UNIVERSITY OF SOUTHAMPTON

THE POTENTIAL NETWORK EFFECTS OF TRAVELLERS' RESPONSES TO TRAVEL DEMAND MANAGEMENT MEASURES

by

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ABSTRACT

FACULTY OF ENGINEERING AND APPLIED SCIENCE
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THE POTENTIAL NETWORK EFFECTS OF TRAVELLERS' RESPONSES TO TRAVE DEMAND MANAGEMENT MEASURES

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There has been a growing acceptance by transportation professionals that the traditional 'predict and provide' transport planning approach will not solve the transport problems that prevail in towns and cities and that Travel Demand Management (TDM) policies will need to play an increasingly important role in towns and cities. However, the extent to which TDM can significantly reduce the growth of traffic, and therefore ease congestion and improve air quality, is uncertain. There is little empirical evidence to substantiate the extent of potential effects. Modelling offers a potential solution but unfortunately a model capable of being used to study all the potential impacts of TDM does not exist, nor does the understanding of the underlying fundamental behavioural responses. Further, the data requirements to calibrate and validate such a model would be enormous. This research aims to assess the potential network benefits/disbenefits of expected traveller responses as a result of TDM policy measures of road pricing, trip suppression and peak spreading. The methodology used is a 'what if-best estimate' approach based on evidence from the literature and from modelling using the CONTRAM model. The modelling approach adopted makes it possible to test hypothetical scenarios where there is a lack of existing empirical evidence. The 'what if-best estimate' approach reduces the need to develop data hungry predictive behavioural models, while greater advantage is taken of the much more and better developed network scheme evaluation assignment models such as CONTRAM which was adopted in this research. The evaluation in this work is predominantly based on the overall network performance since this can capture the net effect arising from the benefits in the priced areas and the potential disbenefits in the boundary or uncharged areas. The results of the inelastic modelling undertaken in this work reinforced existing evidence that network performance could deteriorate with increasing toll level as trips re-routed away from tolled facilities to free routes in the boundary areas. Although the results suggested an overall network deterioration as measured from total network vehicle hours, it was found that time savings in excess of three minutes were possible for individual O-D movements using the tolled facilities. Multiple cordons were seen to perform worse than single cordons under inelastic modelling when total network vehicle hours were the comparison criterion. However, their potential to raise revenue was seen to be far higher than that of single cordons. The elastic modelling showed that with only a 2.5% decrease in overall network vehicle hours at normal congestion, the overall network benefits of peak spreading were not very high. The benefits from trip suppression approximated to about a 9% reduction in overall network vehicle hours at normal congestion. This was about four times the benefits from peak spreading. Combining peak spreading with modest levels of trip suppression appreciably improved the network effects beyond that of peak spreading alone but were less than the benefits that would accrue from suppressing the car trips altogether instead of spreading them to the peak shoulders. It was possible to double the network effects of peak spreading through such combined behavioural responses. Re-routeing as a result of tolling, was found to undermine the benefits that might arise from suppressing or peak spreading key radial O-D movements into the charged cordons such as the central business district (CBD). This was because the benefits gained from suppressing or peak spreading such trips appeared to be offset by the disbenefits arising from re-routing to boundary routes.

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1 INTRODUCTION

1.1 Background

There has been a growing acceptance by transportation professionals that the traditional 'predict and provide' transport planning approach will not solve the transport problems that prevail in towns and cities and that Travel Demand Management (TDM) policies will need to play an increasingly important role. It has been noted that it will not be possible to accommodate predicted traffic growth on UK roads (e.g. Potter et al, 1997; Goodwin and Coombe, 1991, Goodwin, 1999; Orski, 1989; Taylor, 1999). Forecasts made in 1991 predicted an increase of between 72 and 121% in road traffic over the period 1990 to 2025. Furthermore, resulting road congestion was expected to occur in more areas for longer periods of the day. There is a gradual but sure realisation and acceptance that Travel Demand Management policies will need to play an increasingly important role in addressing prevailing traffic problems. However, achieving a practical balance between maintaining accessibility and managing demand presents one of the major challenges of land surface transportation today.

Solutions increasingly receiving attention as offering the potential to tackle urban traffic problems, exclude substantial infrastructure for new capacity, but include low capacity additions through junction or pavement widening, advanced traffic management systems, travel behavioural changes, or a mixture of them (e.g. Taylor, 1999; Meyer; 1999). As both Meyer and Taylor note, the term Travel Demand Management (TDM) has become prevalent recently. However, some of its core concepts were embraced in the preceding terms Transportation System Management (TSM) and Transportation Control Measures (TCM) that emerged in USA transport policy literature from the 1970s. The earlier terms were especially clear in their intention by emphasising the importance of addressing both the supply side and the demand side of travel demand (Meyer, 1999). However, this shift towards demand management should not totally preclude the role of traditional capital intensive road capacity additions (e.g. Dawson, 1986). None-the-less, road construction will, increasingly become less prominent as a solution to congestion management.

The following reasons have been put forward for this change in strategy (e.g. van Vuren et al, 1995a, Bhatt, 1994):

- Capacity addition cannot match the rapid travel demand increase especially car growth as evidenced mainly in developed economies.
- The thrust towards market led economies rather than public sector funding has seen less and less resources for road construction.
- Environmentalists have increasingly questioned the environmental implications of providing for traffic growth in terms of gaseous emissions, noise and severance of the landscape.
- Land as a resource is limited and so new rights of way for infrastructure cannot be acquired, nor can they be provided for by demolishing historical structures or other existing buildings.
- There is concern that increased capacity induces latent demand rather than provides for the projected demand. The M25 London orbital is frequently cited as testimony to this. SACTRA (1994) is one of the most frequently quoted sources of this phenomenon. In American literature, Orski, as early as 1989, also noted that specific contemporary road projects had reached their design capacity and hence saturation in progressively shorter time periods than had been planned for.

There has been a realisation, that no single measure can offer the 'ultimate' solution. A 'package' approach that combines a number of traffic measures which may sometimes necessitate both supply and demand management is advocated. Indeed, within TDM itself, packages may include incentives and disincentives in order to provide alternatives or substitutes that are both viable as well as acceptable to those affected.

The extent to which TDM can significantly reduce the growth of traffic and therefore ease congestion and improve air quality is uncertain (e.g. Orski, 1991). There is little empirical evidence to substantiate the extent of potential effects. Short of full scale experimentation, modelling offers a feasible option to try to understand the complex choices and potential impacts of TDM measures such as road pricing schemes (Harvey, 1994). Unfortunately a model capable of being used to study all the potential impacts of TDM does not exist, nor does the understanding of the underlying fundamental behavioural responses which forms the focus of demand management. Furthermore, the data requirements to calibrate and validate such a model would be enormous. Thus, there is a general intuitive assumption that the impacts or behavioural changes of TDM will reduce congestion and that the potential network benefits of these impacts will be substantial. However, the extent of these potential network benefits remain largely unquantified, particularly at a network wide level.

In the absence of fully specified models, modelling techniques based on simplifying but plausible assumptions may be employed to help build up an understanding of the many factors that influence impacts and therefore aid in quantifying or estimating potential network benefits.

1.2 Research Objectives

The objective of this research is the estimation of the extent of the potential network benefits arising from specific expected driver responses to TDM measures such as road user charging. It is an attempt to contribute to the understanding of how specific behavioural responses arising from such TDM measures will affect congestion. The research notes that there seems to be an implied view that driver responses to TDM will ease congestion, but little has been said about the potential extent of the network benefits that may arise. The specific aims of this research are thus as follows:

1. To model the re-routeing effects of cordon tolls and to compare the effects for different cordons or combination of cordons. This inelastic modelling assumes that re-routeing is the only response by travellers encountering cordon tolls and therefore defines the lower bound effects of cordon tolls.
2. To model and estimate the potential network benefits/disbenefits of travellers' elastic responses to TDM measures such as road user charging. The elastic responses considered were peak spreading and trip suppression. The objective here is to estimate the extent of the network effects if travellers responded to TDM measures by peak spreading their car trips or by suppressing some of their car trips.

The main parameter used to evaluate the potential network benefits is the change in total network vehicle hours because this captures the net effect arising from both the positive effects of TDM measures in the charged areas and/or times and the negative effects at the boundaries of the charged areas/and or times. The suppression or peak spreading of car trips adopted here is in line with the Southampton Provisional Local Transport Plan 2000/1 to 2004/5 since this work was based on the Southampton network. In this plan, it was argued that as a city at the heart of an economically active region in southern England, it was essential that the City and its regions continued to develop and attract an increasing number of people to support its activities. Therefore, current road traffic reduction targets for Southampton, concentrate mainly on the car borne commuter trip.

1.3 Methodology

Most models in transportation are largely road scheme evaluation models and lack plausible consumer behavioural choice prediction capabilities (e.g. Allen Jr, 1995; van Vuren et al, 1995a; White et al, 1995; Wachs, 1998; Giuliano, 1998; Dahms, 1998). The lack of a comprehensive model to evaluate the impacts of policies such as road user charging is evident from the literature, although on going research efforts in this area are taking place. Developments in discrete choice modelling are a major step forward, but there are concerns about the cross sectional nature of the collected data as well as the amount of data required for their calibration and validation. Also, there is lack of understanding in identifying the variables/factors that should appear in the utility function and in the specification of the demand functions. There are also concerns about the modelling of equilibrium and, hence, the interaction between demand models and the network model in order to estimate the network effects. Usually, the costs in the demand models (often represented by a generalised cost function) and indeed within different modules of the demand model itself, are inconsistent with each other and with those in the network models. More significantly, if the travel choices predicted by the demand model are questionable, the potential network effects subsequently modelled will also be subject to doubt.

In view of the limitations of current approaches for use with TDM, this research has assumed best estimates of behavioural change and then explored the potential impacts at a network level. The approach adopted is therefore largely hypothetical and is of a 'what if' nature. It provides a rapid and inexpensive means of testing a larger number of potential scenarios using a well established assignment model.

The literature provides evidence of what is currently known from limited empirical, demonstration trials, laboratory studies and modelling, and provides a basis for the behavioural assumptions. The methodology makes it possible to test the potential network effects of impacts that have hitherto never been experienced. In this respect, it can be used to provide guidance on of the nature and range of impacts that can yield the most benefits should a TDM or road user charging policy is implemented. The literature review's role is threefold:

i. it helps with problem definition;
ii. it provides inputs for the modelling and;
iii. it allows for comparison between the evidence available and what can potentially be achieved.

The network model used in the research is the CONTRAM (Continuous Traffic Assignment Model; Leonard et al, 1989) assignment model, partly because a calibrated model of the City of Southampton network was available and partly because the model is well established. It also has some unique network modelling capabilities as explained in Chapter 4.

1.4 Layout of Thesis

In Chapter 2, a literature survey of TDM measures in general and road pricing in particular is undertaken with emphasis on their potential to alleviate congestion.

In Chapter 3, a critical review of current travel choice and transportation policy evaluation models is undertaken. Both assignment based and demand based techniques of representing the elastic responses of travellers to transportation policies are reviewed. The aim was to highlight that these methods are often complex and require data that is often costly to obtain. The chapter argues for the use of simple but plausible methods of representing driver behavioural changes with a view to devoting more effort to analysing what the potential network effects of these responses might be.

In Chapter 4, the modelling approach used in this research is explained and follows directly from the critical review of currently existing models reviewed in Chapter 3. A review of the CONTRAM assignment model and its selection for use as the network evaluation model in this research is explained. A critical discussion of its capabilities to model congested networks is a major output of this chapter.

In Chapter 5, the modelled inelastic or re-routeing effects of road user charging using CONTRAM for the Southampton network are described. It is argued in this chapter that although inelastic response alone is unlikely in real life, the interpretation of the results of such modelling may indicate which trip making movements are likely to respond elastically in real life.

In Chapter 6, the elastic effects of selected behavioural responses are estimated, assuming that the TDM measure causing them is road user charging. Peak spreading of car trips, general trip suppression of car trips and a combination of these behavioural responses are studied. The simplicity of the behavioural modelling used in this research enabled the potential network benefits from peak spreading to be differentiated from those of general car trip suppression.

The research conclusions and suggestions for further research are summarised in Chapter 7.

2 LITERATURE REVIEW OF TRAVEL DEMAND MANAGEMENT MEASURES

2.1 Introduction

In this chapter, the problem of traffic congestion in urban road networks is introduced. A literature review of travel demand management (TDM) measures and its potential for congestion relief is undertaken. A detailed review of the different ways by which various researchers have classified TDMs is undertaken, noting that despite the different approaches to classification, the core of TDM as a means of managing traffic growth and congestion by changing travel behaviour remains a common thread. A more detailed literature review of road pricing measures is given, in its context as a TDM instrument. The literature review in this chapter is essentially undertaken with the view that an understanding of the basics of TDM can lead to an understanding of how to model the behavioural outcomes of such policies. In line with the broad aims of this thesis, it is envisaged that this understanding can lead to the adoption of simple methods of representing the travel behavioural outcomes of TDM policies in general and road pricing in particular. The adoption of these simple but plausible ways of representing travel behavioural changes can in turn enable more detailed evaluation of the potential network effects of the travel behavioural changes due to TDM.

2.1.1 Urban Transport Problem: Imbalance between Traffic Growth and Infrastructure

The rapid and continued growth in the use of the single occupancy vehicle (SOV) has prompted a global response to the need for a new approach to the urban transport problem especially in the western world. For example, in the absence of any policy to limit vehicle use in the Netherlands, passenger car road traffic would grow by 70% between 1986 and 2010 (de Jong, 1995). In the U.K., between 1983 and 1993, road vehicles increased by 23%, road vehicle km by 42% and passenger km by road by 33%. In the same period, road length increased by only 5%, passenger km by bus and coach decreased by 13% while passenger km by rail went up by only 9% (Bly, 1996). More recently Goodwin (1999) quoting 1997 National Road Traffic Forecasts noted that the proportion of the existing national motorway and trunk road network suffering serious congestion would increase from 14% to 26% in 2016. Peak hour journey times on urban motorways were forecast to increase by 70%. Estimates for the 15 EU countries for the decade 1985 to 1994 showed a population increase of 3.4%, a car ownership increase of 31%, a car travel (passenger kilometres) increase of 40% and a road network length increase of only 10% (Marshall et al, 1997). The forecasts clearly show an increased use and dependence on the private car, which if unchanged, is unsustainable. Earlier, Goodwin and Coombe (1991) had noted that the revised Department of Transport road traffic forecasts of 1989 suggested that traffic would increase by between 82% and 134% between 1988 and 2025. Setting aside any criticism of the forecasting models used to derive these figures, the policy implications of the figures were identified as more critical. It was quite clear, that despite substantial new road building, it would not be possible to increase road supply at a level which approached the forecast increases in traffic. Whatever road construction programme were to be followed, the amount of traffic per unit of road would increase and not reduce as a result of both normal growth and induced traffic. Therefore, it appeared inevitable, that demand management would become an essential feature of future transport strategy.

2.1.2 New Developments in Transport Policy

The lack of a clear and consistent transport policy in many countries is a major setback (May, 1995; Krammes, 1994; Larson & Krammes; 1994). Larson and Krammes noted the complexity of the U.S. transportation planning system. In particular, a large number of 'players' (50 states) made transportation decisions difficult with no one having a clear cut final responsibility. However, they also noted positive developments such as the U.S.$150 Million 5 year Strategic Highway Research Program (SHRP), the Clean Air Act Ammendments of 1990 and the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA). More recently, Meyer (1999) provided a review of developments in US transport policy noting in particular that the Transportation Equity Act for the 21st Century (TEA –21) continues most of the demand management initiatives of ISTEA.

A clearer policy statement exists though in The Netherlands (May, 1995; de Jong, 1995). As early as 1993, Elsenaar and Fanoy in a paper entitled 'Urban Transport: Sustainable Development in The Netherlands' reported on a number of proposed demand based measures to combat unsustainable car use. The broad aim and target was to limit the increase in traffic between 1986 and 2010 to 35%. May noted the efforts by the United Kingdom government into co-ordinated transport planning but argued for a clear statement of national and regional transport policy. Ashiru et al, (2000) noted that the concept of target setting is now a major component of UK national transport policy. The Road Traffic Reduction Act (1997)(RTRA) obliged local authorities to review existing and forecast levels of traffic on local roads and report on their findings. The reports were to contain targets for either reducing existing levels of traffic on local roads or targets for reducing the rate of growth of traffic on these roads. The Road Traffic Reduction (National Targets) Act 1998 became law in 1998. Targets must be considered separately for England, Scotland and Wales under the Act. The Act does not, however, extend to Northern Ireland.

Goodwin (1999) provided a review of the transformation of transport policy in Great Britain in recent times. He provided a brief comparison of pre 1989 and post 1989 transport policy in Great Britain. 1989 was defined as the watershed when transport policy changed from predict and provide to demand management. Thus, as Goodwin points out, the 1998 UK White Paper: "A new deal for Transport: Better for Everyone", did not 'come out of the blue', but was the result of a build up in new thinking from the mid 1990s cutting across the political divide and across the 'barriers of the different professions and disciplines'. Some of the more significant policy issues associated with the 1998 White Paper are:

- The Transport Bill (House of Commons, 1999) still progressing through its Parliamentary stages, amongst other initiatives seeks to authorise local authorities outside Greater London to introduce road user charges (RUC) and workplace parking levy (WPPL) schemes. The Bill additionally provides for the revenue generated from such schemes to be used specifically for local transport improvements (hypothecation). Such powers already exist for London through the Greater London Authority (GLA) Act 1999 and their application will provide much needed funds to make public transport more attractive.
- Public participation in local transport planning, although not a statutory requirement is encouraged in the Full Local Transport Plan Guidance by the DETR (now DTLR following the 2001 election). This is aimed at fostering participation and hence building a consensus from the outset in local transport plans between local authorities and their constituents (Hartson, 2000).

2.1.3 Negative Impacts of the Single Occupancy Vehicle

The European Conference of Ministers of Transport (ECMT, 1990) set out at least 8 negative impacts of the widespread use of the private car.

1. Traffic congestion leading to longer and less predictable journey times;
2. Traffic accidents and road safety;
3. Traffic noise;
4. Vehicle pollution;
5. Carbon dioxide emissions and global warming;
6. The abuse or misuse of some public spaces by illegal parking;
7. Severance of social networks;
8. The general unpleasantness of using street spaces on foot.

Yet Coombe (1995) noted that while the problem of increased travel demand, especially car growth, was acknowledged, there were, the dilemmas and intricacies inherent in the problem. He illustrated this by quoting the Royal Commission on Environmental Pollution, which wrote:
' it would be inequitable to impose high barriers against the acquisition of cars by families who have not been able to afford them until now'. This view is shared by Bell (1995) who stated that as an essential household possession (consumer perspective), there did not seem to be a scope to limit the growth in car ownership. Regulatory measures were likely to fail politically while taxes would be futile. Control of car use offered a more realistic approach. Policies such as road pricing, that focussed on car use, in tandem with selective reductions in road capacity offered a long term global solution.

2.1.4 Different National Goals

Policies that spearhead political pressure for action vary from country to country even within Europe (Jones and Hervik, 1992, O.E.C.D. 1988, Marshall and Banister, 2000). For example, in London it is traffic congestion which has been the driving force while in Milan and Athens, it is air pollution. Road safety is uppermost for some, while global warming is now becoming of world wide significance.

The measures adopted to achieve these policy objectives have been as varied as the policies themselves (Jones & Hervik, 1992, Marshall and Banister, 2000); traffic calming measures to reduce accidents and environmental impacts in Germany and The Netherlands; the imposition of access controls to historic Italian cities and the introduction of tolls on urban roads in Norway to finance road schemes.

2.2 Travel Demand Management

2.2.1 TDM: An Old Adage?- a brief historical perspective

The concept of applying restraint measures to control demand rather than provide for it is by no means novel. Mierzejewski, (1991), Meyer (1999) noted that TDM initiatives in the United States were undertaken in the early and mid 1970s based on legislation to maintain air quality. Authorities not meeting air quality standards had to prepare transportation control plans which typically included vehicular emission control programs, transportation operations improvements and transportation demand management actions.

The fuel crisis of the 1970s was another early initiative. While energy conservation was the main thrust, the measures taken were similar to the TDM actions driven by ambient air quality standards. Carpools and vanpools were some of the measures to emerge.

Larwin et al, (1976) reported a case study of 'transportation system management' programme for the Santa Barbara, California central business district (CBD). The study objectives, namely 'maximising non automobile access, minimising automobile access and maximising internal circulation' would be synonymous with TDM measures even today.

Rye (1999) reports a 'brief flurry' of interest in the UK in the late 1970s and early 1980s on alternative transport modes to the car for the home – work trip to reduce peak hour congestion. The measures included car pooling, minibus pooling and staggered work hours. The government-of-the-day encouraged employers to implement such schemes.

Jacobsen (1969) reports early government interest in the Netherlands on measures to improve public transport and encourage its use by travellers. There was an emphasis on the need for travellers to be more 'discriminating' in their use of the private car especially for home to work trips.

The term 'Travel Demand Management' (TDM) is now common and accepted within the transportation field. The primary purpose of TDM is to reduce the number of vehicles using the road system while providing a wide variety of mobility options to those who wish to travel (COMSIS, 1993). The term describes a 'whole range' of measures designed to control or remove traffic congestion (Bell, 1995). TDM measures are thus designed to maximise the people-moving capacity of the transportation system by:

- increasing car occupancy or changing mode to public transport since buses can use road space more efficiently;
- influencing the time of travel;
- influencing the need to travel;
- influencing route choice where applicable.

A common dilemma that arises in the consideration of TDM measures is that of reducing congestion, whilst attracting more people to activity centres such as the CBD without simultaneously increasing the number of vehicles entering the CBD (Larwin et al, 1976). The greater context of this problem is described by for example Bell (1995) and Kain (2001) amongst others, who note that more 'car attractive' out of town developments have resulted not only in urban sprawl as the elite seek the 'greener belts' for homes, but business have also relocated to these green belts abandoning traffic congested CBD's. This dichotomy between reducing congestion by restraint measures while maintaining accessibility to activity centres and ensuring their economic and social vitality presents one of the major challenges of land surface transportation today.

2.3 Classification of TDM Measures

There are various terms in the literature used to describe measures aimed at relieving congestion through methods other than road building. These include Travel Demand

Management (TDM), Transportation System Management (TSM), Transportation Control Measures (TCM) and Traffic Restraint Measures (TRM) (e.g. Taylor 1999; Meyer 1999). As Meyer pointed out, the evolution of TDM as a crucial component of transportation policy is difficult to benchmark. This was because many actions have been tried out before, which today would be classified as TDM, but were not in the past. Thus, TCM was an early term used in the United States to describe actions aimed at reducing car use for the purpose of curbing air pollution in US cities. The term TCM is still in use today in US literature where it generally encompasses all forms of traffic management including TDM, TRM and TSM (e.g. Pansing et al, 1998). Transportation System Management (TSM) was a US federal policy in the mid/late 1970s aimed at using existing transportation facilities more efficiently through traffic engineering, public transportation, regulatory, pricing, management, operational and other improvements. The impetus for TSM included environmental considerations, capital shortages, opposition by certain sections of the public to highway construction and later the need for energy conservation (ITE, 1982). Traffic Restraint Measures (TRM) are physical measures designed to manage traffic by making car use less attractive (IHT, 1997). These physical measures may for example reduce the speed of cars (e.g. speed humps) and/or extend travel distances (e.g. one way streets and banned turns for cars), or reallocate road space to public transport. Traffic calming measures, traffic collars and traffic cells and mazes constitute traffic restraint measures. It is important to note at the outset that TDM is primarily concerned with changing travel behaviour. However, supply or network measures are also closely related to TDM, and as 'incentives' or 'disincentives' work to support TDM (OECD, 1994). Inevitably, at times no explicit distinction is made between 'Demand' side measures and 'Supply' side measures especially where one serves to support the other. The major basis of commonality between demand and supply side measures in this context is that none of the measures involves large scale capacity addition through road construction.

Jones and Hervik (1992), divided TDM measures into three groups:

2.3.1 Measures that do not involve explicit Restraint

Such measures include:

(i) The 'do nothing' option whereby congestion itself is left to restrain traffic. However, although such a system might be seen as 'fair' by the private motorist, it is unacceptable from an economic and environmental point of view as it overlooks the facts that:

- some journeys are more important to the economy than others (e.g. business travel);
- some travellers place a higher value of time to their travelling than others;
- journeys are not of equal length and so long distance journeys impose more costs on the transport system than do shorter journeys;
- road transport externalities are not accounted for.

(ii) Controls on stationary traffic – these measures are mainly by the control of on–street and off-street parking.

