travel time curve and the free speed travel time line. The value of this total delay is what is normally called the cost of congestion.

Not all of this travel time (or delay) is taken into account in travel decisions. Travellers take account only of the time they expect to spend, and this is given by the average travel time curve. The area under the average travel time curve therefore represents the part of the total travel time which has been taken into account. It includes the whole of the free speed travel time plus a part of the delay. This *internal* delay is represented by the area between the average travel time curve and the free speed travel time line.

The remaining delay, represented by the area between the average and marginal travel time curves, is the *external* delay — the externality associated with congestion.

The proportion of total delay which is external depends on the form of the travel time functions and on the volume of traffic. A useful reference point is provided by an average travel time function of the form

$$t_a = t_o.\left[1 + a.x^n\right] \tag{III.1}$$

where

t_a = average travel time per kilometre;

t_o = free speed travel time per kilometre;

x = volume–capacity ratio; and

a is a parameter.

Although it has been superseded, this function is of interest because it leads to an external delay which is a constant fraction, equal to $n/(n+1)$, of total delay.

The travel time function in equation III.1 has been widely used following its original development by the US Bureau of Public Roads, which used a value of n = 4. It can therefore be concluded that, in all the work based on this value, 80 per cent of congestion delay was borne externally.

The form of the average travel time function used in our work is given in appendix II and is repeated below.

$$t_a = t_o\left[1 + a\left\{(x-1) + \sqrt{(x-1)^2 + bx}\right\}\right] \qquad \text{(III.2)}$$

where

t_a = average travel time per kilometre;

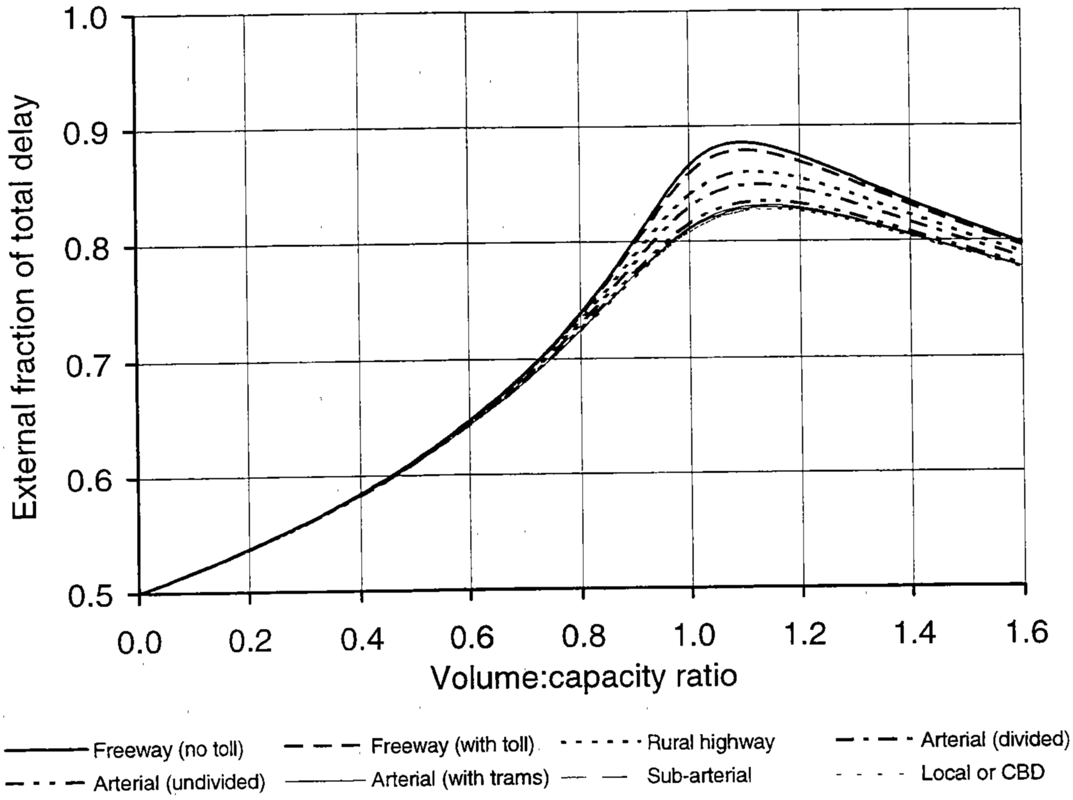
t_o = free speed travel time per kilometre;

x = volume–capacity ratio; and

a and b are parameters.

Although the calculations with this function are more complex than with III.1, the principle is the same. The fraction of total delay which is external now turns out to depend on the level of traffic x and on the parameter b, but to be independent of a. Figure III.2 shows how the fraction varies with traffic for the road types used in this TRANSTEP model of the Melbourne network.

Most delay is expected to occur on undivided arterials, sub–arterials and CBD streets with volume–capacity ratios near one. On these roads the external fraction is between 70 and a little over 80 per cent. This is in line with the estimate, in chapter 4, of an overall fraction for the network of 66 per cent.



Source BTCE estimates.

Figure III.2 External fraction of total congestion delay

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ABBREVIATIONS AND GLOSSARY

BTCE	Bureau of Transport and Communications Economics
CBD	central business district
ITS	Institute of Transport Studies at the University of Sydney
lane-km	lane-kilometre(s)
O–D	origin–destination
OECD	Organisation for Economic Cooperation and Development
RTA	Roads and Traffic Authority of New South Wales
skim	a measure of the cost (in terms of distance, time or money) of a trip between a particular origin–destination pair. Usually found in the term 'skim matrix', a matrix of such costs for all origin–destination pairs.
TRANSTEP	The urban transport model developed by R. J. Nairn and Partners used in this work.
veh-min	vehicle-minute(s)
veh-hr	vehicle-hour(s)
veh-km	vehicle-kilometre(s)
VEHOP	RTA study of vehicle operating costs
VTES	Victorian Transport Externalities Study