Controlling on street parking increases link and junction capacity, while limiting the amount of both on street and off street parking in an area or zone restrains the number of vehicular trip ends into the area. Parking curbs to achieve this objective include regulating the duration and timing of parking, limiting the total number of parking spaces available and regulating the charging for parking.

The major shortcomings of parking controls are that:

- through traffic is far less affected than terminating traffic;
- non-compliance by motorists is rife;
- from an efficiency perspective of road use, parking controls are a 'second best' optimal measure as they are not directly related to the contribution to congestion of the particular vehicle;
- municipalities usually control a limited stock of the total available parking. The rest is controlled privately. In particular, private non residential parking (PNR) such as is attached to offices, work places, shops and various public buildings constitutes a significant proportion of parking spaces within local authority boundaries.

Proposed measures to tackle parking in non residential areas include measures on current/existing supply, and/or measures on future supply. To tackle current/existing supply, local authorities could:

- acquire the large private parking garages and make them available to public use at non subsidised prices; this would be very expensive unless central government rather than local authorities funded such acquisitions;
- charge a tax for each existing private parking space and use the income to fund employer transport schemes or in improving public transport.

To tackle future supply, local authorities could:

- restrict future supply by restricting the non – operational parking spaces attached to new developments;
- similarly tax such private parking as above.

The issue of parking in non residential areas is an area of research in its own right. Its potential behavioural impacts and the network effects need to be understood (e.g. IHT, 1997).

(iii) Use of catalytic converters–improvements in car technology more generally, is expected to reduce the atmospheric pollution from vehicular traffic. European regulations now require that all petrol engines from 'K registration' vehicles onwards, be fitted with a catalytic converter in the UK (e.g. AA, 1997). Catalytic converters help in cleaning engine exhaust gases particularly by reducing the harmful exhaust components hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x). There are concerns though, that in the absence of some form of traffic restraint, the gains made by improved car technology to reduce exhaust emissions could be undermined by the growth in vehicle numbers.

(iv) Information technology–Advanced Transport Telematics (ATT) measures such as improved traffic control systems, pre–trip information, in–vehicle route guidance etc. aim to ensure efficient use of available capacity through advanced traffic control systems and provision of timely information about the transport network.

- advanced sensing;
- information processing;
- communications
- control technologies.

It is argued that although ATT systems improve efficiency and/or driver information they will also tend to induce suppressed traffic and, thus, might have a limited sustainable role for solving global traffic problems in the long run. However, in the short to medium term, ATT systems can potentially increase capacity by 10 to 20% (Jones & Hervik, 1992). Krammes (1994) addresses the need to integrate supply (through IVHS (Intelligent Vehicle Highway System)/ATT) and demand in solving congestion. This 'evolution' of ATT technologies to embrace public transport and transportation demand management applications and thus be integrated with demand management is seen as the way forward for their implementation.

2.3.2 Controls on moving traffic by Non-pricing Traffic measures:

These act by limiting the capacity of a link, junction or network by deliberately restricting space or time available for vehicular movement.

These include:

- Traffic calming measures;
- Traffic collars;
- Traffic cells and mazes.

Alternatively regulatory measures are used to control the road user class allowed access to the link or area. Examples include:

- Regulatory bans of motor vehicles in designated pedestrian areas or links;
- Even/ odd number plate on alternate days as in Athens;
- Blanket bans on all motorised traffic other than specially selected ones such as local residents;
- Restrictions on designated vehicle types;
- Entry by permit.

The above measures primarily act as **disincentives** to car use and thus encourage a modal shift to public transport or non-motorised modes.

2.3.3 Controls on moving vehicles by road user pricing traffic measures.

Economic efficiency lies at the core of using road user pricing measures to ration the use of available road capacity. Ideally road pricing should charge vehicles according to their contribution to congestion at that particular place (spatial variation) and time (temporal variation of congestion). The distinction of road pricing from other fiscal measures such as fuel and road taxes, parking charges and parking taxes is that road pricing seeks to charge motorists for their true costs of driving and thus reconcile car use with its contribution to congestion. The other measures do not make this direct link, but act as surrogate charges.

Policies that focus on car use with road pricing and with selective reductions in road capacity are seen as offering long term solutions to road congestion. Capacity reduction measures serve to support the former and prevent the inducement of latent demand. A more detailed look at road pricing is given in section 2.5.

2.3.4 Classification by COMSIS

COMSIS (1993) provide an inventory and synthesis of TDM measures. They catalogue 11 different categories of such measures. These are further divided into three broad groups as listed below:

(i) Improved alternatives

1. Transit Service Improvements
2. Carpool Programmes
3. Vanpool Programmes
4. Bicycle and Pedestrian facilities and site improvements.

The principle to this measure is to provide equally attractive alternatives to the SOV.

(ii) Incentives and Disincentives

5. Employer complementary support measures
6. Preferential High Occupancy Vehicle (HOV) treatments
7. Economic incentives
8. Parking supply and pricing management
9. Tolls and Congestion pricing.

Incentives and disincentives; the so called 'carrot and stick' approach, are necessary to solicit the required travel behavioural shifts.

The principle to these measures is the realisation that the SOV has an unfair advantage over HOV modes. By applying 'disincentives' to car users and 'incentives' to non car users an attempt is made to address this imbalance as well as provide alternative choices for motorists displaced from their vehicles.

(iii) Alternative work arrangements include:

10. Variable work hours/Compressed Work weeks
11. Telecommutting/teleworking

This group of measures aims to shift the time of travel to less congested periods or to reduce the frequency of travel through alternative 'home based' work patterns. The former change the temporal distribution of traffic so that demand at all times does not exceed capacity. The later may remove or reduce car trips through 'home - working' or reduce car trip lengths in the case of 'tele-cottages'.

May (1986) categorises restraint methods according to the stage in car acquisition and use at which the restraint policy is brought to bear and according to the type of penalty imposed as follows:

- on car ownership generally or to a specific area;
- on the destination for a journey;
- while the car is in use.

Four types of penalty or controls are given:

- physical restrictions;
- time penalties;
- regulatory controls;
- price.

	Target		
Penalty	**Ownership**	**Parking**	**Use**
Physical	N/A	Closure of spaces Supply constraints	Traffic cells; mazes; Speed humps;
Regulatory	Household maxima parking space requirements	Opening hours Duration limits Permit systems	Permit systems Odd/Even numbers
Delay	N/A	N/A	Zones & collar Gating
Fiscal	Taxation Selective taxation	Parking charges	Road pricing Area licensing Cordon pricing

Table 2.1. Types of restraint measure (From May, 1986)

May, interestingly and importantly notes that restraint measures maybe imposed on any vehicle but are most frequently aimed at the private car. Table 2.1 above shows at which stage each penalty is appropriate.

Marshall and Banister (1997) note that travel reduction strategies or policies cannot be designed in isolation of the travel trends necessitating such measures. Travel reduction strategies may be applied directly to influence the trends which are the subject of concern, or indirectly by addressing some of the contributing factors to those trends.

These travel reduction strategies maybe classified in terms of their potential for influencing switching or substitution mechanisms. These switching and substitution mechanisms represent the outcome of travel reduction strategies in terms of travel behaviour and maybe listed as:

- Switching modes
- Switching destination
- Switching time
- Substitution by linking trips
- Substitution by technology
- Substitution by trip modification.

The significant influences of each travel reduction measure on a switching or substitution behavioural response maybe seen in Table 2.2 overleaf.

2.3.5 Implementation Issues

Although not presented as a classification criterion in the literature, it is important to differentiate TDM measures according to who can or does implement them. This is important since certain measures may require legislation while at the other end some initiatives can be at the individual's discretion. In a review of implementation for the seven European countries in the DANTE project, Marshall and Banister (1997) found that local authorities were the largest single category responsible for implementation. They dominated the 'restriction to access and parking' and 'physical measures' classes of TDMs. TDMs concerning prices and taxation were the responsibility of central government. The remainder of the measures were implemented by various organisations including employers. Rye (1999) using US, UK and Dutch experience argued that only a minority of employers will voluntarily implement employer transport plans. Hence regulation or fiscal measures maybe required to encourage widespread adoption of Employer Transport Plans (ETP) by organisations. Meyer (1999) also noted the importance of some form of stringent regulatory measure to ensure take up and hence effectiveness of employer based strategies rather than making them voluntary. Elsewhere, Potter et al, (1999) proposed changes to the UK taxation system to promote the adoption of employer or green transport plans by employers.

	SW			SUB		
Measures	Mode	Destination	Time	Link Trips	Technology	Modification
Capacity Management and Traffic Restraint	*	+		+		
Pricing, Charging and Taxation	*	*	*			
Land Use Planning: Location and Access	+	*		*		
Communications and Technology	*			+	*	*
City and Company Travel Policies	*		+	+		
Physical Measures: Road space and Priority	*			+		
Subsidies and Spending for sustainable modes	*			+		
Restrictions on Access and Parking	*	*	*			
Deliveries of Goods and Services	+			+		*
Public Awareness	*	+	+	+	+	+

Table 2.2. Travel Reduction Measures and Mechanisms (Marshal & Banister, 1997,2000).

SW = Switching Mechanism
SUB = Substitution Mechanism
* = Significant influence + = Some influence

2.3.6 Classification by measures of Evaluation and Comparison

Classification can also be by various criteria of comparison. May (1986) advocated comparison of the restraint policies by:

- Effectiveness to reduce congestion and or environmental intrusion;
- Flexibility to respond to uncertainties;
- Selectivity by specifically targeting and penalising each journey, user class or vehicle type according to its contribution to congestion or environmental intrusion;

- Simplicity so that both the user and operator understand the controls and the responses expected;
- Containment so that the effects of the control measure do not spill over and transfer congestion and/ or environmental intrusion to other areas, times, or impose problems on other modes or non travellers.

Johnston et al. (1995) presented a comparative discussion and qualitative multi-objective evaluation of 8 capacity allocation measures for reducing urban traffic congestion. The capacity allocation methods were classified and qualitatively compared against four criteria; effectiveness to reduce congestion, economic efficiency, income distribution effects and flexibility of access for urgent trips.

- The laissez - faire allocation method in which no control is exercised on entry and exit from the roadway is akin to the 'do nothing' scenario described by Jones and Hervik (1992). Drivers are left to enter the road until the congestion cost they experience exceeds the costs to them of taking an alternative route, mode or deferring the trip. Despite allowing access for all users, this approach is ineffective, very inefficient and inequitable as time costs are high for wealthier travellers.
- Allocation by passenger load - HOV lanes were introduced in the USA to both maximise highway passenger carrying capacity (persons per hour) and to provide incentives for carpooling and transit use by providing faster travel times on those lanes. In areas where land use and travel patterns are not conducive, HOV lanes can be underused. This results in lower passenger carrying capacity of the roadway by the removal of a mixed flow traffic lane. In the UK, bus lanes are meant to provide less travel impedance to buses and sometimes other selected classes of vehicle such as taxis at the expense of the SOV. HOV lanes are moderately effective but they are economically inefficient, since willingness to pay is not exercised as a means to gain access. Such lanes are considered 'somewhat equitable'.

In the United States SOV users have been given access to HOV lanes for a fee (Chu & Fielding, 1994; Dahlgren, 1999). Such lanes, termed High Occupancy Toll (HOT) lanes allow SOV and HOV to use the same lane. The rationale is that a HOT lane uses HOV facilities more efficiently by giving free access to vehicles with three or more occupants while permitting other vehicles to pay a toll for access if they value time savings more than the toll. Misgivings have been expressed by others on the hypothesis that HOT lanes would discourage ridesharing since it reduces the travel time for SOV users who could afford to buy access. However, these fears have been disputed by Chu and Fielding (1994). Using a simulation model they showed that HOT lanes using electronic road pricing could result in increased average vehicle occupancy (AVO).

- Ramp metering is another road allocation method common in the USA. Allocation to roadway is on a first come, first served basis or 'First In, First Out' (FIFO). Ramp metering has been known to reduce average trip times and increase freeway vehicle flow. Although perceived as socially fair due to its FIFO approach, it is, however, economically inefficient as it does not allow 'front liners' to trade their spots with 'back liners' for monetary compensation and time spent in ramp queues can be significant. It is not very equitable as it does not consider travellers' differing values of time. Blocking back of downstream junctions can be a problem. Considerable research into ramp metering as an access control measure, has been undertaken, e.g. (TRG, 2000; TRANS–AQ, 2000); Banks, 2000, King and Gillen, 1999). These studies employ various methodologies ranging from simulation models to field trials to study the benefits and disbenefits of ramp metering. The potential impacts of ramp metering were recently outlined by PATH (2000). Benefits include efficient use of capacity, improved safety, reduced vehicle emissions and travel time savings. Costs include diversion, equity, installation and maintenance costs, on ramp emissions, possible promotion of longer trips, ramp delay and spill back, public opposition and transfer of land values.
- Road pricing - road pricing rations capacity on the basis of willingness to pay. From the perspective of economic theory road pricing is the most efficient method of capacity allocation. Where charges are varied appropriately to reflect contribution to congestion, road pricing would be effective and efficient. Where revenues are invested into improving transport choices, equity is also achieved. Access by low income groups may not be flexible.
- Allocation by trip purpose - This method draws its inspiration from the public's acceptance to give preferential right of way to emergency service vehicles such as fire services, ambulances and the police in recognition of the importance of

the 'purposes of such trips'. The author argues that this trip purpose road space allocation could become broader and more complex if a workable 'prioritisation of trip purpose' were developed. Problems of dealing with simultaneous similar trip purposes and enforcement are evident. Then there is also the question of how to deal with mixed - purpose trips or trip chaining. Such a system has the potential to reduce congestion only in cases where there is a substantial mix of trip purposes demanding road way use at peak times. If successful, allocation of road space by trip purpose would be 'somewhat effective', not very efficient and 'somewhat equitable'.

- Rationing - This could take several forms such as rationing by Vehicle Miles Travelled (VMT) per hour, rationing permission to use specific segments of road way or rationing of goods associated with road use such as land for parking. The medium of trading could be electronic coupons based on automatic vehicle identification (AVI) technology. Non tradable or transferable rations would arrest profiteering at the expense of flexibility and overall economic efficiency. Tradable rations would allow low income earners to trade their rations to supplement their income. This would result in a progressive income redistribution. Although difficult to administer and moderately effective, tradable rationing would be somewhat efficient and equitable.
- Mixed strategies - It is widely accepted that mixed strategies are likely to make practical, economic and political acceptability ahead of single measure strategies. Examples include:
- road pricing and public transport subsidies, plus bus lanes (or mixed flow capacity reductions) for equity and public acceptance (+ curtail latent demand);
- road pricing with limited permits to local residents to reduce inequities;
- peak period pricing combined with ramp metering for those unwilling to pay for economic efficiency;
- road pricing accompanied by public transport and road improvements to provide alternative modes and for political support.

A summary of Johnston et al.'s multi–objective capacity allocation methods is given in Table 2.3 below.

Capacity allocation measures	Ratings on Policy Objective (high = best)			
	Practical Congestion reduction effectiveness	Economic Efficiency	Economic Equity for Poor	Immediate Access Flexibility
Road Pricing	Med -High	High	Med - High	Med - High
Tradable Rations	Med -High	Med - High	Med - High	Med - High
Allocation by purpose	Low – Med	Low – Med	Med	High
Ramp metering	Low – Med	Low	Med	High
Allocation by occupancy	Low – Med	Low	Med	Med
Non tradable rations	Low – Med	Low	Med	Low – Med
Laissez-faire	Low	Low	Med	High

Table 2.3. Multi-objective Evaluation of Capacity Allocation Measures (From Johnston et al. 1995)

2.3.7 Other Examples of TDM Classification

There are other examples of classifications adopted by different authors, although there is evident overlap with the classifications noted above. Koppelman et al (1993) for example very broadly classified demand management actions into simply two strategies:

i. **Demand Reduction Strategies**–these alleviate congestion by reducing the 'built in biases' that favour solo auto commuting. To this end the authors subdivide these strategies into actions that promote ride sharing through 'ridesharing incentives' and actions that promote ridesharing through single occupancy car use disincentives. The main issue in demand reduction strategies is that reduction in car use and hence car numbers on the network must occur through some form of mode change or increase in vehicle occupancy. This could also embrace reduction in solo auto use through teleworking or telecommuting for example in which both the car and person trip are foregone. It could also include mode change to cycling or walking.

ii. Demand Shifting Strategies in which congestion is alleviated by such mechanisms as 'temporal dispersion' of peak period traffic through flexitime, shift in work hours and 'voluntary' peak spreading in order to avoid congested peak periods. The main characteristic in demand shifting strategies is that very often there is 'modification' in behaviour to solo car driving but no reduction as such in overall car numbers.

This simplified two pronged classification into 'demand reduction' and 'demand shifting' mechanisms is attractive for modelling and comparing the network effects of specific behavioural changes attributable to specific TDM measures.

Meyer (1999) divides TDMs into three broad categories, namely:

- Those strategies whose action is by offering travellers one or more alternative transportation modes or services that result in higher per vehicle occupancy (mode changes)
- Those strategies whose actions provide incentives/disincentives to reduce travel or 'push' trips to off peak periods and/or
- Those strategies in which the **trip purpose** is accomplished through 'non – transportation' means such as through substituting the use of telecommunications for work or shopping trips.

There is clearly overlap between Meyer and Koppelman's classifications. However, Meyer explicitly pointed out the need to accomplish the 'trip purpose' even if no physical trip was made. This not only acknowledges the derived nature of travel, i.e. that trips are not made just for their sake, but that trips are associated with specific utilities by those who undertake them and which may place constraints on the ability of those affected to respond in particular ways. To this end Meyer notes that TDM measures can only specifically target certain travel markets and/or specific trip purposes (see Table 2.4). Therefore the type and effectiveness of actions to influence the commuting trip might be different from those oriented towards the shopping trip. This is reflected in the limited evidence in the literature of elasticity estimates specific to travel markets (e.g. Brown et al, 1993; Richards, 1994; Turner et al, 1999). Meyer concludes that the targeting of TDM actions and the corresponding incentives/disincentives to specific travel markets is one of the key challenges to the success of a TDM policy. Meyer's assertions are consistent with Bonsall et al, (1998) findings based on, amongst other things, stated preference surveys and laboratory simulator experiments in which constraints were found to limit traveller choices to road user pricing, for example.

	Geographic Coverage of TDM Measure		
Trip Purpose	Local Site Level	Sub-area/Corridor	Regional
Work	Carpools Vanpools Public/private transit Bicycling/walking Alternative work hours Site telecommuting Parking policies	Suburban rideshare Corridor HOV Parking policies Transit subsidies Sub-area telecommute	Area-wide rideshare Transit service HOV lanes Area-wide pricing Area-wide telecommute Trip reduction ordinances Area-wide traveller information system
Shop	Shuttles Transit subsidies Pedestrian access Urban design Tele - shopping	Shuttles Park and Ride Transit services	Tele-shopping Transit subsidies Area-wide transit services Area-wide traveller information system
Tourist	Shuttles Parking policies Transit services	Park– and– ride lots Parking management Shuttles Transit services Bicycle/pedestrian amenities	Regional transit services Marketing Park and ride lots Area-wide traveller information system

Example Delivery Mechanisms for TDM Programs

Site level	Sub-area/Corridor	Regional
Employer transportation coordinators Part time transportation manager Voluntary participation Negotiable traffic mitigation Site design	Transportation management associations Chambers of commerce Trans. Management districts City or MPO coordinator	Trip reduction ordinances Adequate public facilities ordinances Growth Management State, MPO, or transit agency coordination

Table 2.4 Demand Management Tools as applied to travel markets (Meyer, 1999)

A recent classification by Litman (2000) divides TDM strategies into six categories as follows:

i. **Enabling Programmes** – these provide an overall institutional framework for implementing TDM. This includes the 'reforming of transportation institutions' to support TDM such as the guidelines provided by the British government into supporting Green Transport Plans (GTPs) or Employer Travel Plans (ETPs)

ii. **Alternative Mode Improvements and Encouragement** – such measures aim to increase the number and quality of travel choices, and provide users with incentives to use more efficient modes. This includes, for example, transportation allowances, subsidised public transport passes; park and ride facilities; public transport improvements; rideshare programmes and so on.

iii. **Driving Disincentives** – these measures discourage car use and include full cost or direct user pricing; increased fuel taxes; and vehicle restrictions amongst others.

iv. **Parking Programs** – these are based on more efficient parking management and should ideally be comprehensive parking programs that avoid 'interjurisdictional competition and spillover'.

v. **Marginalising User Costs and Reducing Automobile Ownership** – these are based on the fact that cars are relatively expensive to purchase and relatively cheap to use. Marginalising costs by converting fixed costs into variable costs might be effective at reducing vehicle use. Thus normally fixed costs such as insurance, licensing and registration could be say distance–based.

vi. **Land Use Management** – these measures aim to create more 'transportation efficient communities' through for example higher density/mixed land use developments. Other land use based measures include 'neotraditional' neighbourhoods and public transport oriented development. According to Litman, neotraditional neighbourhood design emphasizes small scale blocks, an interconnected street network, good pedestrian and bicycle facilities, and moderate to high density mixed land use. Public transport oriented designs ensure higher density development within reasonable walking distance to public transport facilities and design features that support a variety of modes. Further, services such as cafes, shops, child care facilities, cinemas and so on must be located at public transport and employment sites.

2.4 Land Use and Travel Demand

It is now accepted that the amount of travel in total is related to the spatial locations of activities such as homes, jobs, schools, shops and so on (e.g. Bell, 1995; Bowman & Akiva, 2001). Constraints on land use imply that the degree of substitution between activities or between locations is limited. The extent to which increases in network costs are likely to influence location choices of home, work place, schools and shops is likely to be minor in the short term and uncertain in the long term. Nevertheless, there is a recognition of the role of land use planning in easing travel demand.
The potential for land use changes to reduce travel demand could arise from:

(i) In the shorter term existing land uses have to be adapted to minimise car travel demand. Some of the methods of achieving this include:
(a) the provision of on site services or amenities at work. Facilities such as on site cafeteria, convenience stores, banks and so on should reduce mid day travel as well as travel during and after work;
(b) the provision of public transport amenities close to work and commercial sites. This minimises walking distances to public transport facilities.

(ii) In the long term the design of cities with a more compact urban form, incorporating mixed, compatible land uses, higher density development in corridors, concentrated centres and explicit plans for pedestrian and bicycle access should result in:
(a) shorter trips and hence less VKT;
(b) possibility of more trips being made by cycling or walking;
(c) more efficient use of public transport.

The concentration of both residential and employment sites fosters non car oriented travel by removing impediments to the use of public transport, carpools, walking and cycling. Zoning laws that limit the number of parking spaces that can be provided on employment sites, also curb car oriented commercial development.

2.4.1 Impacts of TDM

TDM measures are expected to bring about travel behavioural changes or impacts. While the typology of impacts is relatively well known, the magnitudes, sequence or hierarchy of impacts is not well understood nor are the potential network implications of these behavioural changes (Harvey, 1994). It is believed that different market segments will respond differently. This should translate into aggregate travel choices generally leading to reduced travel demand, in total or at certain times of the day; lagged traffic growth and hence reduced congestion. As a result it is expected that network performance should improve. However, the extent of network improvements due to specific behavioural changes are not often quantified; there mainly being an intuitive assumption that these network benefits will be significant.

There is concern and speculation that the improved network level of service might induce latent demand, as evidence on capacity addition seems to suggest (SACTRA, 1994; Noland, 2001). Therefore capacity reductions or reallocation of 'freed' capacity from mixed traffic or SOV to public transport and/or pedestrians is often considered an essential ingredient to the realisation of the full potential of TDM measures (e.g. FitzRoy & Smith, 1993).

This research is mainly concerned with quantifying and comparing the extent of the potential overall network changes that may result from specific travel behavioural responses. It is not specifically within the realms of this study to investigate how and if indeed such network benefits might be realised. Rather, the objective has been to define a realistic upper bound to the network effects that might accrue from selected behavioural responses arising from TDM measures. A list of these behavioural changes is given in Chapter 3.

2.4.2 Remarks

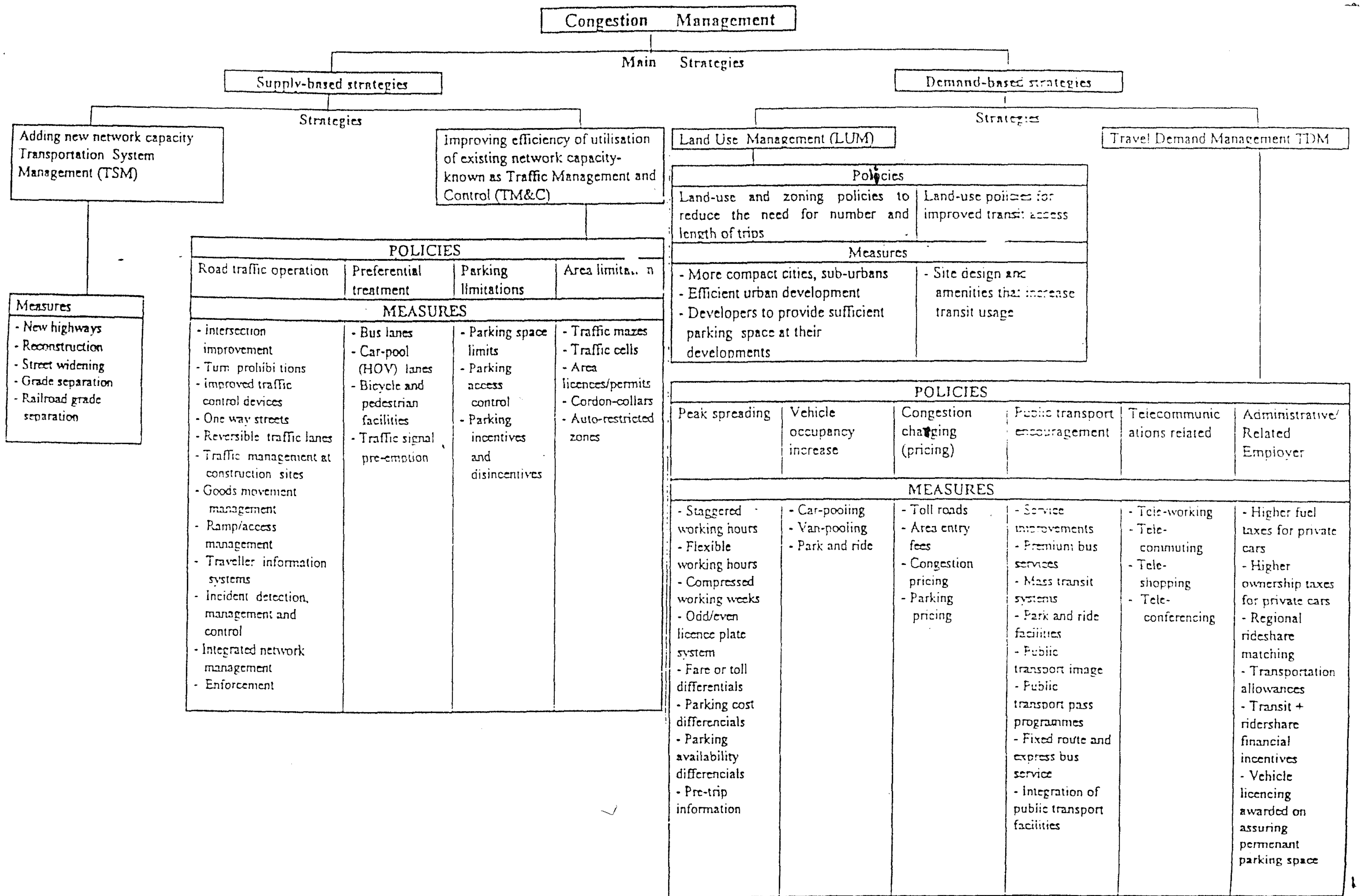
The above review has shown that, whilst there are various ways in which different authors describe TDM measures, there is a remarkable degree of consistency in what these measures are and what they aim to achieve. There is wide consensus that the cornerstone and focus of demand management is to influence the individual behaviour of travellers in such a way that alternative mobility options are used instead of relying on the single occupant vehicle (e.g. Meyer, 1999; Litman, 1999). This reliance for success on people changing their travel behaviour is also its biggest challenge.

The potential role of TDM as a means of alleviating congestion is now acknowledged. However, its acceptance and implementation, is still an area of great debate. The nature of its impacts and the associated network effects are also not very well understood. Indeed, it maybe concluded that a major factor that will aid political and public acceptance of TDM measures is the clear identification and quantification of benefits associated with these impacts. Such evidence will be useful in supporting the argument for the case of TDM measures such as road pricing. Another point of uncertainty in the literature is the extent to which direct user charging methods are more effective than other TDMs, although there seems to be a view that because of their more aggressive coercive nature, direct user charging methods might be more effective than other TDMs. However, it is important to remember that;

- Solutions cannot be universal but each particular situation must be looked at in its own context. Often a mixture of demand side and supply side measures will be required to complement and support each other.
- Alternative choices must be made available to overcome mobility restrictions placed by TDM measures. This implies striking a proper balance between incentives and disincentives.
- A balance must be struck between reducing congestion on the one hand through the imposition of TDM measures while maintaining accessibility and mobility to activity centres to ensure the economic vitality of affected areas.

While public acceptance and political misgivings pose serious challenges to the implementation of TDM measures such as road pricing, another grave issue is that of 'boundary effects'. There is fear that car restraint policies might not have the desired effects such as a large scale switch to public transport but instead may result in motorists switching their activities to other destinations not subject to restrictions, or drive to the edges of restricted areas. These fears call for the need to extend car restraint policies over large geographical areas if they are to be effective. This will require the co-operation of neighbouring local authorities. These wider concerns, while important in ensuring competent and fair TDM measures, are beyond the scope of this research. The issues nevertheless serve to depict the various intricate issues about these measures and hence the complex mechanisms that may influence the impacts of these measures.

Abbas et al, 1997 has produced a comprehensive hybrid categorisation of congestion management strategies using European, American and Australian documentation. This Figure is reproduced here as Figure 2.1. It shows TDM in relation to other congestion management measures in general.


Congestion Management
Main Strategies
Supply-based strategies
Demand-based strategies
Strategies
Adding new network capacity Transportation System Management (TSM)
Improving efficiency of utilisation of existing network capacity- known as Traffic Management and Control (TM&C)
Measures
- New highways
- Reconstruction
- Street widening
- Grade separation
- Railroad grade separation
POLICIES
Road traffic operation
Preferential treatment
Parking limitations
MEASURES
- intersection improvement
- Turn prohibitions
- improved traffic control devices
- One way streets
- Reversible traffic lanes
- Traffic management at construction sites
- Goods movement management
- Ramp/access management
- Traveller information systems
- Incident detection, management and control
- Integrated network management
- Enforcement
- Bus lanes
- Car-pool (HOV) lanes
- Bicycle and pedestrian facilities
- Traffic signal pre-emption
- Parking space limits
- Parking access control
- Parking incentives and disincentives
- Traffic mazes
- Traffic cells
- Area licences/permits
- Cordon-collars
- Auto-restricted zones
Strategies
Land Use Management (LUM)
Policies
Land-use and zoning policies to reduce the need for number and length of trips
Measures
- More compact cities, sub-urbans
- Efficient urban development
- Developers to provide sufficient parking space at their developments
- Site design and
transit usage
POLICIES
Peak spreading
Vehicle occupancy increase
Congestion charging (pricing)
Telecommunications related
Administrative/ Related Employer
MEASURES
- Staggered working hours
- Flexible working hours
- Compressed working weeks
- Odd/even licence plate system
- Fare or toll differentials
- Parking cost differencials
- Parking availability differencials
- Pre-trip information
- Car-pooling
- Van-pooling
- Park and ride
- Toll roads
- Area entry fees
- Congestion pricing
- Parking pricing
- Premium bus services
- Mass transit systems
- Park and ride facilities
- Public transport image
- Public transport pass programmes
- Fixed route and express bus service
- Integration of public transport facilities
- Tele-working
- Tele-commuting
- Tele-shopping
- Tele-conferencing
- Higher fuel taxes for private cars
- Higher ownership taxes for private cars
- Regional rideshare matching
- Transportation allowances
- Transit + rideshare financial incentives
- Vehicle licencing awarded on assuring permenant parking space

2.5 Road Pricing

In the sections that follow, a more detailed review of the main issues on road pricing are considered.

2.5.1 Fiscal Measures of Charging for Road Use

Road pricing is just one of a number of possible fiscal measures that can be used to charge for road use. A more comprehensive list of such fiscal measures would include:

- Fuel taxes
- Differential fuel taxes
- Purchase taxes
- Annual taxes
- Tyre taxes
- Poll taxes
- Parking taxes/charges
- Road or motorway tolls
- Shadow tolls
- Workplace charging
- Congestion charging and road pricing/direct road user charging or full cost pricing (these terms are used interchangeably in this work) although there may strictly be variations depending on the context in which these terms are used (see e.g. Milne, 1997; IHT, 1997; Litman, 2000).

Smeed (1964) divided the measures into direct and indirect methods as shown in Figure 2.2. Fundamentally, indirect methods such as purchase tax and annual licences are easier to collect than direct methods. However, indirect methods are not specific to the journey in terms of location of congestion, and time of congestion. Thus, from a marginalist point of view, indirect charging methods are inferior to direct charging methods.

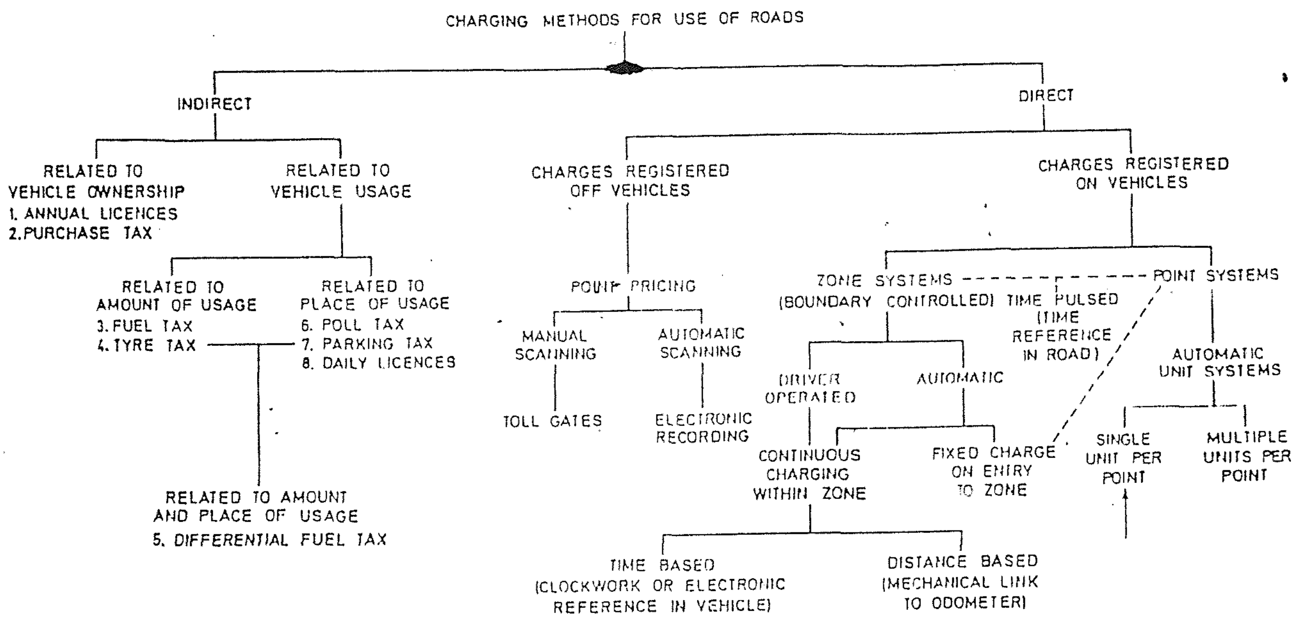


Figure 2.2 Classification of Charging methods for use of roads (Smeed , 1964)

2.5.2 The impetus for Road Pricing

The strength of congestion pricing lies in its economic rationale. Indeed, quoting Arnott et al, 1994, Verhoef et al, (1997) notes that economists are quite baffled as to the rejection by politicians and the motoring public of what is 'obviously a good idea'. This view is reiterated by Thomson (1998) who quotes Evans (1992) when he wrote that 'the theoretical case for road pricing was irrefutable.' The interest being shown in road pricing in the 1990s can be said to be due to (e.g. Bhatt, 1994):

- The need to use the existing infrastructure more efficiently – this is the economic rationale behind charging motorists for road use.
- The need to reduce congestion – pricing will regulate travel demand directly through a price mechanism. Motorists that do not value their journey above the true costs of their driving will be 'priced off' the road. This will lead to less traffic and improved traffic flow conditions. In the United Kingdom congestion reduction has been seen as the main rationale for the case of road pricing (Jones & Hervik, 1992).
- Revenue generation for infrastructure provision or enhancement – as funding for infrastructure becomes scarce, tolls have been used to generate revenue for this purpose. Revenue generated is also seen as a means of financing public transport improvements. This has been the case in some tolling schemes in Norway. Tolling for infrastructure provision e.g. bridges and tunnels are also in operation in the UK. Examples include the Severn bridge, the Humber bridge, the Itchen toll bridge, the Mersey tunnels and the M25 Dartford river crossing east of London amongst others (e.g. Button, 1987). Shadow tolls are also in use in the UK. In this case the cost of road building is borne by the private sector. The government then pays a fee to the investor for every car using the road over a set period. Subsurface sensors count the vehicles using the road.
- The need to improve air quality – environmental considerations are playing an important role in the case for road pricing. For example, in the United States the Clean Air Act Amendments (CAAA) of 1990 prohibits new capacity addition in areas failing to meet federal air quality standards.
- Advances in technology make automatic toll collection possible without disrupting traffic flow.

A number of the reasons for introducing road pricing are consistent with those for introducing other TDM measures.

2.5.3 The Theoretical case for Congestion Pricing

Perhaps the case for road user charges could not have been put better than by Walters in the 1968 World Bank Staff Occasional Papers Number Five; 'The Economics of Road User Charges' when he wrote, quote:

'Cost is the economic bedrock of the user charge. The price for the use of the road should measure the value of the resources expended in providing the service. With a user charge reflecting the cost, the road user can decide whether his interests are best served by 'buying' the road journey or by purchasing some other commodity; and the resources will be devoted to the use that most satisfies him. When prices reflect costs, resources will be efficiently distributed between road journeys and other things, and between one sort of road and another, and between one agency and another. This, stripped of the qualifications, is the essence of the case for economic user charges.'

This idea is usually traced back to the 1920s debate of Knight and Pigout, and by some authors (Mogridge, 1990) to as early as the French engineer, Dupuit in 1844, and by Morrison (1986) to Ellet in 1840 and Dupuit in 1849. The idea embodies the fundamental economic principle of marginal cost pricing which provides the theoretical background of congestion pricing. The principle states that road users using congested roads should pay a toll equal to the difference between the marginal social cost (MSC) and the marginal private cost (MPC) to maximise social net benefit (Yang & Huang, 1998). A driver entering the road will only consider the cost that he or she personally bears. This cost represents the average or private cost of congestion at each level of demand (measured as number of trips or traffic volume). The marginal private cost (MPC) is therefore the additional cost borne and perceived by the driver on entering the traffic. However, the driver is unaware of the cost that they impose on other drivers or to society as a whole as a result of their entry onto the road. The additional cost to other drivers of adding one extra vehicle to the traffic stream is called the marginal social cost (MSC). The difference between the MSC and the MPC at any given level of demand or traffic volume, reflects the economic costs of congestion at that demand. It is the optimal toll that represents the extra cost that a driver entering the traffic stream at that point must pay above their private costs.

From an economic perspective, the problem of traffic congestion arises because road systems have grown up everywhere without 'direct reference to market forces (Beesley, 1973). Excess demand arises because there is no 'rent' for the use of scarce road space. As a result users are only aware of the costs they pay for their driving (such as vehicle running costs) but ignore the 'opportunity cost' of their decisions such as delays to other motorists (see Table 2.5). Since road space is not sold with reference to market forces, high demand road space for certain time periods has a 'price' similar to low demand space or low demand time period. This failure to ration high demand by some means such as by road pricing causes increases in the use of private cars and reduced public transport patronage (Kolsen & Dowcra, 1977).

Traditionally, the response to traffic congestion has been to add or build more capacity. Beesley (1973), however, notes that the response of supply to excess demand is both slow and uncertain. There is therefore a need to use existing capacity efficiently and road pricing is the 'first–best option'. Ideally a 'marginalist' pricing system would differentiate by:

- degree of congestion;
- time of day;
- by location;
- by road type;
- by vehicle type.

The optimal toll would thus vary dynamically as road conditions changed. Such a complex charging system would, however, fail to conform with some of the fundamental requirements identified by Smeed (1964) in that:

- prices should be stable and readily ascertainable by road users before they undertake the journey;
- the method should be simple for road users to understand.

Another point to note is that this 'congestion delay' based approach of the case for congestion pricing is an oversimplification of the theory of marginal cost pricing. This is because it overlooks the fact that in theory such a mechanism must address all the externalities of motoring shown in Table 2.5. The quantitative information on some of these costs is difficult to work out. (e.g. Newbery, 1998). Thus it is not an easy task to determine an optimal toll taking into account all relevant externalities.

Cost Categories	Social Cost	
	Internal/Private Costs	External Costs
Transport Expenditure	-fuel & vehicle costs;tickets/fares	-costs paid by others (e.g. free provision of parking spaces)
Infrastructure Costs	-user charges, vehicle taxes & fuel excises	-uncovered infrastructure costs
Accident Costs	-costs covered by insurance, own accident costs	-uncovered accident costs (e.g. pain and suffering imposed on others)
Environmental Costs	- own disbenefits due to poor air quality	-uncovered environmental costs(e.g. noise disturbance to others)
Congestion Costs	- own time costs	-delays/time costs imposed on others

Table 2.5 Classification of the Costs of Transport (from: The European Commission document 'Towards Fair and Efficient Pricing in Transport-Policy Options for Internalising the External Costs of Transport in The European Union')

2.5.4 Environmental Considerations

While congestion is the main evaluation criteria in this thesis, it is relevant to mention that environmental considerations are also at the forefront of TDM and road pricing initiatives (e.g. Newbery, 1998). Newbery noted that the main social costs of road transport arose from the health consequences of air pollution, the unpleasantness of noise, the loss of amenity caused by visual intrusion and landscape severance as well as from accidents.

In order to appreciate the role that road pricing may play in alleviating pollution (particularly gaseous emissions) from transport sources, it is important to understand the ways in which motorised transport emissions may arise in the course of trip making. The Transportation Research Board (TRB, 1995, 1996) considered emissions from transport as a function of several variables. These included travel related factors, driver behaviour, highway network characteristics and vehicle characteristics. Travel related factors included trip taking and vehicle use, speed, acceleration and load. Emissions varied according to the different vehicle operating modes during trip taking and according to distance travelled. Catalytic converter technology has been most effective in reducing running emissions which are a function of vehicle kilometres travelled. Start up emissions, especially cold start emissions occur irrespective of distance travelled. TDM measures such as road pricing can alleviate pollution from a trip making perspective by reducing the number of trips and hence cutting down on start up emissions. For instance Lyons (1998) considered that TDM could result in the adoption of telecommuting. The author argued that adopters of telecommuting tended to have longer commuting distances. Therefore, increased telecommuting would reduce vehicle kilometres travelled, and ease congestion leading to reduced running emissions. Another advantage of telecommuting, however, would be that the removal of any physical commuting would reduce cold start emissions, which are emissions not governed by how long the trip distance was. The author noted that a typical 5 mile trip generated 61% of the hydrocarbon emissions of a typical 20 mile trip because a high proportion of the emissions occurred during the cold start, the first few minutes that the engine was running. Trip reduction or suppression as a result of TDM measures could therefore potentially reduce both vehicle kilometre associated emissions and cold start emissions. Emissions are also highest in low speed, congested driving conditions. TDM measures may reduce congestion and therefore result in freer-flowing conditions with lower emissions. Driving behaviour may ease emission levels by avoiding sharp accelerations which increases engine load. This is because emissions are known to be a function of smoothness and consistency of vehicle speed. By reducing the traffic on the network through behavioural changes such as peak spreading and trip suppression, TDM measures have the potential to enable those drivers still on the roads to drive more consistently in cruise-type driving conditions and thus reducing on the frequency of heavy accelerations.

Tate and Bell (2000) noted that there was little that was known about how effective travel demand management strategies could be in reducing pollutant concentrations in sensitive areas. They argued that studies up to then, appeared to have been evaluated on small quantities of data and that a number of key variables such as weather, seasonal changes and variations in traffic flow had not been considered. Their study investigated a gating strategy upstream of a series of congested junctions in a SCOOT controlled region of the city of Leicester with the objective of managing the congestion and air pollution in the area and reduce the population's overall exposure. The gating strategy was designed to relocate queues in the morning peak period from sensitive areas with high pedestrian activity, in order to restrict high idling emissions to an open unpopulated area. The study assessment was broadly based on a 'before and after' comparison approach with data collected by direct monitoring of actual changes in traffic and pollutant concentrations and the employment of simulation modelling using the SATURN and DRACULA network models. Details of the methodology, the gating design and the results can be found in the reference. However, the study was able to demonstrate that it was possible to reduce pollution levels in highly populated activity areas at the expense of areas with little or no pedestrian activity. Also, it was concluded that quantifying the effect this change had on people's exposure to pollution required further research. One interesting output of the modelling results was that both SATURN and DRACULA estimated a slight increase in CO emission rates over the network due to the travel demand gating strategy. This was considered to be not a major concern where exposure minimisation was the aim since there was only a small increase in emissions in the area to which the queues were relocated. The impact would thus be reduced by the greater dispersion and lower population activity in the area. The work by Tate and Bell was thus a demonstration of the potential of TDM strategies to reduce the adverse effects of environmental pollution due to road transport.

Emissions also depend on vehicle factors such as vehicle age, engine size and fuel type. These are factors mainly relating to vehicle technology and so the intervention of direct user charging or other TDM measures is less obvious. However, some authors have called for the imposition of vehicle characteristic taxes as economic incentives to reduce pollution from road transport (Johnstone and Karousakis, 1999). The authors noted that although, an emission tax would be the closest approximation to a first-best option to addressing vehicle pollution externalities, the cost of implementing such an emissions tax would be very high. This would be because such a measure would require that actual pollution from each individual vehicle was determined. They therefore argued for a second-best option in the form of a vehicle characteristic tax. Such a tax would be levied on the basis of pollution related vehicle characteristics such as vehicle weight, fuel type, age and engine size. Other authors have called for more stringent tests on cars for on-road emissions to try and control the increased emissions from ageing vehicles (Pickrell, 1999). The author noted that in the USA, on-road emissions averaged four to ten times those of new cars under test conditions. The main cause of this difference was normal deterioration in new cars' emission control systems as they aged, malfunctioning emission control systems, and differences between the carefully-controlled conditions that new cars are subjected to, compared to the conditions encountered in real-world driving. The author, therefore argued that current strategies remained too focussed on technologies to make new cars cleaner under test conditions while doing little to reduce the gap between test and on-road emissions.

2.5.6 Objections to Road Pricing

Perhaps no subject in transportation planning has invoked so sharp and divergent views as the subject of congestion pricing. There is such apparent disagreement even within the academic world as to make the subject 'controversial' (see e.g. Verhoef et al, 1997, who cites a number of debates from the literature on the subject).

Langmyhr (1999) notes that there is a big imbalance between theory and practice in road pricing. Indeed some authors have expressed scepticism about road pricing being accepted in democratic societies (Else, 1986; Borins, 1988). The reasons for this pessimism have been discussed by a number of authors e.g. (Pretty, 1988; MVA, 1995;Verhoef et al, 1995; Langmyhr, 1999; OECD & ECMT, 1990; Fitzroy and Smith, 1993). These include:

- That road pricing would be another tax on the motorist – motorists and motorist organisations consider that they are taxed heavily already. Road pricing could be acceptable if the overall tax on the motorist is not increased i.e. existing taxes must be cut or removed if road pricing is introduced to ensure the same tax levels. Difficulties arise in that current taxes are administered by central government. Local authorities want to retain road pricing revenue for local transport improvements. This potential conflict has to be resolved satisfactorily. Hypothecation of revenues is seen as one way of achieving this.
- Concerns on administering and enforcing road pricing. Technological advancement in vehicle detection, identification and electronic toll collection shows that this should not be a problem now.
- Concerns about invasion of privacy. This arises firstly from concerns about Automatic Vehicle Identification(AVI) technology used in electronic road pricing. Legislation could restrict use of this AVI data. The second concern arises from automatic recording of vehicles. However, the use of surveillance to curb traffic offences e.g. overspeeding and for traffic management is now common in developed countries.

- Concerns that low income motorists will be affected most. Equity issues identify the losers and winners. It is considered that improvements to public transport users, a high proportion of which are low income earners should weaken this stance. Equity considerations will influence public acceptance and hence political will.
- Concerns that public transport would not cope. Revenues generated should see improved quality in bus services and investment in fleet maybe necessary. Converting some of the released capacity into exclusive bus lanes should improve bus speeds and service reliability.

2.6 Innovations in Improving User Acceptance

While there are a number of researchers who have argued that direct user charging would be difficult if not impossible to implement in its current proposed state because of lack of user acceptance, some have suggested ways of reducing unacceptability and resentment (e.g. Richards, 1994; DeCorla–Souza, 1994; Muller and Bernstein, 1998; Harrington et al, 2001). DeCorla-Souza explains that the public perceived themselves as losers under direct user charging because they viewed it as 'just another tax' while some saw it as having a 'disproportionate' impact on low income groups. The author suggested that using 'cashing out' policies as had been successfully done with employer provided parking in the United States could help overcome these objections. Cashing out employer-provided parking is a strategy whereby employers would give their employees the cash equivalent of any parking benefit provided, and employees could then either spend that cash towards paying for the parking rather than receive it for free. The employees could spend it towards any other purpose, including public transport. Some studies (e.g. Bianco et al, 1998) have suggested that public transport ridership for the home-based work trip could increase by as much as 9% as a result of implementing cashing out parking policies. Muller and Bernstein (1998) advocate for 'user neutral' congestion programs in which the total cost of travel including tolls does not increase after the programme is put in place. Using numerical optimisation techniques the possibility of developing more acceptable ' user neutral' congestion pricing programs was demonstrated in which it pricing programmes that increased user costs by no more than 5% and yet yielded welfare gains of about 25%.

Harrington et al, (2001) used a Computer Assisted Telephone Interview (CATI) survey to find out if the details of policy design can make congestion pricing more attractive and hence acceptable to the motoring public. They concluded that a promise to offset the imposition of congestion fees by other taxes (e.g. sales tax reductions; vehicle registration fee reductions, income tax credits or through vouchers or coupons) resulted in a 7% increase in support for congestion pricing policies. Further the restriction of congestion pricing to a single lane on a freeway attracted from 9% to 17% of additional support. One of the main points of resentment about congestion pricing, was that motorists regarded the use of direct charges as coercive in that they had few, if any, practical alternatives to paying the fee.

Odeck and Bråthen (1998) concluded from surveys of empirical evidence in Norway that, public support could be greatly enhanced if:

- the advantages of such schemes in relation to other options were demonstrated;
- the scheme was treated as a wider part of an integrated transport planning measure or package of measures (e.g. use of revenue to improve public transport),
- clearly presented to the public the project 'package' including investment costs, time schedules of implementation and the benefits for road and public transport users.

These findings were consistent with those of Jones (1991), one of the few pioneering papers on how public support for road pricing could be gained. They were also consistent with findings by Collins and Inwood (1996) on attitude surveys to road pricing in the Bristol area and with Bartley, (1995) who reported on MIRO, an EU sponsored project under the DRIVE II Programme which investigated the acceptability and potential effectiveness of a number of experimental demand management initiatives. Despite these positive findings some disagreements remain, especially based on economic principles of efficiency that argue that it is inequitable and inefficient to return revenues from pricing specifically to transport improvements (Mayeres, 2000; Litman, 1999).

2.6.1 Forms that Congestion Pricing Could Take

Congestion could take any one of seven possible forms:

- Point Pricing – a road user incurs a charge on passing the charging point. Point pricing could occur as a single charge point on a specific congested road (i.e. facility pricing) or it could occur a charge points on a number of congested routes, or it could occur as charge points on all approach routes to an area (as a form of cordon pricing).
- Cordon Pricing – road users entering a congested area are charged at entry points to the area. Multiple cordons could be implemented as required, thus progressively limiting the amount of traffic reaching the core of an area; limiting the number of vehicles that are not affected by the cordon charge.
- Zone Pricing – road users travelling within a cordoned area are charged a fee, which could be additional to a cordon charge.
- Higher Parking Charges – higher charges are given to motorists travelling in congested periods or in congested areas. Although 'surrogate' in nature, such parking charges differ from conventional parking charges in that they are congestion related.
- Charges for distance travelled – a per/km charge is made to motorists in congested areas or on congested routes;
- Charges for Time Spent in an area – a charge per unit of time spent in a congested area or route is imposed; fluctuations in traffic conditions and hence speed such as through jams or incidents would cause the charges to rise sharply. This is a source of criticism of time based charging.
- Congestion-specific charges – users are charged for both time spent and distance travelled in a congested area or route.

It is imperative to bear in mind as has been noted earlier, that on a strictly 'marginalist' basis road pricing is meant to ensure the efficient use of scarce road space at given times and at given places by setting the price of a trip to equal the social marginal cost. It is possible from this economic approach that success could be considered to have been achieved even if congestion is not reduced, as long as motorists paid the true costs of their travel. In such an inelastic market, revenue would be generated from all motorists.
Among transportation planners and engineers road pricing has taken on a 'generic meaning to refer to the imposition of direct charges on road use, with a variety of

objectives in mind' (Jones and Hervik, 1992). It is in this context that road pricing is commonly perceived.

Table 2.6 illustrates how road pricing 'objectives' influence the form of road pricing scheme to implement.

Road Pricing Objective	Targeted Travel Behaviour /Response	Design Form of Road Pricing Scheme
Raise revenue for road building	- minimal or no trip suppression - maximum number of motorists required to pay	- Area cordon covering all approach roads - cordon located to intercept maximum number of trips in the urban area - uniform charge - minimal charge set by equity, political acceptability + need to prevent trip suppression
Reduce Congestion	- Trip suppression of some car trips; - Rescheduling of some car trips - Diversion of through trips onto orbital routes	- Area cordon ; Area Licence Scheme; Zone pricing - Depending on extent of congestion cordon or multi cordons; or geographical extent of zone determined; - Need to locate cordon(s) such that through traffic can divert without charge - Depending on temporal distribution of congestion, charges varied to reflect congestion level; higher charges in peak
Environmental air quality improvement	- trip suppression of vehicle trips; - suppression of both long distance and short distance trips; - use of 'green' modes-walk; cycle;bus - purchase of small cars; - purchase of new 'low' pollution vehicles	- An area wide cordon or multiple cordons to intercept significant proportion of vehicle trips including through trips; - Area covered likely larger than for congestion case; - Charges could cover a wider period of time than for congestion; - Charges to be lower for 'green' vehicles e.g. small engine; fuel efficient, quiet ; non/low polluting; newer vehicles

Table 2.6 Possible relationships between Road Pricing objectives and Type of Scheme Introduced) (From Jones & Hervik, 1992)

2.6.2 Issues on Impacts of Road Pricing

It has long been recognised that road pricing will impact on various sectors of society. Before any such scheme is implemented the impacts on these various sectors must be evaluated. Different studies have sought to address different issues pertaining to TDM in general or to road user charging in particular. European projects such as MIRO, ADEPT, GAUDI, EUROTOLL, CONCERT, TRON 1, TRON 2 and the recent Edinburgh project amongst others have addressed issues such as standards and technical evaluation, technology demonstration, market assessment and user response and impact assessment (Blythe, 1996, Hayes et al, 1999).

Lo and Hickman (1997) drew a comprehensive list of 11 impact areas to be considered in a road pricing scheme from the literature. The list maybe considered to apply equally to any TDM policy.

1. Demand Side Impacts – how do different user groups respond in terms of route choice, departure time choice, mode choice, destination choice etc and the magnitudes of the demand shifts? Many uncertainties exist about these impacts.
2. Supply Side Impacts- the performance of the network by time of day, on priced versus unpriced facilities, effects of mixed vehicle lanes, effects of implementing bus lanes or other HOV dedicated incentives, response of the network to changes in demand levels etc.
3. Impacts on Urban Economy- fears that road pricing will adversely affect businesses in priced areas are addressed; boundary effects such as impacts on free standing towns as compared to conurbations. The long term impacts of land use changes are also considered.
4. Equity – the effect on the market segments identified in (1.) above on the distribution of costs and benefits. This attempts to identify the 'winners' and 'losers' and is an issue of debate about road pricing. Horizontal equity requires that consumers be rewarded in proportion to what they pay. To this effect horizontal equity seems to justify dedicating revenues from road pricing to improving transport facilities/services for those who pay and not necessarily those who are priced out. Vertical equity on the other hand requires that disadvantaged people receive more public resources than those who are relatively advantaged. This seems to justify that revenues raised be used to improve those adversely affected by road user charging (Litman, 1996,1999). This is still an area of debate (e.g. Litman v Roth; 1999 on www.hhh.umm.edu/;).
5. Environment and Safety – the air quality implications in terms of gaseous emissions and noise are considered. Potential changes in accident rates and accident severity are studied.
6. Financial – is the scheme financially viable? What are the magnitudes of sunk costs, recurrent annual costs, revenues? What is the payback period and how will revenue generated be administered and used?

7. Enforcement and Compliance – how and at what costs will enforcement and compliance be achieved? What penal charges should be made to defaulters or violators?
8. Technology – how will charges be made and collected? How reliable is the technology and is it fair and discrete? Can it cope with high flow rates?
9. Public Acceptance – public acceptance invariably influences political will and authority. Public acceptance will amongst other things be influenced by the potential benefits as well as by the redistribution of these benefits and costs.
10. Impacts on Institutions and Organisational Changes – can the affected institutions such as the implementers cope or adapt to the new system by way of changes in operation procedures and network management and co-operation with other 'interested' institutions e.g. banks and private investors. What will be the role of central government?

2.7 Concluding Remarks about Road Pricing

Direct user charging literature and research is a very dynamic area because of increased interest by both the academic community and governments in recent times. Papers that predominantly explore theoretical aspects of road pricing include Mun (1994) who used a dynamic model of traffic flow formulated on the kinematic wave theory to extend the theory of optimal congestion tolls to the treatment of traffic jams. Yang and Meng (1998) used a combined application of the space time expanded network (STEN) representation of time varying traffic flow and conventional equilibrium modelling techniques to model peak period congestion and optimal pricing in a queuing network with elastic demand. Wie and Tobin (1998) developed two types of dynamic congestion pricing models that addressed route choice in networks with capacities and travel demands that were stable from day to day; and where they fluctuated significantly from day to day respectivley. Glazer and Niskanen (2000) have used numerical methods to evaluate the consumer benefits of congestion tolls. Their modelling considered the reassignment effects of tolls on consumer welfare. The authors considered the effect of a toll on either the slow mode/route or the fast mode/route in order to gain an indication of which tolls would be politically acceptable. They argued that it was important to consider the short term effects of tolls on consumer welfare because political support for road pricing would depend to a large extent on what the immediate benefits would be.

Their findings were that, in the short term, a toll on the fast mode/route would cause some users to switch to the slow mode/route. This would increase congestion on the slow mode/route and further hurt users on these facilities. However, travellers already travelling on the slow mode/route presumably had low values of time anyway. However, the users remaining on the fast mode/route must have high values of time and would enjoy even more benefits as drivers at the margins were priced off these fast facilities. The overall effect of tolling the fast mode/route in the short term would be a net improvement in consumer welfare. On the other hand, it was concluded that in the short term, any toll on the slow mode/route (i.e. urban roads) would reduce consumer welfare and hurt most users. Their explanation was that tolling the slow mode/route would induce some people initially on the slow facilities to switch to the fast facilities. This would increase congestion on the fast facilities and the consumer welfare of those already travelling on the fast facilities would decline. Users priced off from the slow facilities would consider themselves losers since they do not value time very highly. Therefore, in the short term, tolls on the slow facilities such as congested urban roads would be unpopular with most users. The authors used these findings to explain why tolled highways designed for fast travel appeared to suffer little public and political opposition compared with the introduction of tolls on local urban roads. Thus, those with high values of time could use these high speed facilities while those with low values of time used the untolled parallel local roads. The study also concluded, that politically acceptable tolls could increase congestion or increase average travel times. This was because tolls on fast facilities caused users at the margins to divert from the fast facilities to the already congested slow facilities, and therefore further increasing congestion on the slow facilities. A main gain of pricing the fast facilities was the immense revenue potential due to tolls paid by the affluent drivers with high values of time.

Mayet and Hansen (2000), developed a model for steady-state congestion pricing in which the VOT has a continuous distribution in a population of commuters. As with the Glazer and Niskanen model, the Mayet and Hansen model was based on a hypothetical network. The two road network consisted of a tolled road and a free road. It was concluded that heterogeneity of the VOT had important implications for the theory of road pricing. The concept of a socially optimal toll was found not to be unique but to depend upon whether it was in monetary units or in time units.

Meyeres (2000) used an applied general equilibrium (AGE) method in Belgium to examine and compare the policy effects of road pricing, fuel taxes and public transport subsidies on congestion, air pollution and accidents. The applied general equilibrium model was a static model whose time horizon was the medium term. Although the model distinguished between passenger and freight transport, and different transport modes (rail, road and inland navigation), its network representation was very aggregate. It was assumed that the road network could be represented as a one-link system with homogeneous traffic conditions. Nevertheless, the modelling was able to show that:

a. Compared to fuel taxes and higher public transport subsidies, peak period road pricing led to a relatively large reduction in the traffic flow in the peak period when congestion was most severe. This was achieved by consumers switching from the peak periods to the off peak periods.

b. The fuel tax performed worse than the peak period road pricing in addressing the congestion problem. However, it performed better in reducing air pollution and accidents. This was because fuel taxes had the largest impact on the total traffic volume, unlike with peak period pricing which simply spread the traffic over a wider time profile. The author argued that the total volume of traffic was a main determinant of externalities associated with pollution. They concluded that, in general, raising money via road pricing or fuel taxes could therefore have significant benefits by curtailing congestion and environmental externalities.

Very few of these papers base their research on real life networks. By using the Southampton network, the research described in this thesis attempts to quantify the network effects of specific behavioural responses as might arise from TDM measures such as direct user charging. It is often assumed that potential behavioural responses to TDM, which include peak spreading, trip suppression, destination changes and re-roteing amongst others would result in significant network benefits. This research by modelling specific responses using a real network might give an indication of how significant these benefits might be.

2.8 Summary of Chapter

This chapter has provided a review of TDM measures in general, and road pricing in particular. It was noted that the reasons why TDM measures are applied may vary by locality and indeed various countries may have national goals that are specific to that country. However, the common thread is that of the need to manage increased traffic growth by influencing travel behaviour rather than by providing capacity through road building. The chapter detailed the different ways in which TDMs are classified and also briefly referred to the potential behavioural changes that may arise from implementing TDMs. The potential role of TDM measures in alleviating the adverse effects of pollution from road transport was briefly outlined. The various forms which road user charging could take were also discussed. The review of TDM measures and road pricing in this chapter provided the basis for understanding of these policies in influencing travel behaviour. An understanding of the basic operations of TDMs can lead to the understanding of how the behavioural outcomes of these measures may be modelled. In line with the broad aims of this thesis, it is hoped that this understanding may lead to the adoption of simpler methods of representing the behavioural changes, with a view to evaluating in greater detail the potential network implications of these behavioural changes.

In the next chapter, a review of the models used in transportation to represent behavioural changes is undertaken. Where possible the adoption of these models to represent the travel behavioural changes of the TDMs described in this Chapter 2 is highlighted. The aim is to illustrate that these models are usually very complex and require detailed data which is expensive to collect. Further, the predictive capabilities of these models in the light of unavailable data with which to validate the models, and a lack of comprehensive understanding of travel behaviour, may create doubts about the output of the models. It is argued that there is a need for simple but plausible ways of representing travel behavioural changes so that more effort may be placed in evaluating the potential network effects of these behavioural changes.

3 REVIEW OF MODELS WITH RESPECT TO MODELLING THE ELASTIC EFFECTS OF TRANSPORTATION POLICIES

3.1 Introduction

In its publication 'Urban Traffic Models: possibilities for simplification (Paris,1974), the Organisation for Economic Co-operation and Development (OECD) listed a number of features which would make a traffic model suitable for road traffic restraint studies. The list is reproduced here is:

- a mechanism for re-roteing and
- mode choice;
- a mechanism for trip generation and suppression;
- sufficient detail as output to allow different types of restraint to be analysed and evaluated on a common basis;
- an adequate description of peak loading and the effect of peak spreading;
- a mechanism with provision for differential user responses to charge levels or different levels of restraint;
- a mechanism to ensure that trip demand changes are consistent with traffic changes.

Perhaps the important thing to note is that not only was it necessary to model re-roteing, as is the case with a fixed matrix, it was also necessary to model 'elastic' behavioural responses of traffic restraint or TDM measures. Since TDM measures depend for their success on travellers changing their travel behaviour, the fixed trip assumption in which potential responses such as changing mode, destination, departure time or frequency of travel are ignored, becomes inappropriate.

The aim of this Chapter is to review the methods and/or models used in the literature to model the 'elastic behaviour' of transportation policies such as TDM. The review is conducted in the context of substantial advances in transport modelling in general and behavioural modelling in particular (e.g. van Vuren et al, 1995a; Bowman and Akiva, 2001). It is also conducted against a backdrop of uncertainty as to the accuracy and validity of the predictions of these models in view of inadequate understanding of human behaviour (Giuliano, 1998). Giulliano argued that good predictions would be easier in a stable world devoid of continuous and rapid changes. Unfortunately, transport models have to be developed for a world of rapid changes such as urban sprawl, urban migration, changes in household characteristics and changes in economic productivity amongst other things. These many changes made it difficult to predict travel behaviour accurately and to isolate the effects of the different factors at play. The reasons that made it difficult to develop validated models include resource constraints (e.g. time, money and data), modelling complexity, the loss of network detail at the expense of behavioural detail and vice versa. Even demand models that have posted significant advances in behavioural modelling are rarely able to evaluate and quantify the detailed network effects of the predicted behavioural changes. However, vital the knowledge about behavioural changes, it is inadequate in itself if the associated network effects are not known accurately.

A methodology to circumvent these issues in order to better understand and compare the network effects of specific behavioural responses is described in the next chapter. The methodology emanates from a critique of current methods as much as it is an acceptance of the lack of a comprehensive current model at this point in time. The CONTRAM (Leonard et al, 1989) assignment model, which is the main network model adopted for this research is also described in the next chapter.

3.2 The Potential Impacts of Transportation System Changes

The behavioural responses of travellers to changes in the transport system in general are well documented in the literature (e.g. SACTRA, 1994; Noland, 2001 on capacity addition; Deakin, 1994 on road user charging measures; Manheim, 1979; Coombe et al, 1991 on transportation system changes; IHT, 1997 on changes in the transport system; Cairns et al, 1998 on capacity reductions; Kuppam et al. 1998 on parking pricing strategies). They are usually referred to as the impacts of the policy measure. The list of possible impacts is given below:

- No change in travel behaviour.
- Reassignment or change of route.
- Reschedule time of travel.
- Mode switch including change in vehicle occupancy.

- Trip chaining - defined as a trip with intermediate stops to pursue additional activities (Allen, Jr. 1995).
- Change in Trip frequency and activity selection.
- Trip suppression or forego trip.
- Switch destination but for same trip purpose.
- Change residential location.
- Change employment location.
- Change of car ownership.

It is widely agreed that present understanding of human behaviour in response to changes in the transportation system, although continuing to improve, is still inadequate (e.g. Maclver, 1999; Bowman and Akiva, 2001). Hence the main task of predicting how many individuals, of what characteristics (e.g. income group, geographic location, etc), travel for which trip purpose; and how they will respond to change remains largely unclear and unsolved. Maclaver, for example argued that trip distribution continued to create confusion amongst transportation practitioners. The author noted that the predictions made using current models bore little resemblance to actual trip distribution patterns. In addition, practitioners did not have the time or resources to obtain all the data required to develop robust models. Bowman and Akiva, outlined some advances in modelling travel demand. They noted that the choice processes that some models represented had become better understood through research on the nature of individual activity and travel decisions. They singled out the modelling of tour decisions as an improvement over the more traditional one-way trip based models. A tour is defined as the travel from home to one or more activity locations and back home again. However, they argued that although tour-based models managed to address complexities such as trip chaining, they ignored the constraints and opportunities associated with activity schedules that included at-home activities and multiple tours. They concluded that it was necessary that tour-based models were extended to explicitly model an individual's entire day. Although the authors managed to make this extension, they were only able to provide a prototype demonstration, noting that an operational implementation would require more empirical data and model refinements. This once more showed how resource constraints such as empirical data made it difficult to validate models.

3.2.1 Transportation System Changes

The term "changes in the transportation system" encompasses a whole range of policies that could result in one or more of the impacts listed in section 3.2 above. The first of these is congestion itself. Since about the early 1990s there have been a considerable number of papers (e.g. White et al, 1995; Rogers; 1991; Mekky, 1995,1996,1997; Al–Azzawi, 1997) on incorporating 'elasicity' using assignment based techniques such as matrix capping. The rationale is that even in the absence of intervention by a network operator, travellers make changes to their travel in order to avoid congestion. Therefore, not accounting for these changes in models may result in incorrect evaluation results. White et al, (1995) for example tested different assignment based techniques on three networks representing different examples of congested areas in England. The techniques tested included matrix capping, shadow networks and elastic assignment. All the techniques tested produced reductions of between 7% and 17% in the unrestrained matrix. The authors concluded that, the fixed trip matrix assumption, which implied that travellers were unresponsive to changing levels of congestion other than through re-roteing gave incorrect results about the economic value of a scheme. Rogers (1991) tested the matrix capping method on a congested network of Trafford Park in Greater Manchester. The technique was found to substantially reduce the number of overloaded links in the network. It also reduced traffic in the final trip matrix by 15% compared to the unrestrained trip matrix. It was concluded that matrix capping improved the reliability of economic evaluations by minimising unrealistic modelled queueing. Studies by Al-Azzawi and by Mekky also independently concluded that assignment techniques such as matrix capping and shadow networks reduced demand matrices based on the concept that as travel costs increased, (such as through increased congestion), trip suppression would occur in addition to re-routeing. Details about assignment based techniques are discussed further in Section 3.4.1.

Other policies include traditional capacity addition through construction (e.g. SACTRA, 1994), minor improvements to links, junction improvements and other small scale improvements to the road system etc (see e.g. Goodwin and Coombe, 1991). Recently there has been a growing interest towards in the potential for using TDM measures, or a combination of measures (package), to achieve appropriate impacts and to alleviate congestion or reduce traffic growth. (These TDM and restraint measures have been discussed in Chapter 2.) The potential network effects of the impacts of these measures remain largely unquantified and is the main interest of this research. This is, to a large extent, due to inadequate understanding of the interaction between travel demand and changes in 'network travel costs' be they monetary, time, poor travel conditions arising from congestion or a combination of factors. As a result, modellers have tended to concentrate on modelling the re-roteing effects of policies where greater understanding and model development has been most significant (e.g. Mekky, 1995, 1996, 1997; Wie and Tobin, 1998; Yang and Huang, 1998; Milne, 1997). Mekky's work in Canada concluded that it was possible to adopt a four stage model to evaluate the re-roteing effects of tolls. It was assumed in the modelling that apart from re-routeing, other driver responses such as mode changes and destination changes would not occur and were therefore not modelled. The results of the modelling showed that the percentage of diversion from the tolled route increased with the toll level as expected. Where attempts have been made to account for elasticity, the tendency has been to use simplified networks rather than real life networks (e.g. Wigan and Bamford, 1973; Akiva et al, 1986). Where real life networks have been used, there have been uncertainties about the nature of the relationship between demand and travel cost (e.g. Milne, 1997 suggests up to 4 elasticity functions). Further, as Milne points out, there has been considerable difficulty in the modelling in distinguishing the separate demand responses.

3.3 The Transportation Prediction Problem

The urban transportation system can be viewed as a three part system (e.g. Manheim, 1979; Williams and Lam, 1991). These are:

(i) The Activity System (A)-the pattern of social and economic activities.

(ii) The Transport Supply or Transportation System (T) - this forms the physical channels or links between land use activities. Such links include footpaths, roads, railways, bus routes and tramways and are characterised by their operational characteristics of travel time, costs and service frequencies.

(iii) The Traffic Flow Patterns (F) - the pattern of flows of volumes of goods and people moving in the transport supply system from origins to destinations, using certain routes at given times.

While there are many other significant impacts, the core of any transportation system analysis, however, is the prediction of changes in flows as a result of changes in the activity system, the supply system or both arising from some policy change (Mainhem, 1979). A major problem facing transportation practitioners is how best to predict the results of various policy measures, which emerge as a part of the process of 'formulating a transportation strategy for an urban area (IHT, 1997). Changes in the activity system in particular are difficult to due to the many factors involved. For many studies, however, some form of model is essential if an objective evaluation of alternative measures is to be made (IHT, 1997).

At a symposium entitled 'Transportation Models In the Policy - Making Process: Uses, Misuses, and Lessons for the Future', Giuliano (1998) summed up the demands expected of transportation models in an increasingly dynamic society as Giuliano wrote:

'Good planning requires good predictions and good predictions require good models. ......Unfortunately, transportation models used in planning practice today are not good models'.

According to the author, this was because current models are not internally consistent. They also fail to replicate the behavioural patterns of households and firms because they have no basis in behavioural theory. The errors in prediction arose from major societal structural changes and exogenous factors such as:

- Urban sprawl or suburbanisation (leading to a decline in commuter trips to city centres, increased cross commuting; longer distance commuting; mode shifts from public transport to the SOV).
- Changes in household characteristics (e.g. smaller household size resulting in increased total trips, automobile use and non-work travel).
- Increases in female labour force participation (contributing to increased vehicle kilometres travelled (VKT), car use and trip chaining).
- Economic productivity increases leading to higher incomes, increased values of time and more discretionary travel.
- Emerging information technology leading to possible flexible working practices, changes in how goods and services are produced and even distributed.

3.3.1 Levels of Choice

Manheim (1979) points out that travel choices are just but one of a number of several choice 'levels' that an individual must make in the pursuit of a 'full and satisfying life' (see Figure 3.1). Choices reflecting life style aspirations are at the top, followed by the individual's desired activity patterns at particular locations and times. This leads to choices of residential and work place locations and, in order to access these desired activities, travel choices about where, when and how to travel are made. Thus travel choices are derived from the need to take part in the activity pattern. This illustrates the complexity of the scenarios and interdependencies within which travel choices must be modelled. Some of the choice adjustments may be made in the immediate term while others such as locational and work place choices usually change in the mid to long term.

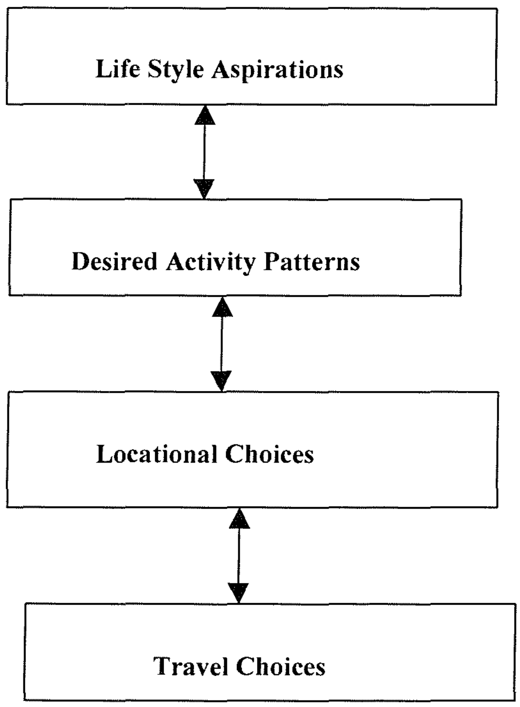


Figure 3.1 Levels of Choices for an Individual (source: Manheim 1979)

Further, a policy may result in a combination of responses from different segments of the travel market. There will usually be a primary response mainly determined by the nature and design of the policy and a series of secondary responses (Johnston and Rodier, 1994). It would be impossible to develop and manage a single 'simultaneous-choice model' that included all these choices.

3.4 Types of Models

Techniques or models to represent the behavioural effects of transport policies can be either assignment/network based or demand based. One of the main issues that these models must address is the relationship and interaction between demand and network changes or costs (e.g. Milne, 1997; Allos, 2001). Not only does this affect the model output, but also potentially the model complexity or computational task and possibly the costs of developing, calibrating and validating and applying the model. Simple but authentic methods of representing this issue are therefore necessary (White et al, 1995). As Maclver (1999) and White et al, (1995) noted, in most real life applications of transportation modelling, there is a shortage of time and resources. Data to calibrate sophisticated state-of -the art models which might not even produce good results is costly to collect. Therefore, practitioners usually need less complicated ways or models that can be calibrated and used within relatively short time periods to evaluate transportation policies.

This research is mainly concerned with the mid to short term responses and thus precludes land use based models which predominantly assess long term locational changes

3.4.1 Assignment Based Techniques

Assignment based techniques have mainly been applied to finding a simple response mechanism to account for the effects of congestion on travel behaviour. This mainly arose because researchers realised that in urban networks, forecast traffic growth might not be achieved due to limitations of network capacity especially at peak periods (e.g. Rogers, 1991; Hounsell, 1991; Mekky, 1994; White et al, 1995; Al-Azzawi; 1997). Therefore evaluating traffic schemes on these matrices could produce unreliable results because of the unrealistically large volume of traffic modelled as queued and therefore given large travel times (Rogers, 1991). This required that some trips be suppressed or cut off when network conditions fell below some critical threshold. The behavioural response that is commonly represented by these techniques is trip suppression (e.g. White et al. 1995; Milne, 1997; May and Milne, 2000) although with more sophisticated manipulations, peak spreading, park and ride and mode changes can be represented (Al-Azzawi, 1997). The three main assignment techniques are:

(i) Matrix Capping is a link based method of trip suppression. The method constrains the number of trips in the trip matrix so that link volume/capacity(v/c) ratios do not exceed a specified threshold value usually between 0.9 to 1. In CONTRAM a link v/c ratio of 0.9 indicates significant queues, while a value greater than 1 indicates oversaturation associated with congestion. In Matrix Capping such thresholds are used to effectively reduce the demand for those zone pairs using the overloaded links. Special software is used to implement matrix capping e.g. ME2 in SATURN; and versions of EMME/2 (since release 5.0). Details of the matrix capping procedure are described by, for example, Rogers (1991) and Al-Azzawi (1997).

The traffic 'lost' through matrix capping encompasses traffic that would be reallocated by the assignment, modal split and/or distribution sub models in a multi-stage strategic transport model (Rogers, 1991). Advantages of matrix capping include:

- The process requires no major increases in network representation.
- There are no problems with choice of demand functions.
- The procedure reduces both long and short distance trips through bottle necks to an equivalent extent.
- The results of the technique are self evident.

Disadvantages include:

- The process can take a considerable amount of computer run time since a number of iterations may be required. Advances in computer technology may reduce this problem.) For example White et al, (1995) concluded that run times for matrix capping on a 66 - MHz DX 486 PC could be ten times longer than for a normal assignment. Al-Azzawi, (1997) independently conluded that in terms of computer run time, matrix capping required the most and elastic assignment the least.
- There are also uncertainties about the behavioural authenticity of the method; i.e. what value should be used for the target v/c ratio, since this is related to the travellers' tolerance of congestion and may differ by area (White et. al. 1995).

(ii) The Shadow Network approach involves duplicating the real network. This shadow network is connected to the real network at origins and destinations only. Some characteristic of the origin - destination journey (rather than links) i.e. average journey speed is used to suppress trips. All shadow links are assumed to have fixed chosen speeds and infinite capacity. When travel 'cost' between an O-D pair at the chosen 'shadow network' fixed speed is less than the minimum path cost in the real network, the trips between the O-D pair concerned divert to the shadow network. The traveller thus has the choice of making the entire trip either on the real network or on the shadow network. The shadow network is thus used only when the average journey speed for a given O-D falls below the chosen level in the real network, typically 10km/hr to 15km/hr (White et al, 1995). The trips diverted to the shadow network are considered to be suppressed i.e. the trip does not take place when the average journey speed on the real network for the given O-D pair falls below the critical speed.

Apart from modelling trip suppression, shadow networks can be used to simulate peak spreading, park & ride and mode changes from car to other modes. However, this requires sophisticated manipulations (Al-Azzawi, 1997).

Concerns about the authenticity of shadow networks include:

- There must be some doubt as to the realism of the assumption when the suppression speed is reached, all further growth in demand is suppressed and diverted to the shadow network(Al-Azzawi, 1997).
- They tend to suppress short trips because when a junction becomes saturated, the effect will be most pronounced for shorter trips.

(iii) In Elastic Assignment the number of trips(T_{ij}) from origin i to destination j is related to the cost of travel c_{ij} by:

$T_{ij} = f(E, c_{ij})$ where:

f is a decreasing function of cost and $T_{ij}^0 = f(c_{ij}^0)$ where

T_{ij}^0 is the reference or base year demand given base year costs c_{ij}^0.

E is a user provided elasticity value.

The elasticity, E, of this function is a measure of the proportional change in the number of trips for a given proportional change in the travel cost. Various forms of elasticity demand functions are possible. For example, White et al, (1995), Milne (1997) list power or constant elasticity, simple exponential, elastic exponential and logit as possible functional forms. Each of these functions represent alternative ways in which cost and demand may be related. Each would be expected to yield somewhat different results if used in an identical context with similar elasticities (Milne, 1997). The work by Milne (1993, 1997), and earlier work reported by Smith et al, (1994) assumed a constant elasticity function because of its simplicity. An elasticity value of -0.5 based on literature evidence (e.g. Goodwin, 1992) was assumed although it was recognised that the number of trips suppressed would be sensitive to the value of the elasticity figure adopted. The results of the modelling concluded that the order of efficiency in providing network benefits was delay based charging, time based charging, distance based charging and cordon charges.

Elastic assignment is incorporated within an existing assignment model through the specification of an extended network of pseudo links, which incorporates the chosen elastic demand function as part of an additional route for each O-D movement specified in the O-D matrix. As the highway network becomes more congested, or as travel costs c_{ij} increases, $T_{ij} = f(cij)$ decreases, and more trips are diverted to the pseudo links. These diverted trips generally represent trip suppression but can, with more complex manipulations be used to simulate peak spreading or mode changes (Al-Azzawi, 1997).

The use of pseudo links between each i,j pair increases the number of links in the network. However, this has the advantage of allowing suppression functions to be defined on a zone to zone basis. Another advantage of elastic assignment is that no interaction is required with an external strategic model.

The main problem in elastic assignment is the choice of the demand function. This entails both its mathematical form and the values of any parameters. For instance, a logit form tends towards greater suppression of longer trips while a power function form tends towards greater suppression of shorter trips (Al-Azzawi, 1997; White et al, 1995). White et al, (1995) further noted that convergence difficulties required that a significant number of iterations be made in SATEASY. SATEASY is an elastic assignment model that was developed as a module of SATURN. It is the model that was used by Milne (1997) to model general trip suppression under road user charging.

In theory, elastic assignment can be programmed to simulate impacts such as peak spreading, mode changes and destination changes. However, this would require considerable modifications to be made and would increases the model complexity (Milne, 1997).

Other assignment based techniques include the Speed Limitation Method and the Level of Service Limitation Method. These perform between the extremes of the main methods described above (White et al, 1995). Both methods were found to be highly dependent on the assumptions made about the tolerance of travellers to levels of congestion. The former also characteristically had long run times.

3.4.2 Concluding Remarks on Assignment Based Techniques

The assignment based techniques have mainly been applied to accounting for the effects of trip suppression in response to increases in congestion rather than to modelling behavioural responses to TDMs. Indeed Rogers (1991) and White et al, (1995) noted that, in principle, the problem of forecasting realistic road traffic volumes under conditions of a high trend in growth in demand could be solved by using a multi-stage, multi-modal transportation model instead of the assignment techniques described above. However, multi-modal models required multi-modal travel and network databases coupled with satisfactory calibration and validation of the sub models for the base year. They also required data on variables of peripheral interest such as public transport networks and fares etc. These requirements are demanding and simpler techniques such as those outlined here offered more affordable alternatives.

The research at the Universities of Leeds and York which modelled the network effects of four road user charging systems based on elastic assignment was the only research identified which employed assignment based techniques. The work was reported in a series of papers e.g. Milne (1993); Smith et al, (1994); Milne, (1997); May and Milne, (2000). This was achieved using the SATEASY program in SATURN. Even so, the modeling represented trip suppression in general and did not specifically differentiate between different suppression responses such as peak spreading or destination changes. Also, there were uncertainties as to which 'elastic functional form' was the most appropriate and the elasticity value to adopt. Nevertheless, this work was one of the first to model the network effects of direct user charging using a real network and without the need for interaction between a strategic model and an assignment model.

3.5 Demand Based Techniques

Demand models usually applied in transportation may be classified as:

- Simplified Demand Techniques;
- Four Stage Model;
- Strategic Models;
- Discrete or Behavioural Choice Models (DCM);
- Activity - Travel models;
- Land use Transport Models and Demographic Models.

What follows below is an illustrative review of how the above model types have been applied to research in recent years. Allen, Jr. (1995) and Dahms (1998) noted that most existing models were developed for planning transportation facility improvements and are thus not well suited for analysing pricing strategies or indeed TDM measures. The adaptation of these models by some researchers to model TDM in general or road pricing in particular is highlighted wherever possible.

3.5.1 Simplified demand techniques:

These techniques employ limiting assumptions which enable the analysis of the problem using simple model features and readily available data. The need to use such techniques may arise due to budget and/or time constraints, inadequate data or due to the inappropriateness of more detailed techniques. They are useful as simplified macro-transportation planning techniques to carry out broad strategic level planning on land use and transportation system options before the use of detailed planning at a localised level. Examples include trend analysis, elasticity based models such as incremental elasticity analysis; and pivot point analysis (see for example, Ortúzar and Willumsen (1994) and Manheim (1979)).

The simplest form of such techniques is trend analysis where historic demand data levels are plotted against time, and future demand is obtained by extrapolation. The strength of this technique is its simplicity. Its major weakness is that it assumes a constant nature of change in demand which persists into the future.

Elasticity based models and pivot point analysis also constitute simplified demand techniques. The elasticity of demand maybe with respect to any relevant variable such as bus fare, travel time, fuel price, bus headway and so on. Direct demand elasticity involves variables relating directly to the demand in question such as the elasticity of car use with respect to fuel increases. Indirect or cross-elasticity relates to variables characterising other competing modes of travel.

Examples of the application of simplified demand techniques include Gifford et al, (1996). The authors investigated the elasticity of demand with respect to changes in highway tolls with emphasis on tolls that are time varying. The time varying schedule of tolls were by day of week rather than time of day. They used time series data from the Golden Gate bridge in the USA from 1979 to 1984 to examine travel demand under these time varying prices. While the elasticity and cross-elasticity of demand could be estimated by detailed behavioural models at low levels of aggregation such as at the individual, household or company level, the extraordinary data demands imposed by such models was a major drawback. The authors thus adopted a simplified aggregate travel behavioural model which estimated the travel demand (T) as a function of tolls, fuel price, employment and time. The most significant conclusion of the study was that travellers responded to time dependent (day-of-week) toll increases by reducing their overall travel and not by shifting travel to reduced price periods from increased price periods. This suggested that increasing tolls, even on one business day a week could be effective in reducing overall traffic levels in situations where alternative route and mode alternatives are highly constrained as in the Bay Area in which the study was conducted.

Schimek (1996) calculated fuel and travel demand elasticities using 1950 to 1994 time series data for the United States. The author also used 1988 to 1992 pooled cross sectional data for states of the USA. Although fuel demand was found to be inelastic with respect to price in the short run, it was found to be -0.7 in the long run. The response to price changes was analysed for motor vehicle ownership, driving and fuel efficiency, and the study focused on personal car travel and not travel for commercial purposes.

For given annual data, the time series model was of the form:

Const = f(Pgast, Yt) where

Const is the per capita gasoline consumption for annual data or year t

Pgast is the real price of gasoline for year t

Yt is the real income per capita for year t

The time series cross section model was similar but was modified to add variation across states in addition to variation across time. A further variable was included in this model to measure the effects of urbanisation.

The authors concluded that the price and income elasticities of fuel consumption estimated in their study was consistent with earlier estimates of international studies which concluded that income elasticity is nearly twice as large as price elasticity. Thus, as income rose, per capita fuel consumption was bound to rise unless fuel prices rose twice as fast in order to counteract the tendency to buy more fuel as income rose. The income elasticity of car distance travelled was also about the same magnitude as its price elasticity. Per capita travel could therefore increase as per capita income rose. Also, it was found that there is a measurable long-run increase in driving, associated with reduced vehicle operating costs due to fuel efficiency standards.

Allos (2001) recently described a technique of arriving at the point of equilibrium between supply and demand based on a knowledge of demand and supply elasticities. The methodology is essentially pivotal and avoids an iterative procedure between supply and demand by calculating elasticities about a defined base point equilibrium state or scenario (x_0,y_0) where x_0 is the demand at travel cost y_0.

3.5.2 UTMS (Traditional four stage model) and Enhanced UTMS:

The four stage model is well documented in the literature. It is a non behavioural model consisting of four stages; trip generation, trip distribution, modal split (split into Private and Public transport) and trip assignment.

Many modellers e.g. Tatineni et al, (1994); Manheim (1979); Wohl and Martin (1967) have highlighted the shortcomings of the four stage model. These include:

- The inconsistency of the values of the variables used in the different stages; for instance the costs used in the mode split stage and/or in the distribution stages are different from those in the assignment stage.
- The basis for forecasting travel choices as defined in terms of variables and parameters is inconsistent between the various stages.
- Evaluation of alternative policies using the sequential modelling process is complex and time consuming.
- The trip generation stage is assumed to be independent or insensitive to the price of travel.
- The model lacks credible behavioural predictive ability because of its failure to establish an interrelationship between the demand for travel (number of trips made) and the character and price of the transportation service actually available.

Milne (1997) has argued that data provision and the simplistic treatment of junctions compromise the four stage model. The four stage model still, however, enjoys wide spread use for a variety of reasons. For example (McDonald et al, 1997) lists the following reasons;

- The required zonal and socioeconomic data is usually available from census information, and past travel surveys.
- Proven software exists.
- The models are sensitive policy tools for major infrastructure and traffic management schemes.

Some examples that employed the four stage model includes work by Mekky (1995,1996,1997). The author used the strategic Greater Toronto Area (GTA) model to evaluate the impact of tolling Highway 407. Highway 407, a four to six lane freeway in the GTA, was required as a relief to Highway 401. The core of the modelling was to identify the scenario which maximised total gross revenue from a number of toll pricing strategies. The GTA mathematical model, a traditional sequential four stage UTMS model, was used as the modelling tool. The model operates within the transportation planning package EMME/2. It uses regression analysis for trip generation, a gravity model for trip distribution of work trips and the Furness method for other purposes, a logit model for modal split and an equilibrium assignment for trip assignment. The strategic model had 1366 zones, about 5000 nodes and 19000 links.

The tolling strategies were influenced by the market which was modelled as consisting of three segments or classes; Highway 407 users willing to use transponders, Highway 407 users unwilling to use transponders and the rest of the travellers in the area. The later two groups would pay a fixed toll (to be determined so as to maximise gross revenue) while the former group would be subject to a distance (constant $/km price) based variable toll option. A study was developed to estimate the changes in the travel (i.e. number of users) and revenue of Highway 407 if a fixed toll option were allowed simultaneously with a variable one. A major issue was to identify the users of each class under various values of the fixed toll ranging from $1.00 to $5.00. The variable toll rate was taken as 7.5 cents /km.

The study showed that generic modelling software could be used to deal with the evaluation of tolling strategies. Several multi-class generalised cost assignment steps with feedback loops were successfully used to model the operations of a toll highway under fixed and variable toll schemes simultaneously. The results indicated that allowing the fixed toll option did not increase the number of highway users and only increased the revenues in a marginal way. It was concluded that using only a variable toll scheme would maximise the net revenue for the year under consideration. Thus, the study investigated the effect of tolls on route choice where users had the option to choose between paying for faster driving conditions or not paying for driving in congested conditions. Other impacts such as possible future destination changes and redistribution were assumed to be negligible.

Soberman and Miller (1998) also employed EMME/2 to model the environmental effects of 'full cost pricing'. The authors concluded that, vehicle kilometres travelled (VKT) and carbon dioxide (CO_2) emissions were reduced by up to 2.45% and up to 2.53% respectively as a result of 'full cost pricing'. These reductions were found to be over 6% when the intervening policy was a combination of pricing and land use changes. Tolofari (1997) in a paper presented to the UK TRIPS user group meeting in London described the application of TRIPS a four stage model, in modelling 'the potential for Park and Ride and Road Pricing' in Leicester as part of the Leicester Environmental Road Tolling Scheme (LERTS). The modelling used the TRIPS Demand Modelling software, MVMODL. In MVMODL, a hierarchical choice structure was used in two stages. In the first stage, an incremental logit model was employed to determine choices made between travelling by car or by public transport. In the second stage an absolute logit model was used to determine the proportion of car users that then chose to use park and ride. Results from the modelling suggested that disincentives such as bus priority measures on their own did not significantly shift car drivers to P & R. However, there was a four fold increase in P & R demand when bus priority measures were combined with pricing measures such as increased parking charges and direct tolls.

3.5.2.1 Modifications to UTMS Models

Tatineni et al, (1994) argued that the travel choice process in reality does not consist of separate decisions with regard to destination, mode and route choice as is implied in the traditional four stage sequential model. Instead the interdependency of these choices and the common costs considered must be reflected in the modelling process. They note that the traditional sequential procedure by which transportation policy is often performed, is deficient in several aspects including:

- The inconsistency in the values of variables such as travel time and costs used in the different models. Travel times and costs used in the trip distribution and mode split are different from the times and costs determined in the solution to the trip assignment model.
- The evaluation of alternative policies using the sequential modelling process is both time consuming and complex. Further, the effects of these policies may not be clear because of the inconsistencies in the models.

Tatineni et al, (1994). argued that in order to model true equilibrium conditions of travel, there is need to feedback the travel costs determined from the traffic assignment model to the trip distribution and mode choice models. Solving the models iteratively must continue until the costs of the trip distribution and mode split models are equal to the costs resulting from the traffic assignment model. To achieve such iterative procedures, sequential models could be time consuming and there is also the added problem of the use of different variables to express travel costs in the different models. Therefore, the researchers proposed a model that avoided these inconsistencies by combining the trip distribution, mode split and trip assignment models into a 'single model and solution procedure.' Such models consider a **common cost function** to model the various travel choices and use an iterative solution procedure so that the final equilibrium travel conditions result from destination, mode and route choices and not on route choice alone. Thus in such models, the traveller's choice regarding destination, mode and route are considered as part of a single decision making process with user cost minimisation the main criterion.

The model introduces a **choice dispersion constraint** in order to consider dispersion of choices from a strictly cost minimising behaviour which might occur because of imperfect user knowledge and other factors not considered in the model such as comfort and convenience. The authors did not specifically develop the model to deal with pricing strategies. The authors used their model for the Chicago region in the USA to model three policy changes, namely:

- Varying public transport/transit fares.
- Varying fuel costs and.
- Varying land use densities.

The effects of each policy change were considered on mode choice, trip length, travel time, congested vehicle kilometeres and generalised costs. The authors claimed that the 'internal' consistency with which travel costs and choice are determined in the combined model provided a better basis to analyse the effects and cross effects of varying costs on travel patterns. They also claimed that the ease of applicability of the model enabled their analysis to be completed in a relatively short time.

Levinson and Kumar (1993) also note that available evidence suggests that UTMS is not a behavioural representation of trip making especially as there is no feedback between the travel time on the network and the estimation of demand. Further, the UTMS model does not account for the impact of signal control on route choice and travel demand. The authors evaluated the relative advantages of building feedback and intersection control using data from the Baltimore-Washington metropolitan area (USA). The model called TRAVEL/2, differs from the conventional UTMS model in a number of ways. In particular, the TRAVEL/2 model is set up for internal feedback so that when an elastic demand assignment is performed, the travel times input to the demand become identical to those output from the assignment when the model converges to a solution. The model also contains responsive intersection control. In conventional models, this is static or non responsive. Lam and Huang (1992) employed a combined trip distribution and assignment model for network scheme evaluation in Hong Kong. The authors argued that such a combined model simplified the sequential process of the traditional four stage model. They also argued that a combined model was closer to the consistent choice of travel observed in travellers. The authors compared the output link flows of their combined model with the link flows of a four stage model. They concluded that the results of the combined model was more consistent to the real life situation than that of the four stage model. The authors also concluded that the feedback effects of travel costs on trip distribution (i.e. the interaction between trip distribution and traffic assignment) tended to be ignored by modellers because of the substantial computational time especially in congested networks.

3.5.3 Activity Based Models

Bowman and Akiva (2001) state that activity based theory is summarised in two basic ideas:

1. The demand for travel is derived from the demand for activities.
2. Humans face temporal – spatial constraints; functioning in different locations at different points in time. Time and costs are expended in moving between locations. A further constraint is that there is generally a need to return to a home base for rest and personal maintenance.

Activity based models therefore aim to simulate individual and household decisions regarding their daily activities by capturing the activity behaviour of the individual and household as to which activities they perform, where, when, in what sequence, with whom and how. Activity models differ in terms of the assumptions about people's activity behaviour and computational techniques employed (Wang et al, 2000). Bhat and Singh (2000) state that activity based models can reliably evaluate urban travel demand management policies because they explicitly model activity patterns and consider these patterns to be the fundamental influence on travel decisions.

On the down side, Wang et al, (2000) note that activity modelling constitutes a highly complex decision problem as various choice facets are interrelated. The choice options for each facet can be combined in every possible way leading to a 'combinational explosion'. Restricting assumptions therefore have to be made. The authors assert that the uncertainties about activity models are reflected in the different activity based models reported in the literature such as:

- Models for enumerating feasible alternative schedules like PESAP and CARLA.
- Discrete choice based models like STARCHILD.
- Models for generating schedules such as SCHEDULER and SMASH.

Recent applications of activity based models have been reported by Bowman and Akiva (2001); Yee and Niemeier (2000) and Wang et al (2000) amongst others. Bowman and Akiva (2001) extended the concept of tour-based models to take account of an individual's choice of an entire day's activities. However, they were only able to use a prototype to demonstrate the system concept and verify the model structure due to the need for more empirical data to demonstrate an operational implementation. Yee and Niemer (2000) examined the factors associated with activity generation and activity duration. They used longitudinal panel survey data containing household, person, and trip diary information for every household member of driving age. The relationship between demographic factors and the duration of activities, and how these relationships changed over time, was studied. In their modelling, activity durations were characterised as a function of trip making, and personal and household attributes. The activity durations for visiting, appointments, free time, personal business and shopping were studied. It was concluded that the duration of activities were temporally unstable as captured by the factors considered. Therefore research was needed to assess whether other factors could be used to gauge activity duration that exhibited greater temporal stability. Wang et al, (2000) argued that most existing activity-based models were developed from revealed preference (RP) data. They proposed an approach to developing activity-based models from stated preference (SP) data. The model conceptualised activity behaviour as a choice on two facets. These facets were choice of destination and choice of stop pattern. The approach was tested using data collected in the Netherlands whereby respondents were asked to make combined choices of destination and stop pattern to implement a given programme The choice data was then used to estimate a some forms of logit models. It was concluded from the research that the proposed stated choice approach provided an alternative to the revealed choice approach in developing multi-facet choice models of activity behaviour.

3.5.4 Discrete Choice Models

Discrete choice models generally postulate that the probability of an individual choosing a given option is a function of their socioeconomic characteristics and the relative attractiveness of the available options. The models operate at the level of individual decision makers. This is because although policies are in general concerned with aggregate quantities of the travel market, it is recognised that this aggregate behaviour is the result of individual decisions (Akiva and Lerman, 1985).

The models are used to analyse situations in which a decision maker is faced with a finite set of mutually exclusive discrete choices or alternatives (Genc, 1994). The models provide as output, the probability that an individual will select a given alternative. The attractiveness of the alternatives are represented by the concept of utility. The utility function can be expressed as a sum of observable and unobservable components. It is assumed that the option selected is the option which maximises the net personal utility of the individual according to their own underlying evaluation.

The most common model used is the multinomial logit model (MNL) which has a simpler form than the probit model. The assumptions of the MNL model lead to the infamous property of independence from irrelevant alternatives (IIA) so well documented in discrete choice modelling by the celebrated red bus/blue bus paradox (e.g. Munizaga et al, 1997). An improvement to the MNL model is the hierachial or nested logit model. The model groups positively correlated options into nests within which each of the assumptions of the MNL model apply (e.g. Forinash and Koppelman, 1993; Munizaga et al, 1997). Discrete choice models can be calibrated from revealed preference or stated preference data. The later enables responses to future or hypothetical scenarios to be explored.

In order to use DCM in forecasting it is necessary to resort to an aggregation method and different methods of aggregation can be employed related to the type of data used (Genc, 1994; Munizaga et. al. 1997). Aggregation in DCM is an area of uncertainty and has received extensive research attention in its own right (e.g. Yai, 1989; Genc , 1994; Bhat, 1998).

Discrete choice models continue to enjoy widespread research interest. Recent developments and applications are provided by for example Munizaga et al, (1997,2000), Brownstone et al, (2000), Nielsen (2000), Garrido and Mahmassani (2000) amongst others. For example, Munizaga et al, (1997,2000) investigated the robustness of the much used simpler multinomial logit model compared to the theoretically more accurate but computationally complicated probit model. Simulation experiments to solve the probit model and compare them to the simpler MNL model showed little differences between the two model outputs. It was concluded that the robustness of the simple and convenient MNL model was confirmed by these results. Brownstone et al, (2000) investigated the use of discrete choice models based on joint revealed preference and stated preference (RP/SP) choice data to model households' preference of cars that used alternative fuels. The demand model used was a mixed logit model, which is a general class of models for joint RP/SP choice data. They concluded that there are advantages in merging RP and SP data since the data sources tended to complement each other. RP data appeared to be critical for obtaining realistic choices, but were 'plagued by multicollinearity'. On the other hand, SP data was critical to obtaining attributes not yet observed, but pure SP models gave implausible forecasts. Nielsen (2000) presented a framework for public transport assignment that was built on a probit-based model. Although the model performed well in predicting public transport route choices, it was considered that the many parameters in the model complicated the model calibration. Garrido and Mahmassani (2000) applied a multinomial probit (MNP) model to analyse and forecast freight transportation demand. The authors concluded that the model showed significant correlation between the forecast shipments and the actual shipments in the tested samples.

3.5.5 Strategic Models

These models seek to cater for as many user responses as possible. Examples include two or three tier models such as were used in the London Assessment studies. Milne (1997) provides a detailed critique of the most commonly used models in transportation modelling. He noted that Strategic Models have serious limitations such as constraints by cost and computing power, despite their detailed representation of demand. The road network is usually very coarsely represented and demand data is also aggregate. This aggregation fails to capture local variations. Nevertheless strategic models have been employed widely in transportation modelling and some examples are given below:

London Models

Coombe et al, (1990) describe a two tier strategic model. The upper tier LTS (London Transportation Study) model is a strategic model used to assess proposals with area wide impacts. This model could be used to estimate;

- Modal diversion (a switch from one public transport mode to another).
- Trip redistribution (switch to new destinations for the same trip purpose).
- Travel effects of changed land uses (development impacts) while recognising that land use changes themselves have to be estimated exogenously.
- Effects of income growth.
- Effects of population and employment changes.
- Modification of vehicle occupancies to reflect changes in the use of private vehicles.
- The assessment of the reassignment effects of very large strategic road schemes.
- Assessment of area wide public transport proposals.

The lower tier model was a series of local road traffic and public transport assignment models. These models are needed for detailed assessment of the reassignment effects of road proposals in the particular locality or individual assessment study. These network models are capable of detailed network modelling including the ability to model junction queues and delays in considerable detail.

An example of a three tier model is the APRIL model used in the London Congestion Pricing study. APRIL is described later below.

Hong Kong ERP Model

Harrison et al, (1986) describe a three tier modelling methodology used in the transportation planning component of the pilot Electronic Road Pricing (ERP) project in Hong Kong. Amongst other things the model was mainly to assess the likely impacts of a road pricing scheme on travel behaviour . The authors noted even at that time, that apart from the limited Singapore Area Licencing Scheme, virtually no practical evidence of motorists' response to road charges existed. Modelling seemed to be the only logical solution forward. Effort was thus put into developing appropriate techniques using both Revealed and Stated Preference approaches. The Model structure consisted of three components:

The first component termed the 'reference models' was a four stage strategic model. This was used to forecast the design year transport demands before the road pricing was introduced.
The data requirements for this model were existing zonal aggregated data that was used to calibrate the four stage model.

The Impact Model was the next tier. This specifically aimed to predict the changes in travel demand that would result solely from the introduction of a road pricing strategy i.e. predict the choices. The model, drawing on existing data and social research concentrated on modelling market segments expected to change behaviour and on the most sensitive aspects of that behaviour.

The social research identified the most likely short and medium term responses to road pricing charges to be a change in mode (note this is mainly because of the more 'draconian' car ownership policies in Hong Kong; availability of a good public transport system and the relatively short journey times); a change in time period of travel, and a change in route (though limited by number of alternative routes in the network). The changes in behaviour were derived from an incremental logit model. The Network model was used to assess the road network supply conditions corresponding to the various demand patterns predicted by the reference and impact models.

Data Requirements/Inputs

In all, four main data inputs to the modelling process were required as follows

a. Existing data , principally 1981 census data plus a government 22,000 household interview survey called 'Travel Characteristics Survey (TCS) in the same year. ((Note that Hartgen (1976) reports of interview surveys on up to 10 000 households)This provided input mainly for the Reference models. The output was a trip matrix /forecast of trip demands categorised by:

- Trip purpose.
- Car ownership;
- Mode.

This was for input to the impact models. (Note that elsewhere, Hartgen (1976) reports of interview surveys on up to 10,000 households)

b. Guidance from the social research programme up and above the already existing data in (a) above to fill in gaps in:

- Defining of market segment from Revealed Preference(RP) Surveys.
- Attitudes to travel and the role of the car in Hong Kong (RP Surveys).
- Awareness and comprehension of ERP as a concept and in practice using Stated Preference(SP) Surveys.
- Likely responses to road pricing to focus the development of the impact model (SP Surveys).
- Other data such as characteristics of car-licence holders etc not available as published data but nevertheless important to the analysis (RP Surveys).

a. Policy options relating to socio economic, demographic, public transport fares, taxi fares, fiscal measures (e.g. car taxes) and other governmental influences.

b. Design options relating to alternative methods of implementing road pricing in general and ERP in particular.

Thus, for instance, the mode choice model data requirements were:

- Individual observations collected in the Travel Characteristics Survey;
- Telephone interviews to estimate drivers' licence availability;
- In vehicle time and cost derived from network models;

The work trip re–timing model required data obtained from SP Surveys. The data was used to estimate a linear utility function whose independent variables were:

- monetary savings;
- the square of the time change.

The market segments considered were Low, Medium and High. income. Consideration was also given to the market segment that received assistance on motoring costs from employers. Other segmentations and issues considered were:

- Division of respondents into those with fixed working hours and those with variable ones.

Multinomial logit models were used to estimate the proportion who chose to retime their trips and those who did not. Some of the findings from the Hong Kong study were that if pricing were to be introduced, the main responses would be re-roteing, change in mode and trip re-timing. Only a small proportion of motorists said that their car would be used by someone else if it was left at home as a result of pricing. It was concluded that destination change would be a minor response. Due to the effort placed in demand modelling, budget constraints meant that detailed network modelling was not done. Instead area speed/flow relationships were derived. The aggregate nature of the network modelling implied that junctions were not explicitly modelled.

The programming and other tasks involved in such models are enormous and costly. The data requirements as shown above are collosal in terms of model development, calibration and validation as well as attempts at trying to improve understanding. Transferability may not be possible without recalibration and so the models are not necessarily universally applicable.

Other models aimed at modelling impacts include;

SATCHMO–(**SA**TURN **T**RAVEL **CH**OICE **MO**DEL) This is a multi-modal transport submodule that complements SATURN (Willumsen et al, 1993). It was developed by Steer Davies Gleaves and WS Atkins Planning Consultants. The model provides facilities to model new policy measures (other than road based schemes) and the responses. This should for instance evaluate the impacts of measures such as road pricing and traffic restraint measures which have hitherto been provided for in network terms through SATURN and CONTRAM for example.

SATCHMO provides for public transport and demand choice modelling capabilities. Detailed local congestion and traffic schemes and their implications on route choice, time of day, mode and destination choice can be modelled. Also, strategic transport modelling using buffer networks and public transport travel choice models can be represented. By controlling local models to the results and networks of larger scale strategic ones, SATCHMO provides a significant enhancement to the interface between strategic and tactical transport planning and decision making.

The demand and choice models are modelled using the two SACHAS and SACHDI. SACHAS uses a generalised logit formulation to estimate the proportion of trip makers travelling by car and those choosing other alternatives. The alternatives can be presented in a number of ways including using a nested structure where required. The logit equation is applied to each O-D pair ij and is of the form:

$$p_k = \frac{\exp(-\beta GC_k)}{\sum_k \exp(-\beta GC_k)} \qquad [1]$$

P_k is the probability of choosing alternative k;

GC_k is the generalised cost of choosing alternative k;

β is a coefficient to be determined.

The alternative can be:

- a mode;
- a time of day;
- an alternative destination where practicable or appropriate e.g. shopping trip;
- not to travel at all.

SACHAS models simultaneous choice and assignment (route choice).

The generalised costs are provided by SACHAS while the coefficient β can be calculated from stated preference surveys or from other sources.

SACHDI was developed to deal with incremental and classic distribution and mode choice models outside an explicit equilibration network. The modal split models are also of the logit type while the distribution model is an incremental version of the gravity type. One advantage of using the incremental gravity type version is modelling destination choice where the conventional gravity model has not performed sufficiently well. More details of SATCHMO are described by Willumsen et al, (1993).

TRAM–(Traffic Restraint Analysis Model) This is a strategic model developed with the primary aim of testing restraint policies in general and parking control policies in particular (Bates et al, 1997). It is a member of the TRIPS software. Policies that can be tested include time varying pricing measures with respect to moving vehicles and parked vehicles; capacity reduction measures particularly for parking and a variety of improvements to public transport and the 'slow' modes of walking and cycling. As a strategic model TRAM has a high level of spatial and network aggregation to keep model run times manageable.

The travel choices or impacts represented in TRAM are:

- trip frequency;
- trip destination;
- mode use;
- time of travel.

TRAM does not model;

- car sharing;
- land use effects i.e. changes to the location of activities
- second order effects arising from the use of the car during the day by non-commuting household members.

The model uses a nested series of incremental logit formulation to deal with the various travel choices. This is done for each combination of trip purpose, time of travel and household type. The hierarchy or sensitivity of the travel choice is assumed to increase in the order:

Frequency-Destination-Mode-Time-Route-Parking.

Policies to be tested e.g. capacity reductions, parking controls, etc are represented by changes in supply which influence travel costs. Such costs are a combination of time and and money i.e. generalised costs. As an equilibrium model, TRAM iterates between changes in demand and the generalised costs until convergence is reached.

The demand is represented by a set of matrices of O–D movements. Travellers are segmented by:

- trip purpose;
- car ownership;
- mode of travel;
- income group;
- time period.

The market segmentation recognises that travellers are not homogeneous and so respond in different ways to a given policy.

The concept of 'tours' is used to reflect the influence of the 'various components' of a journey i.e. 'travel out, undertake activity, travel back' (i.e. trip linkage) on travel choice. This is only done for the Home Based (HB) or 'primary destination' tours to ease complexity. The tour concept recognises that ignoring trip interdependence or links for policies such as parking and road pricing is an inaccurate oversimplification.

The data requirements for TRAM include:

- travel demand data;
- transport supply data;
- parking type, pricing and enforcement data;
- model coefficients.

TRAM has been used to model the effects of parking control strategies in Bristol (Coombe et al, 1997; Scholefield et al, 1997).

APRIL–this model is also a strategic transportation model. It was developed for the London Congestion Charging programme to predict changes in travel as a result of various policies associated with congestion charging. Like TRAM, it is an incremental equilibrium model that predicts changes in travel choices as a result of changes in generalised cost, relative to a base case considered to be in equilibrium. APRIL was used in a three tier modelling system with two other models as follows:

APRIL – strategic modelling characterised by a coarse spatial detail; 45 internal zones (within M25 boundary) and 7 external zones;

LTS - base forecasts and network modelling characterised by 'medium' spatial detail (925 zones);

WILTRAM – local level model used for highway modelling and characterised by fine spatial detail.

The travel choices or impacts modelled in APRIL are choices of:

- route;
- time of travel;
- mode;
- destination;
- frequency.

The choices are structured as a flexible hierarchial nested logit formulation. At each level in the nested incremental logit formulation, the choice depends on the generalised cost of the available options. The order of choice in the hierarchy is such that the most sensitive choices are at the bottom. As in TRAM, the HB trips are represented as primary destination tours. For purposes of simplicity, the Non-Home Based (NHB) trips are considered in the normal way as one way trips.

The market segmentation in APRIL is by:

- Trip purpose–4 HB and 2 NHB. The effects of employer assisted motoring are considered through the HBEB (Home Based Employer Business) and HBW (Home Based Work) trips. Within each HB purpose an average of 7 person types are recognised based on a combination of household income, household car ownership and level of employer assisted motoring.
- Mode – Four modes, namely car, bus, rail, slow (walk or cycle) are considered. There is provision to distinguish commercial vehicle (CV) movements between light goods vehicles (LGVs) and all others (OGVs).
- Time Period–up to 7 time periods are considered within which differential charges may be set.

The APRIL model is described in detail by Bates et al, (1996) and Williams and Bates, (1993). Recently ROCOL (2000) adopted strategic models based on the London Congestion Pricing to study the effects of road pricing in central London in anticipation of the new mayor for London deciding to implement such a scheme possibly within their first term.

TPM–The Transport Policy Model (TPM)(also previously known as the Single Link Model(SLM)) is a highly aggregate strategic transport model to assess urban transport policy impacts rapidly and with limited data requirements. It was developed by the TRL.

TPM models an urban area using just two zones: the inner zone representing the central area/CBD; and the outer zone/annulus representing surrounding built up area. There is also an external zone which may be the origin or destination of trips.

Global policy measures that can be assessed are:

- Public transport fares;
- Public transport services;
- Fuel price.

Central area transport policies that can be assessed are:

- Parking charges;
- Parking supply;
- Cordon charges can be assessed;
- Policies in combination such as public transport fare reductions in parallel with central area parking charge increases can also be assessed. TPM generalised cost elements divided into monetary and time costs respectively within the simulation are:

(a) Fuel price, public transport fares, parking charges and cordon charges.

(b) Congestion delay caused by changes in average zonal speeds, access and egress time; public transport waiting time, central area parking search time and public transport overcrowding factor.

Changes in the generalised costs determine the travel choices based on elasticity concepts. The model iterates between supply and demand until equilibrium is reached.

Four modes, car, bus, rail and walk are considered. There are three car ownership groups, 0, 1, and 2 car households. Two time periods, AM Peak and inter-peak are modelled. The PM peak is assumed to be equivalent to the AM peak although were specific data is available for each of these time periods, separate results may be obtained for each of the peak periods. AM peak trips are assumed less elastic than inter-peak due to their 'compulsory nature'. Trip purpose is not explicitly modelled, only differentiated through whether they are AM or Inter-peak trips.

The output from TPM include:

- Changes in trip distribution (trip starts and trip ends);
- Changes in modal choice;
- Changes in passenger kilometres;
- Changes passenger car unit (PCU) kilometres;
- Changes in global CO_2 equivalent emissions.

A major strength of TPM is supposed to be its minimal data requirements. However, the extremely aggregate and strategic nature of the model implies that the output of the model must be regarded as indicative rather than an accurate quantitative prediction of policy measures.

Raha (1997) used TPM to assess the impacts of a number of policy measures for the city of Manchester ranging from a reduction in public transport fares by 50% to combined measures in which public transport fares were reduced and central area parking charges were doubled. The author was quick to point out that because of its highly aggregate and strategic nature, TPM results were best used as a qualitative rather than a quantitative tool to indicate the likely directions of behavioural responses. A conclusion of this model in Manchester was that combined policies involving the 'carrot and stick' approach (e.g. halve public transport fares and double parking charges), appeared to be more effective than single policies such reducing public transport alone or doubling parking charges on its own.

3.6 Summary

The purpose of the above analysis was to show that:

a. Many sophisticated models have been used to model choice behaviour;
b. The programming requirements in terms of man hours are high;
c. The cost in terms of data collection and time are high;

d. The amount of data required is enormous and even with the most comprehensive of databases, supplementary data collection is usually required.

e. The models can usually only be used to study a limited number of travel choices or impacts and have to be calibrated for the specific locality. This limits model transferability;

f. Overal, the different model formulations show that the full understanding of travel choice behaviour does not exist. Therefore it is almost impossible to predict the outcome of policies with accuracy.

This chapter has reviewed the types of models usually employed in transportation to model the behavioural responses of travellers to network policies. The common concerns about the validity of these models in capturing the 'dynamics of interaction' between user decisions and system performance include:

- Inadequate understanding about the behavioural considerations that govern traveller decisions. These include the decision rules that determine the outcomes of travellers' choices as well as the learning process from one day to the next in reaching these choices (Mahmassani and Herman, 1984).
- Inadequate knowledge and also the lack of data that captures the variations across different market segments with travel behaviour preferences and travel patterns policy (Mahmassani and Herman,1984; Akiva et al, 1986).
- The existence and stability of an equilibrium under more general assumptions and in real systems (Mahmassani and Herman, 1984).

3.6.1 Conclusion

From the above review of the literature (e.g. Johnston and Rodier, 1994; Allen Jr. 1995), it would appear that the specifications for a good road pricing model and, indeed any TDM measure would have to include at least the following:

Trip Generation Model: most trip generation models are not sensitive to network characteristics such as congestion level and/or travel costs including direct user charges (e.g. Mekky, 1994). This assumes that travellers do not take into account congestion levels or the cost of travel before embarking on their journeys. It is to be expected that as travel conditions deteriorate and/or the cost of travel increases, trip rates from affected zones may decrease. As a result the trip rates between affected O-D pairs may decrease. In the long term, not only may the number of trips decrease, but car ownership may also go down. Therefore, it is necessary that trip generation models include an endogenous car ownership step sensitive to travel costs including road pricing scheme costs and parking costs. This would capture the pricing scheme's effect on car ownership levels and hence on trip generation. Generalised travel costs should be included in the trip generation stage to simulate the changes in the number and length of the trips made as a result of the pricing measure. Trip chaining could be a response of travellers to increases in travel cost as they seek to make trips more efficiently (Allen, Jr. 1995). Reflection of this phenomenon in the trip generation would be a significant improvement.

Trip Distribution Model Module: as with trip generation, generalised travel costs should be included in this model to better simulate changes in the number and length of trips as a result of the road pricing scheme.

Mode Choice Model: the mode shift effects of price/road user charging could be simulated using a reliable mode choice model that accurately reflects changes in travel cost in **composite impedance**.

Departure Time Choice Model: a departure time choice model sensitive to direct travel costs as well as to time costs is needed to represent time of day shifts due to additional monetary costs on peak period travel such as due to congestion pricing.

Assignment Model: route choice effects should be simulated by supplementary travel time components by a network assignment model capable of capturing the equilibrium between price and time effects.

Finally it is important that the generalised costs used in all the model steps are consistent with that used in the assignment step. This would improve the internal consistency of the models. Internal consistency within the model is important because the same travel costs are considered in the different model steps. Therefore travellers are assumed to consider their travel decisions in parallel rather than as individual sequences. For this to be true, the travel costs must be consistent in the trip generation, mode choice, destination choice, departure time choice and route choice modules. This combined or simultaneous decision process, better reflects the interdependency of these choices in real life, better than the assumption that travellers make these travel choices sequentially.

In the absence of such models, simple but plausible means of gaining understanding of the potential network benefits of travel choices are required. The dilemma faced by any transportation study was perhaps aptly summarised by Blessington(1994), who in the introduction of the paper entitled " Approaches to changing modal split: a strategy and policy context" wrote:
"Any study of transport must recognise at the outset that transport, in itself has no inherent value. Instead, transport must be recognised as the vital link which allows the necessary connections to be made in society, and to that extent our appreciation of the transport system will inevitably be influenced by the wider aspirations of society at any point in time. In other words, it is important not just to discuss in terms of policy and strategy 'how' to persuade motorists to use public transport , but 'why' we should persuade motorists and 'why' particularly at this time". Reconciling the wider aspirations of travellers for each and every trip as characterised and influenced by its purpose, the time at which it is made, the characteristics of the trip maker, the origin and destination of the trip, the network conditions and various other factors, makes the task of predicting and modelling travel behaviour a complex and difficult undertaking.

In the next chapter, the modelling method used in this research to overcome some of the modelling issues discussed in this chapter is explained. The method makes assumptions about the behavioural responses of travellers to TDM measures rather than try and predict the responses. In this way, the network effects of a wider spectrum of responses can be estimated, rather than concentrating on the task of formulating, calibrating and validating a demand model to predict the behavioural responses.

4 MODELLING APPROACH AND THE CONTRAM ASSIGNMENT MODEL

4.1 Introduction

In the last chapter, a review of models used in transportation modelling was undertaken. It was acknowledged that developments in modelling continue to improve. However, it was also highlighted that current modelling techniques still faced limitations in a number of ways. These include:

- model complexity;
- demanding data requirements and the associated costs of such data collection;
- increased computer run times with increasing model complexity;
- uncertainties about the validity of the models in view of inadequate understanding about travel behaviour.

Even the simpler assignment based techniques were shown to suffer from increased modelling complexity when attempting to represent specific behavioural changes beyond general trip suppression. This left little time for modellers to look at the network effects of travel behavioural responses that might arise from TDM measures such as direct user charging. Therefore, the need for simple modelling techniques to evaluate the detailed network effects of transportation policies such as TDM measures, remains an important and relevant aspect of urban transportation modelling.

This chapter outlines the method adopted in this work to circumvent some of these limitations to estimate the network effects of specific behavioural changes. By adopting simplifying assumptions in the modelling approach, this research aims to investigate the potential network effects of a wider range of possible behavioural responses to TDMs such as road user charging. It is recognised that the modelling assumption of hypothetical responses does not represent real life behaviour. However, this does represent a realistic way of understanding key questions in the absence of empirical evidence, limited evidence from demonstration trials or evidence from a fully comprehensive model. Indeed the credibility of evidence from hypothetical scenarios is one that has arisen before in the literature. For example, Edwards and Schofer (1976), faced with such a dilemma in addressing the relationship between land use and transportation energy consumption, asked the question:

' Can the interaction between land use and transportation in a hypothetical city be adequately described without prejudicing the study results by over specifying the behaviour of its residents?'

The use of evidence from the literature as a plausible guide and check of the inputs and outputs of the modelling, does place 'safeguards' against such 'over specification'. This lends credibility and plausibility to the modelling approach adopted.

4.1.1 The 'What if' Question

As the aim of this thesis is to ascertain the potential network effects of various traveller impacts to road pricing or TDM policies, it would be impractical to develop models for each impact. The purpose in undertaking such research is to help in the estimating and comparing the extent of the potential network effects of specific behavioural impacts. This in turn helps in the understanding of how and if these potential impacts, some of which have never or may never be experienced, can affect network level of service. Thus, the consideration here is not so much about what will or has happened but about what could happen. This attempts to answer the ' What if' scenario, a notable gap in transportation research (e.g. Potter et al, 1994). Indeed it is not the aim of this research to investigate how impacts of such a magnitude might be achieved, or, indeed whether they are possible at all to achieve. Rather, the research seeks to ascertain an 'upper bound' effect on network performance of these elastic impacts. As noted earlier, the only safeguard to the plausibility of the assumed impacts is the literature. Within the limited time of this research work, no specific data has been collected to shed light on travel behaviour and why or how travellers make the choices they make. This indeed is one of the reasons why a 'what if' approach is attractive since assumptions can be made of what the behavioural responses could be.

4.2 General Proposed Approach

The principle behind the proposed approach is that for a given network, the network performance or output can be expected to be sensitive to the 'shape' of the Origin-Destination (O-D) matrix. Given a base O-D matrix, specific behavioural changes or outcomes can be expected to 'shape' this matrix in different ways. The exact way in which specific behavioural responses affect this base matrix in response to network policies such as TDM is either unknown or uncertain. This is the main task of demand models. The matrix can also be expected to respond to exogenous factors in addition to the transport policies at play. This further complicates the prediction task. However, one can assume the effect and hence outcome on the O-D matrix of a given behavioural response, based on plausible guidelines from the literature. Basically, the methodology distinguishes between predicting the actual impact of a given policy and measuring or estimating the sensitivity of the network performance to assumed changes in the travel market. The former is much more difficult (if not impossible) than the latter. The latter can be carried out using available assignment models without the need for interaction with a strategic or external demand model. Furthermore assignment is an area of behavioural travel in which transport modellers have the most confidence (e.g. White et al, 1995). The assignment model used in this research is CONTRAM 5 (Continuous Traffic Assignment Model version 5). This was mainly because this software, including a calibrated model of the City of Southampton, was available for this research. CONTRAM has a number of attributes that make it valuable for this task. These are explained in later sections of this chapter. The Origin-Destination matrix used was developed from an extensive range of driver interview surveys conducted during 1992. During this same time period, a database of traffic flows within Southampton was constructed by collecting and averaging detector flows. These were used in the calibration.

4.2.1 Distinguishing the Behavioural Mechanisms at play

The different ways in which specific behavioural changes may affect the 'shape' of the O-D matrix is explained below following OECD (1994). Southampton is the major city in central southern England and is at the heart of an economically active region. It is essential for the City and its region that it continues to develop and attract an increasing number of people to support its activities. For this reason, the current Southampton road traffic reduction targets concentrate mainly on the car borne or single occupancy vehicle (SOV) commuter trip (Southampton Provisional Local Transport Plan 2000/1 to 2004/5). For this reason it is assumed in this thesis that TDM measures will be targeted at reducing the SOV rather than all vehicle types.

1. **Switch or Shift Peak Hour Travel:** as a result of the TDM measure, trips shift to less congested or to non priced or less priced time periods. The effect on the O-D matrix is to **reduce** the SOV trips in the charged periods or time slices, and to **increase** them in the less affected or uncharged periods for the affected O–D pairs. Generally this represents a **modification** to the total SOV travel market rather than a reduction to the number of vehicle trips. The derived need for the trip is undertaken by the original mode but in a modified way, namely by re-timing the trip. The derived need of the trip recognises that trips are rarely made just for their sake but in order to partake in activities at the destination. Therefore, a major challenge for TDM measures is to ensure that the reason why the trip was made in the first place can be achieved through some alternative means.
2. **Switch or Shift from locations affected by the TDM measure:** as a result of the TDM measure travel is shifted from an affected destination to an unaffected one. The effect on the O-D matrix is to **reduce** the vehicle trips made to the affected destinations and to **increase** the vehicle trips to alternative unaffected destinations nearer or further away from the origin. Changes in destination choice may result in changes in route choice with potential changes in total network vehicle kilometers travelled (VKT). Generally a change in destination choice represents a **modification** to the total SOV travel market rather than a reduction in the number of SOV trips. The derived need or the utility associated with the trip achieved by the original mode but in a modified way through changing the destination.
3. **Reduce the length of trips:** as a result of the TDM measure a trip is made to a nearer destination. The effect on the O-D matrix is to **reduce** the SOV trips made to the affected destinations and to **increase** the SOV trips to alternative unaffected destinations nearer to the origin with potential decreases in network VKT. Generally this represents a **modification** to the total SOV travel market rather than a reduction in the SOV trips. The derived need for the trip is undertaken by the original SOV mode but in a modified way by changing to a nearer destination.

4. **Reduce the number of trips:** as a result of the TDM measure, a trip no longer needs to be made. The effect on the O-D matrix is to reduce the number of SOV trips. Generally this represents a **reduction** to the total SOV travel market rather than a modification. The utility derived from the original foregone trip must therefore be attained by some **substitute** e.g. teleshopping, telecommuting, videoconferencing, etc since both the person and vehicle trip may/are not 'physically' accomplished. In essence, fewer SOV trips are made.
5. **Switch to Public Transport:** as a result of the TDM measure a trip is made by public transport. The effect is to **reduce** the number of SOV in the matrix and possibly **increase** that of buses. It is assumed that adequate spare capacity exists on current PT fleets. Although the **car trip** is not made, the **person trip** is made and so the derived need for the original trip is assumed to be accomplished. Generally this represents a **reduction** to the total SOV travel market rather than a modification.
6. **Switch to Non-motorised transport:** as a result of the measure a trip is made by for example walking or bicycling. The effect on the O - D matrix is to **reduce** the number of SOV and **increase** pedestrian and bicycle trips. The implications on pedestrian and cycle facilities would in theory have to be considered but is ignored here. Although the original **car trip** is not made, the **person trip** is made and so the derived need for the original trip is assumed to be accomplished. Generally this represents a **reduction** to the total SOV travel market rather than a modification;
7. **Switch to carpooling:** as a result of the measure a trip is made by carpooling instead of drive alone. The effect on the matrix is to **reduce** the number of SOV. Although the original **car trip** is not made, the **person trip** is made and so the derived need for the original trip is assumed to be accomplished. Generally this represents a **reduction** to the total SOV travel market rather than a modification. Linked trips may also be considered to reduce the number of SOV trips although the effects in terms of VKT maybe more complex. This is because fewer but longer trips maybe made involving a number of destinations.
8. **Partake in Car-sharing schemes:** as a result of the TDM measure car ownership is forsaken for a car sharing option. The effect on the O - D matrix is to **reduce** SOV trips. The utility derived from the original foregone trip must therefore be attained by some substitute e.g. teleshopping, telecommuting, videoconferencing etc since both the person and vehicle trip are not 'physically' accomplished except for the reduced occasions when the incumbent uses a car-share vehicle. Generally this

represents a **reduction** to the total SOV travel market rather than a modification. Car sharing as opposed to carpooling here is when a car rental service is substituted for private vehicle ownership (Litman, 2000). It is important to note that carpooling and car-sharing are not exactly the same. In carpooling, commuters may still own their vehicle but use them less as a result of carpooling. With car-sharing the idea is to reduce both car use and car ownership. Car sharing has lower fixed costs than private car ownership but has higher variable costs. It can typically reduce average vehicle use by 40-60% for those who normally rely on car use. However, its market share is currently small because it is a relatively new concept.

9. **Switch from carpool, public transport or from non motorised transport:** as a result of the TDM measure a trip previously made by other modes or a trip not previously made is now made by car. The effect on the matrix is to increase SOV trips. The derived nature of the trip that used to be accomplished by alternative modes or by some substitution mechanism is now accomplished through travel by the SOV. Generally this represents a **increase** to the total SOV travel market rather than a modification

Apart from reassignment which is considered an 'inelastic' response, item 1 represents peak spreading while items 2 and 3 can be considered to represent destination changes. Items 4 to 8 can be considered to represent various mechanisms of trip suppression while item 9 can be viewed to represent induced trips (trip generation).

Item 9 represents the highly debated issue of whether network improvements as a result of TDM measures will induce trips analogous to the debate on induced trips arising from capacity additions (SACTRA, 1994; Noland, 2001). This item is beyond the scope of this work and is not modelled.

4.2.2 Impact Categorisation for Modelling

For modelling purposes, the 'elastic' impact mechanisms listed in section 4.2.1 above have been divided into impact categories as shown in Table 4.1.With simplifying assumptions, impacts in the same impact category are considered to affect or 'shape' the O-D matrix through the same mechanism. Thus for instance items 4 to 8 have all been categorised under 'Trip Suppression'.

1. **Re–timing Category**–impacts by spreading peak period travel demand in time;
2. **Change in Destination Category**–impacts by changing trip destination.
3. **Trip Suppression Category–**This has been divided in Table 4.1 into 'substitution' and 'switching' mechanisms. In the former, the car trip is all together foregone or the number of car trips reduced by trip chaining, reduced trip frequency or even reduced car ownership through car-share schemes.

In the latter, the car trip is also foregone but the person trip is made by other modes. This often has implications for facilities and or services on the alternative modes. The main issue captured by this methodology for both suppression mechanisms is the reduction in SOV from the O-D matrix. While this maybe simplistic, it is a plausible representation since the original matrix has a far higher proportion of car trips than bus vehicle trips. Even doubling the bus vehicle trips does little to change this proportion. Clearly this is not the case for specific O–D pairs and hence routes on which public transport is a dominant mode. The methodology can, however, be applied to a specific route or corridor with a high proportion of bus vehicle trips including the modelling of park and ride. Specific public transport data such as existing service frequencies, existing bus occupancies, bus types, fleet size, additional fleet numbers required to absorb person trips switching from the car mode; existing bus priority measures and the implications of increased fleets on these facilities, and so on would be required. In the case of park and ride, finer zoning and detailed representation of links to access and leave the park and ride facility maybe required. The fine zoning would enable the park and ride facility to be defined as a zone (as an origin and as a destination) and provide a means of linking this zone to the network to enable detailed localised network effects of the park and ride facility to be analysed. The zoning available for this work was much coarser than would be required for modelling specific bus services such as park and ride facilities. In addition the data required for specific bus services was not available. The level of network analysis in this work was more aggregate rather than specific to particular facilities or routes although attention was paid to the analysis of key links and junctions.

As for a switch to non motorised modes, the available O–D matrix does not include either pedestrian 'mode' trips or bicycle trips, nor does the network specifically represent facilities exclusive to such markets. This would in itself be an area requiring a separate detailed study and is not considered any further.

4. **Reassignment Impact Category** – this groups impacts whose 'mechanism' is route change. The network effects of re-assignment are modelled separately in Chapter 5. This is because assignment is considered 'inelastic' and sets the 'lower bound' network effects were travellers to be insensitive to TDM measures such as road pricing.

To this end it seems reasonable to represent impacts in CONTRAM simply as:

- Route Changes/Reassignment;
- Re timing or peak spreading;
- Destination changes;
- Trip Suppression;

As noted above, reassignment is considered in Chapter 5. Peak spreading and trip suppression are considered in Chapter 6. Since the O–D matrix available was for the AM peak period where work trips can be considered dominant and discretionary trips negligible (e.g. Frick et al, 1996), destination change was assumed to be unlikely in the short-term. This was also the view adopted in the EUROTOLL Project (European Project for Toll Effects and Pricing Strategies), which considered that destination change was a long-term response rather than a short-term one (Francis and Ingrey, 2000). This response was therefore not considered any further in this research.

			O – D 'Shaping'	Matrix Mechanism				
Impact Category	How	Switch or Substitute Mechanism	On 'Affected'	On Alternatives	Resultant Effect on 'Shape' of SOV O–D Matrix	CONTRAM Modelling Representation	'Potential' Causative TDMs	Guidelines Sought from Literature
Retiming	Switch time of travel	Switch	Reduction in SOV trips in affected time slices/periods for affected O – D pairs	Increase in SOV trips in less or non affected time slices/periods for affected O – D pairs	**Modification** of O –D matrix to 'flatter' pea period profile	Suppress SOV trips in affected time slices for affected O – D pairs by reduction factors; Apply multiplying factors to less or non affected time slices; Total number of SOV trips in O – D Matrix is preserved	Differential Congestion Pricing; Differential Parking Pricing; Alternative Work Schedules; Pre – Trip Travel Information	Potential range of peak hour suppression levels; Elasticity and/or cross elasticity estimates; Criteria of redistributing suppressed trips to peak period shoulders; Plausible range of magnitude of time shifts; Guidelines on potential markets – e.g. by , trip purpose, constraints & propensity to retime etc Evidence on specific changes in network performance in affected & alternative periods (e.g. overall Network Vehicle Hours etc) due to re-timing mechanisms
Change Destination	Switch from affected destination zones to alternative unaffected destinations; Change length of trip; Change length of SOV trip through P & R. Note that a P&R facility maybe to same original zone. However, For modelling purposes, the P&R may be defined as a separate zone since trips may begin and end in it.	Switch	Reduce SOV trips to affected destination From specified origin zones; The 'dual mode' effect of Park & Ride not explicitly represented. It can be expected that P & R could affect the vehicle mix and even the design of roads/traffic signals etc in vicinity of such facilities. This requires detailed specific study of the scheme beyond this research	Increase SOV trips to alternative destinations from specified origins;	Modification of O – D matrix mainly by 'spatial' redistribution o trips (changes in desire lines)	Spatially redistribute some trips between selected O – D pairs as follows: Reduction factors applied to O – D pairs with trips end in affected Destination zone; Multiplying factors applied to O – D pairs with affected origins above and to new alternative destinations; Assumed that alternative destination chosen is nearer to origin than original destination. (In reality affected travellers may drive to unaffected destinations further than original ones. The network available does not enable this).	Congestion Pricing; Parking Pricing; Parking Management; Auto Restricted Zones/Zone Access; Park & Ride Facilities; Land Use Policies such as: Land Use & Zoning (High Density Mixed Land Uses) Site Amenities & Design	Potential range of peak hour suppression levels; Elasticity and/or cross elasticity estimates; Criteria of redistributing suppressed trips to alternative destinations; Guidelines on potential markets – e.g. by trip purpose, constraints & propensity to change destination etc Evidence on specific changes in network performance (e.g. overall Network Vehicle Hours etc) due to destination changes mechanisms
Trip Suppression	Reduce number of trips in a affected peak time slices/period; e.g. telecommuting + tele – services, reduce trip frequency, trip chain etc. Car – Sharing schemes or reduction In car ownership	Substitution	Reduce SOV trips in affected period for affected O – D pairs	These SOV trips assumed to be Removed from O - D matrix	Reduction of O – D matrix as SOV trips suppressed not 'redistributed'	Reduction factors used to suppress SOV Trips in affected time slices for affected O – D pairs	Congestion Pricing; Telecom substitutes or policies that encourage them (e.g. telecommuting & other tele- service substitutes);	Potential range of suppression and criteria for suppression; Elasticity estimates; Guidelines on potential market share; e.g. propensity for 'tele- services, trip chaining, trip frequency reduction possibly by trip purpose etc; Evidence on specific changes in network performance due to trips suppression mechanisms (e.g. overall Network Vehicle Hours etc)
	Switch to Public Transport Switch to Non Motorised Transport; Switch to Carpooling, minibuses	Switch	Reduce SOV trips in affected period for affected O – D pairs	Modal changes from SOV to other modes have implications on services and/or facilities of the alternative modes Assumed for instance that adequate PT spare capacity available and/or that extra investment in PT fleets has negligible effect on O – D matrix except on specific routes/ O – Ds (this not within scope of this research)	Reduction in O – D matrix since SOV trips removed by transfer of person trips to alternative modes are 'lost' from the O – D matrix.	Reduction factors used to suppress SOV Trips in affected time slices for affected O – D pairs	Congestion Pricing; Parking Pricing; Parking Management; Auto Restricted Zones/Zone Access; Employer Transport Plans: Trip ReductionOrdinances; etc (see e.g. OECD, 1994) Land Use Policies such as: Land Use & Zoning (High Density Mixed Land Uses) Site Amenities &Design	Potential range of SOV trip suppression due to modal Changes employer reduction measures/ Employer Transport Plans (ETPs) or Green Transport Plans (GTPs); School Travel Plans, Hospital Travel Plans etc: Elasticity estimates; Guidelines on potential market share of above mentioned Travel markets; Evidence on specific changes in network performance in affected & alternative periods (e.g. overall Network Vehicle Hours etc) due to trip suppression mechanisms

Table 4. 1 Proposed Impact Categorisation and Proposed Modelling (Compiled from Literature Review) page 95

4.2.3 The Role of the Literature

It can be seen from Table 4.1 that the literature thus serves three primary roles in this research work:

a. It helps in defining the problem;
b. It provides the inputs to the modelling;
c. It constrains and checks the plausibility of the output from the modelling and also enables comparisons to be made between the results of this modelling with results of other models and other evidence in the literature. Further, comparison can be made amongst different TDM policies.

Figure 4.1 is a schematic diagram of the interaction of the literature and the modelling approach using CONTRAM.

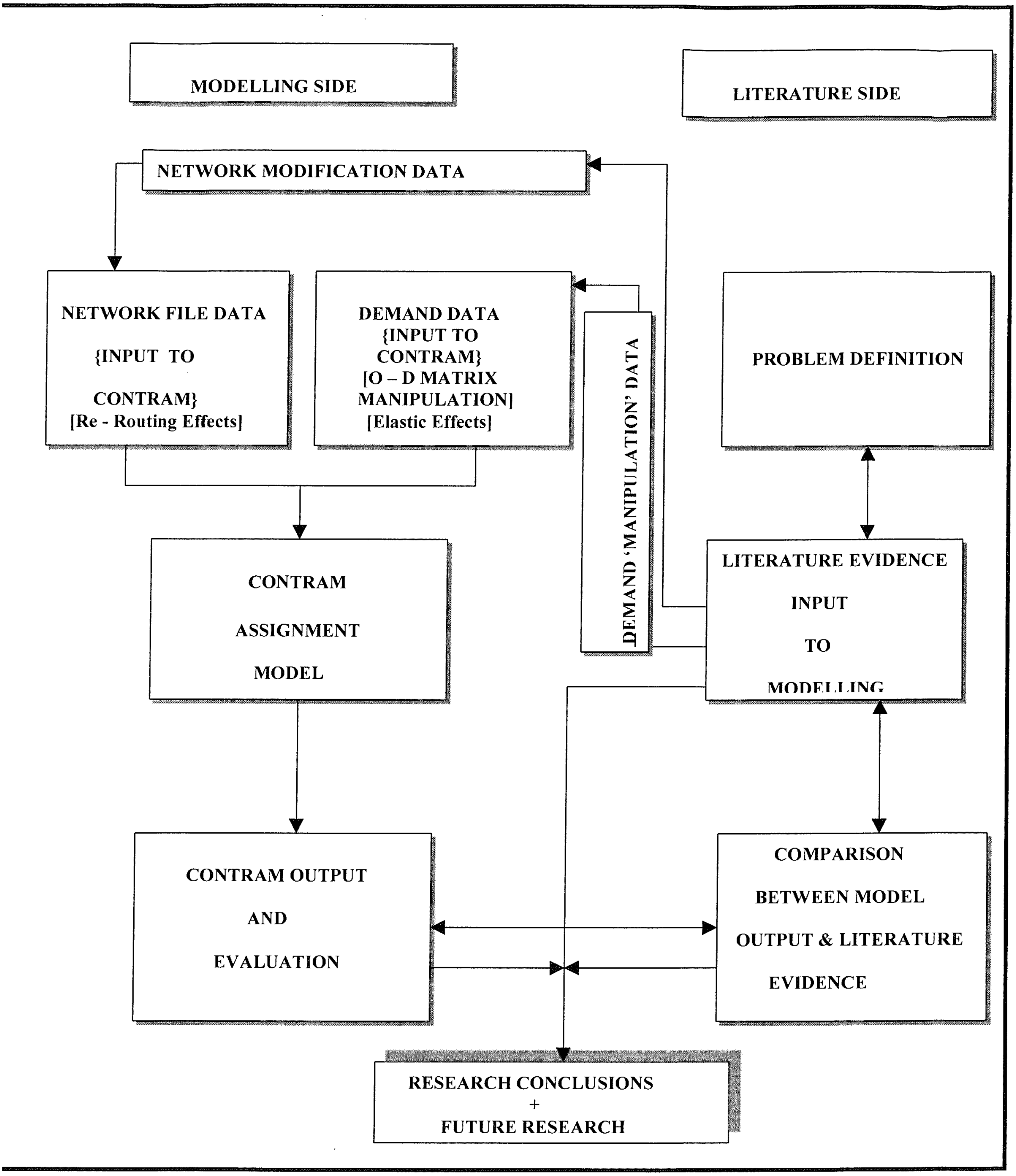


Figure 4.1. Schematic Interaction between Literature and CONTRAM Modelling

4.3 Evaluation

The network effects of the modelled behavioural impacts were evaluated by comparing the summary results from the base case scenario (do nothing) with those obtained from the modelled scenarios. The evaluation involved comparing the journey time measured in vehicle hours for either the total network or for specified travel markets and/or key links in the network. The queuing performance and a selection of other performance indicators were also used where appropriate.

CONTRAM outputs various network parameters that can be used for evaluation at different levels of network aggregation as follows:

- Overall network level;
- Link by link level;
- Time slice by time slice level;
- By vehicle type.

This enables different spatial and temporal levels of network analysis to be carried out. A route file from the CONTRAM output contains information about the specific routes used between specific O-D pairs. This can be used to analyse changes in route and travel times between chosen O-D pairs.

4.3.1 The Case for Aggregate Network Performance Indicators

There are compelling reasons for looking at aggregate figures sometimes termed 'system benefits'. Perhaps most important is the fact that certain impacts such as reduced fuel consumption, reduced air pollution and reduced accident probability for example can be too small to perceive at the individual user level but are significant at system wide level (Khattak et al, 1994). On the other hand some researchers (e.g. Welch and Williams, 1997) have questioned the use of aggregate travel time savings for the economic appraisal of highway, public transport or traffic management schemes. Their concern pertains to small time savings and hence the variation of the value of time with respect to the duration of time saved. This is a problem beyond this research. However, the detailed CONTRAM route file output can be used to work out changes in link travel times before and after the application of a TDM measure.

4.4 The CONTRAM Assignment Model

CONTRAM is a dynamic assignment model that predicts traffic routes, link flows, and queues and delays at junctions as they vary with time in response to changes in demand. The assumption is that drivers are familiar with the network and traffic conditions (i.e. have perfect knowledge) and choose routes that minimise their journey time or cost. This minimisation of journey time or cost takes into account delays at junctions at the times that the vehicles arrive at each junction along their routes. The routeing criteria can be extended from the minimisation of journey time or cost to include a variety of other parameters such as safety, environment, fuel consumption and so on (Leonard et al, 1989; McDonald, 1996).

CONTRAM 5 requires three input files to run it:

- a network file which describes the link-based topology, junctions, signals and link capacities of the road network being modelled;
- an Origin-Destination (O-D) matrix which provides the time varying traffic demands;
- a control file for running the program.

CONTRAM was developed for the assessment of traffic management schemes in urban areas (White et. al, 1998 (www paper); Taylor and Leonard, 1989). Although it is well established and used by many organisations world wide, CONTRAM is predominantly a network model and was not designed to predict or evaluate traveller behavioural impacts. It is not the intention here to give a detailed description of CONTRAM or its structure. The reader is referred to Leonard et al, 1989; Taylor 1990). Instead, the aim is to highlight aspects of the CONTRAM model that make it suitable for evaluating the potential network benefits that may arise from the impacts of TDM measures such as road pricing.

4.5 Some Network Features of CONTRAM

As congestion increases and occurs over longer time periods and larger areas of the network, it is important that an assignment model such as CONTRAM is able to model journeys through time to take into account time varying network conditions and thus predict route choice accurately. Of the available models, CONTRAM is most capable of representing time varying network conditions and their effect on route choice in congested networks (White et al,1998; www.Contram.com/TECH).

4.5.1 Routeing criteria

In CONTRAM the generalised cost determining route choice (or the cost of traversing each of the links constituting the route used between an O – D pair) can be based on the minimisation of:

1. journey time alone;
2. journey time and travel costs in a generalised cost function;
3. a network performance measure that includes a variety of other parameters such as safety, environment, fuel consumption, link tolls and other notional costs.

Research has shown that minimisation of journey time is the most important criteria used by drivers in route choice (e.g. Duffell and Kalombaris, 1988). The assignment criteria in the CONTRAM model available for this research was based on minimisation of journey time.

In CONTRAM it is assumed that drivers have perfect knowledge of network travel conditions beforehand. Therefore the final assignment represents the optimum routes used by drivers during periods of congestion that occur regularly such as the morning and evening peaks during working days. In CONTRAM, the assignment mechanism is such that drivers are assigned to their entire route from origin to destination, in a process whereby the driver to be assigned next depends on their network entry time. This is unlike in the 'single-day' route guidance version of CONTRAM called RGCONTRAM. In RGCONTRAM, drivers are assigned a link at a time to links on their route as far as they can go before they interact with other drivers (Njoze, 1995). As a result RGCONTRAM can model the effect of incidents that a driver may encounter in the course of their journey. This is because in RGCONTRAM drivers are able to change their route when they encounter unusual queues upstream of a link. In CONTRAM, such en-route changes are not possible. This, however, presents no major handicaps to the modelling in this work since if a TDM measure were to be applied, such information would be known to the driver before they left their origin. The route chosen would thus be selected with knowledge of the TDM already available. This would be representative of average day to day 'normal' traffic conditions rather than that of unforseen incidents, as is the case with the 'single-day' model. Another point to note is that CONTRAM tries to find 'optimal' solutions for a given O-D pair. Since perfect knowledge is assumed, the routes chosen by drivers represent routes with the least costs possible for that given O-D pair and no cheaper route is possible. Research done at Southampton University in the 1980's showed that in reality, drivers have imperfect knowledge and so choose their routes inefficiently. This inefficiency resulted in journey times that were 5% to 14% higher on average than those assumed under perfect knowledge. However, this inefficiency was seen to be much less for familiar drivers (McDonald and Hounsell, 1985).

4.5.2 Network Detail

A network file describes the link based topology, junctions, signals and link capacities. All junction types can be modelled. Detailed simulation of traffic signals, multi–routeing for vehicles with freedom of choice of route and fixed routes for scheduled buses, banned vehicle movements can all be represented. As a mesoscopic assignment model, CONTRAM provides a balance of detail between network size and vehicle representation. Microscopic models provide individual vehicle representation at the expense of network size while macroscopic models are too crude.

4.5.3 Time Variation

Two key features are important here. The first is the subdivision of the modelled period into time slices in the demand file. These are typically 10–20 minutes long. Such time intervals are sufficiently short to capture time variations in traffic demand and yet large enough not to reflect ‘noise’ in a particular set of flow measurements. An adequate number of time slices is able to reflect changes in flow patterns covering the times when demand in the network nears or exceeds capacity on come links.

Traffic for each Origin–Destination movement is divided into packets consisting of an integral number of vehicles. The second is that the progression of packets through a network is calculated according to statistical and queuing theory relations between flow increments, the capacities at junctions, and the journey times from one point to another in the network according to the route taken. This makes CONTRAM a time dependent traffic model based on traffic flow interactions rather than a static model.

The use of packets rather than individual vehicles reduces computation time. It is, however, a plausible since it reflects the tendency of drivers travelling between a particular origin and destination, and starting their journeys about the same time, to take the same route as they are influenced by similar traffic conditions. As was explained earlier in Section 4.5.1, the route taken is determined at the start since perfect knowledge is assumed. Once in the network, a packet cannot deviate from the predetermined route. As a result, CONTRAM cannot model en-route changes to route choice as might be required when unpredictable events such as incidents occur after a trip has begun.

4.5.4 Over-capacity

CONTRAM can model relatively short finite periods of over - capacity demand in which drivers can tolerate a certain amount of delay as a result of congestion. This phenomenon referred to as passive peak spreading, results in extended journey times (http://www.contram.com). CONTRAM does not, however, explicitly model departure time choice or peak spreading. Nevertheless, its ability to represent traffic demand by time slice presents a powerful feature that has been exploited by researchers (e.g. Allam and Alfa, 1992). Since CONTRAM calculates travel costs in each time slice, this feature was exploited by Allam and Alfa to use these time slice costs as inputs to a model that tried to predicted the temporal variation in traffic demand as a function of these time varying costs. More details about the work done by these authors is described in Chapter 6, section 6.2.

4.5.5 Network interaction

Willoughby and Emmerson (1999) have discussed the importance of assignment models to represent 'network interaction'. They have also discussed why microscopic models have greater potential to address these issues as computer power continues to increase. Network interaction implies that the effect of one junction on another is taken into account. Such effects include arrival patterns, the downstream effects of bottlenecks and blocking back. They reviewed at least three modelling methods in the U.K. namely SATURN, TRIPS and CONTRAM.

Compared to SATURN which uses 'cyclic flow profiles', CONTRAM which uses 'dynamic assignment' was able to represent blocking back. TRIPS, which uses 'dynamic profiling' is also able to take account of blocking back but unlike CONTRAM, did not at the time load the excess traffic in subsequent time slices. CONTRAM, by dividing demand into packets, is more precisely able to represent the effects of 'bottlenecks' in reducing downstream flows or causing queues to block back than TRIPS. This is because each packet is traced in time and space as it moves through the network.

In SATURN integration is used to calculate average delay throughout the cycle from the modelled queues in each time segment. An additional random component of delay at traffic signals and an additional deterministic component for overcapacity cases is added. TRIPS and CONTRAM both use time -dependent queuing formulae to calculate average queues and delays by time slice.

SATURN's cyclic flow profiles were more able to represent the effect of changes in vehicle arrival patterns due to bunching of traffic as might be caused by upstream traffic signals. CONTRAM and TRIPS only employ general parameters for such effects. Changes in vehicle arrival patterns are important to the estimation of capacities for opposed flows at priority junctions and roundabouts, and to the delays at downstream signals which may be linked to minimise overall delays or achieve green waves. Microscopic models like PARAMICS model the movement of an individual vehicle in very short time intervals typically less than a second. They are thus able to represent the formation and dispersion of platoons of vehicles as they move through the network and identify directly the occurrence of acceptable gaps in determining the capacity of opposed streams of traffic.

The authors concluded that although microscopic simulation offered the potential for dealing with all aspects of vehicle interaction more realistically, further research and understanding is required before the models can be applied with confidence. In particular, understanding of behavioural relationships and parameters adopted needs to be confirmed. On the other hand, apart from the obvious fact that they are less demanding on computer power, aggregate models currently widely used, have a 'strong theoretical or empirical basis' and have been well tried and tested. They also have the advantage for most applications of producing estimates of average travel times directly. Therefore the use of aggregate models such as CONTRAM to evaluate the potential network effects of the likely impacts of TDM measures such as road user charging is still credible. CONTRAM despite being weaker in representing arrival pattern effects, is relatively strong on representing the effects of bottlenecks and blocking back. It combines truly dynamic assignment with sound traffic modelling principles and is most capable of representing time varying network conditions and their effect on route choice (White et al, 1998).

4.5.6 CONTRAM Output

Considerable data is provided as output in CONTRAM. The information is used for traffic engineering and economic assessments of traffic management schemes. The detailed output enables a detailed network analysis to be made and also enables comparison amongst different scenarios. The output includes:

- overall summaries of journey times, distance travelled, average speed and fuel consumption
- link by link values, for each time interval, of flows, queues, delays, percentage saturation, total time spent, distance travelled and averaged speed; the identification of blocking back when it occurs
- summary tables, for each time interval, of flows, queues, mean queue times and average speed on links
- turning movements at junctions for each time interval
- vehicle route information
- average 'point to point' O-D speeds
- convergence parameters.

The summary information is particularly useful. Firstly, it does provide a quick initial means of comparing changes in the network as a result of different policies implemented.

Secondly, it provides, albeit with careful interpretation, a description of the 'macroscopic' behaviour of the network. In order that the network implications of TDM measures such as Road User charging are better understood, it is necessary to evaluate their potential effects at a network wide level rather than at link level only. Some authors (e.g. Papageorgiou, 1998) have argued that macroscopic traffic flow models may never reach the accuracy level of 'other domains in physics and engineering'. However, May and Shepherd (1995), May et al, (2000) point out that, while the use of speed/flow relationships for individual links and junctions are well accepted and are used widely to evaluate capacity addition benefits, the use of such relationships to analyse demand and supply in complex urban networks is time consuming and potentially inaccurate since it may ignore the interactions between links and between adjacent junctions. The aggregate output from models like CONTRAM can help provide an understanding of overall network performance in addition to providing information on link by link and junction by junction changes.

4.6 CONTRAM: Suitability and Limitations for Modelling the Network Effects of Behavioural Changes

As an 'inelastic' assignment model, only assignment is explicitly modelled in CONTRAM. Mode changes and indeed other 'elastic' behavioural responses (e.g. destination change) cannot be explicitly modelled in CONTRAM since the assignment model uses as its input a fixed trip matrix. No intrinsic mechanism currently exists that can directly modify the O-D matrix in response to policy changes in the network. CONTRAM, however, has a detailed demand matrix as input. Three vehicle classes, usually cars, lorries and buses are represented in CONTRAM 5 time slice by time slice. Manipulation of this demand matrix by applying appropriate factors to the time slice demand figures can be used to simulate assumed impacts. This makes it possible to estimate the potential network effects of these impacts.

Assumed levels of mode changes from car to bus can be represented by suppressing car trips in the demand matrix in appropriate time slices (e.g. peak period). However, the detailed representation of these effects requires detailed knowledge of car occupancies, current bus occupancies by service or route in order to calculate extra bus fleets required and hence changes in the vehicle mix or composition on the network (Ghali et al, 1998).

No direct mechanism exists to represent these issues in CONTRAM. In this work it has been assumed that there is adequate sitting capacity (person trips) in the current bus fleet not to warrant any increase in bus numbers as car vehicle trips are suppressed. This also assumes a low car occupancy, a reasonable assumption in developed countries.

Multi-class user assignment: although three different classes of vehicles; car, bus and lorry can be represented in CONTRAM 5, it is not possible to model multi class users of the same vehicle type. This means that for example high income car drivers cannot be explicitly differentiated from low income car drivers and so on. This CONTRAM limitation has been discussed by Ghali et al, (1998).

CONTRAM also cannot represent different trip purposes of the same vehicle type. Clearly, for demand modelling purposes a major problem with an assignment model like CONTRAM is its inability to represent the behaviour of different market segments to a given network policy.
Generative aspects of policy changes in the transport system cannot be modelled in CONTRAM because of its inelastic nature. The effects of income increases on car ownership or of increased car ownership on trip making for example cannot be explicitly modelled. However, traffic growth or an increase in congestion can be represented by applying multiplying factors to the demand matrix.

4.7 Concluding Remarks

This chapter has outlined a methodology with which to evaluate the potential network effects of specific behavioural responses that may arise from TDM measures such as road user charging. The methodology is based on assuming the outcome of such measures based on guidelines from the literature. A review of the CONTRAM assignment model has been undertaken. This highlighted the limitations and advantages of CONTRAM and its suitability evaluating the potential network effects of behavioural changes that may arise from TDM measures such as road user charging. It was shown that although CONTRAM can not explicitly represent specific 'elastic' responses, it can be used to test the sensitivity of the network to changes in the 'shape' of the O-D matrix. By applying appropriate factors to the O-D matrix, the way in which specific behavioural changes might affect the O-D matrix could be modelled and the network implications of these changes evaluated and compared. The methodology thus provides a simple but plausible technique of estimating the potential network effects of specific behavioural responses that may arise from TDM measures without the need for interaction with a strategic model or the need for costly and demanding data collection.

5 THE RE-ROUTEING EFFECTS OF DIRECT USER CHARGES

5.1 Introduction

This chapter predominantly explores the reassignment effects of road user charging. The main issue is to study what the network effects would be if travellers confronted with road user charging were inelastic in their behaviour and therefore responded by changing their routes or indeed not changing them at all. This must be considered in view of current evidence which seems to suggest that wherever possible, the dominant response to charging is re–routeing (e.g. Bonsall et al, 1998; Mekky, 1995; Hug et al, 1997). The assumption of a fixed matrix is as May et al, (2000) point out unrealistic, but it provides a useful lower bound indication of the effects of road pricing were car use to be insensitive to price. Direct user charging is used here as a specific TDM measure to illustrate in more detail the network consequences that may result from re-routeing behaviour.

5.1.1 A Brief Recap of some pertinent issues

Smith et al, (1994) studied the re–routeing effects of four road user charging mechanisms. These are namely fixed tolls, distance based charging, time based charging and delay based charging. Their results ranked delay based charging as producing the most network benefits; i.e. reduction of congestion at comparatively low charges and hence increased network speeds. This was followed by time based charging, distance based charging and fixed tolls respectively. However, work by Bonsall and Palmer (1997), Bonsall et al, (1998) using questionnaires and the VLADIMIR (see glossary for expansion) route choice simulator concluded that even very low charges based on time spent in the network could potentially induce drivers to drive less carefully. This finding was strong enough to prevent time based methods from being tested in field trials (May et al, 1998) and to cause other modellers to weigh distance far more than time in their coefficients (O'Mahony et al, 2000). Litman, (1999) independently concluded that although road pricing that varied by time and location was more optimal than distance based charging, the application of time based charging was constrained by 'transaction costs and privacy concerns'. Therefore distance based pricing appeared to offer the greatest potential for implementation because they are inexpensive to implement using a verified recording of odometer data i.e. "odometer audit". Indeed recent examples of electronic toll collection (ETC) toll road schemes such as the Melbourne City Link (MCL) in Australia and Highway 407 in Ontario, Canada are based on distance based or fixed point tolling respectively. The Singapore ERP also is based on charging at specific points. Also, it is generally agreed that point systems such as cordon pricing are the most likely to be implemented charging systems because of their simplicity (e.g. Cheese and Klein, 1999; ROCOL, 2000). This work therefore assumes a variety of cordon arrangements based on the Southampton network to study the re-routeing effects of tolls. While the work by Smith et al, (1994), Milne, (1997) are based on the Cambridge and York networks where orbital routes provide alternative routes, the Southampton network is more radial and has natural bottlenecks because of the river system (Itchen Bridge, Northam and Cobden Bridges). This provides a unique opportunity to estimate the extent of network effects where route choice is limited although the Southampton network was mainly used because it was available for this research.

5.2 Examples of Charging Facilities and their different objectives

There are quite a number of examples in the literature where direct charges have been incorporated into the assignment model to simulate the re-routeing effects of tolls.

1. Toll roads built specifically to relieve congestion on existing parallel routes

The objectives have mainly been to determine the revenue potential of private financed or government/private partnerships built toll roads competing with free but lower standard and or congested parallel routes. Examples include Highway 407 in Toronto (Mekky, 1994,1995,1997); the Melbourne City Link (MCL) in Australia; some Norwegian toll roads (Tretvik, 1993). Therefore, drivers who diverted from the free route to the tolled route did so because they were trading time for money. Mekky (1995) has reported from modelling, am peak volumes decreases as high as 31 to 33% from congested free routes as traffic diverted to tolled facilities with better travel conditions. These studies and models have thus been a source of value of time information. In the case of Tretvik, (1993) the studies went so far as to compare the actual travel time savings and the perceived travel time savings. There was evidence that perceived values were generally higher than actual times. In many respects, such toll roads appear to meet no resistance since people accept their role and more importantly, because the existing 'free roads' remain available to those unwilling or unable to pay (e.g. Glazer and Niskanen, 2000).

These roads also have potential to provide evidence on how travellers respond to increases in tolls since to remain viable, the level of service must remain considerably higher than that of the parallel routes. Therefore price increases can and have been used to regulate demand and thus provide information on elasticity estimates with respect to price or toll increases. Further, such roads (e.g. MCL, Highway 407) have demonstrated the technological feasibility and possibilities of electronic toll collection (ETC) systems.

The classic case of road user charging, however, pertains to the case of pricing a 'once free' congested road within an existing network in which re-routeing maybe the dominant but not necessarily the only response. In such cases re-routeing to unsuitable roads is a potential adverse response. Therefore toll facilities predominantly built as alternatives to congested free parallel routes and whose tolls are determined predominantly by revenue generation provide little evidence on the behavioural responses of pricing existing facilities where alternatives in choice are limited or unavailable.

5.2.1 Determining the Charge

As mentioned earlier charges can be based on different criteria such as:

1. Congestion reduction, with the charges being based on congestion costs as determined by marginal cost pricing.
2. Revenue generation (e.g. Norwegian Toll Rings; Highway 407; MCL).
3. Environmental based to reduce emissions and or noise pollution (e.g LERTS tested environmental tolls of up to £10 for environmental trials. These were about twice the maximum value tested for other scenarios). The interest of this research was congestion reduction. Therefore, environmental based tolls were not considered any further.

4. Practical Considerations on current motoring costs (see e.g. Dawson, 1986 who noted that theoretically determined congestion based charges were usually far higher than those determined by practical considerations of public and political acceptability, and Collis and Inwood (1996) who expressed similar views for Bristol's Avon Traffic Restraint study). It was not the intention of this research to calculate these charges. Rather it has been assumed that the range of charges evident in the literature should reasonably represent the magnitude of charges that can be expected were a pricing scheme to be introduced on the Southampton network. Such an approach ensures reasonable coverage of the full range of charges that may be expected especially those charges that can be considered practicable in view of potential public and political disquiet.

The range of direct tolls has been found to vary by city size (Cheese and Klein, 1999), while the minimum toll can be set by the need to achieve a reasonable level of revenue generation and/or trip suppression (Smith et al, 1994). It was therefore decided to test cordon tolls between 20 pence and 200 pence. The lower toll values were based on evidence from the literature (e.g. Smith et al, 1994) where tolls from 50 pence were tested for Cambridge. This evidence was consistent with that by Collis and Inwood (1996) for Bristol. There, stated preference surveys indicated that the average willingness to pay charges were between 26 pence and 32 pence per cordon.

For Southampton considering its size, the upper limit set by the Cheese and Klein study was £2.00. This appeared to be a reasonable value and so the £2 upper toll level was adopted. The Smith et al, (1994) and Collis and Inwood (1996) lower bound levels of 20 pence to 50 pence were also considered appropriate for testing in Southampton. Based on current evidence, (e.g. Cheese and Klein, 1999) a £10 toll for the purpose of congestion alleviation, would appear to be too large for a city the size of Southampton. ROCOL (2000) for example, based their core scenarios for charging in London on daily charges of £2.50 for driving in Inner London, and £5 for driving in Central London.

5.3 Value of Time Used in the Modelling

Since the value of time (VOT) varies by vehicle type, market segment and for the same market segment by for example trip purpose, time of day, it is necessary to have data on VOT for such different situations. There have been many studies on values of time in transportation literature, but the value of time is still a source of uncertainty and debate in transportation modelling (e.g. Bates et al. 1996, Wardman, 1998).

The value of time used in the modelling was determined from Transport Economics Note (March 2001) (http/ www.roads.detr.gov.uk/roadnetwork). The note replaced the previous Highways Economics Note No. 2. Table 2/6 in the note gives a 1998 perceived value of time per vehicle of 673pence/hr for a 'Non work' car journey. Table 2/7 can be used to account for forecast growth in real value of time per annum up to 2050. It was decided to use the 2001 value throughout this research as this was considered to cover the period of main relevance in the modelling.

Base Year Value of Time (1998)	673pence/hour	Table 2/6 Transport Economics Note
1998 - 1999	673*1.0341 = 695.9p/hr	Table 2/7
1999 - 2000	695.9*1.0131 = 705.1p/hr	Table 2/7
2000 - 2001	705*1.0219 = 720.5 p/hr	Table 2/7

Table 5.1 Calculation of the Value of Time from the Transport Economics Note

It can be seen from Table 5.1 that applying the forecast growth factors to the value of time (% p.a.) gives an estimated 2001 value of time of **720.5pence per hour or 12.00pence/minute**. The multiplying factors 1.0341, 1.0131 and 1.0219 obtained from Table 2/7 of the Economic Note account for the forecast in annual growth in the value of time.

5.3.1 General Representation of Direct Charges

Essentially, the aim is to convert travel costs as represented by a generalised cost, into a generalised time (e.g. Milne, 1997). This assumes that travel costs are perceived in time units by drivers. Since a toll is essentially a point charge, its effect is only taken into account when a driver traverses that link and passes the tolling point. Once the toll has been paid and the tolling point has been passed, there is no incentive on the driver to modify their travel behaviour beyond the tolling point. Therefore in the modelling, the toll is applied only to the affected 'entry' link after which a paying driver can travel as they please since the toll has no effect on subsequent links.

The variation of link travel time with congestion (measured as the volume to capacity ratio) can generally be represented by an equation of the form (Mekky, 1995):

$$\tau = \tau_0(1 + \alpha(v/c)^{\beta}) \qquad (1)$$

Where

τ = actual link travel time in minutes/km

τ_0 = free flow link travel time in minutes/km

v = link volume or flow in vehicles/hour (or pcu/hr)

c = link capacity in vehicles/hr (or pcu/hr)

$\alpha;\beta$ = coefficients that depend on the link type or standard.

For a link of length L the travel time on the link is

$$\tau_t = \tau_0(1 + \alpha(v/c)^{\beta}) * L \qquad (2)$$

where τ_t is in minutes.

If a toll of T pence is applied to the link then the equivalent time penalty over the link due to the toll is = T/VOT and equation (2) when a toll is applied becomes:

$$\tau_t = \tau_0(1 + \alpha(v/c)^{\beta}) * L + T/VOT \qquad (3)$$

where VOT is the value of time in pence/minute.

Since the link costs are defined per unit length for input into the assignment model, equation (3) becomes

$$\tau = \tau_0(1 + \alpha(v/c)^{\beta}) + [T/(VOT*L)] \qquad (4)$$

The first term ($\tau_0(1 + \alpha(v/c)^{\beta})$, is the travel time per unit length and accounts for the effects of congestion as link flows increase. It has units of minutes/kilometre. The second term accounts for the tolling effect. For a given link, this term is constant and also has units of minutes/kilometre. Equation (4) shows that the time penalty per kilometer is a function of link length as is illustrated in Table 5.2.

Toll in Pence	Link Length in Km	Time Penalty (minutes/Km)
50	0.3	13.9
	0.5	8.3
	1	4.2
200	0.3	55.6
	0.5	33.3
	1	16.7

Table 5.2 Effect of Link Length on Time Penalty/Kilometre

The variation of the time penalty per kilometre by link length introduces modelling complexities. Firstly, the model inputs would have to be considered on a link by link basis since the time penalty per unit length would differ by link length. This could potentially distort the network effects of tolling if the tolled links were of different lengths. The modeling would also be cumbersome. Higher tolls would be difficult to represent.

5.3.2 Representing a Toll in CONTRAM 5

Following the discussions above, it became clear that representing a toll in CONTRAM by converting it into an equivalent time penalty might produce results that could distort the network effects mainly because of the variation in link length. A new card in CONTRAM 5 enabled tolls to be entered directly in monetary units in a generalised cost function. The model available for this work was based on minimisation of journey time. Thus, in the CONTRAM model used in this research, the generalised cost consisted only of travel time, and the assignment was based on minimising the travel time between O-D pairs. Research has shown that journey time minimisation is the most single important factor in choosing a route (e.g. Duffell and Kalombaris, 1988). The generalised cost function if travel time minimisation is the criterion for route choice is of the form:

Generalised Cost (GC) = bT **(5)**

where b is the value of time and T is the travel time. Therefore GC has monetary units. The toll can be added directly to the generalised cost function in monetary units to give a generalised cost function of the form:

Generalised Cost (GC) = bT + Toll **(6)**

This approach assumes that travellers perceive their travel costs in monetary terms and so choose their routes to minimise the monetary costs they incur. Equation (6) therefore represents a traveller's perception of travel costs inclusive of travel time costs and toll costs and is termed the Perceived Cost (PC) in CONTRAM. The term perceived cost emphasises the behavioural implications of these travel costs on drivers' route choice and is the term adopted in this research henceforth. Equation (6) shows that where a link is not tolled, route choice is based simply on travel time costs, which is tantamount to minimisation of journey time as can be seen in equation (5).

5.3.3 Specifying the Input Link Parameters and Tolls for Assignment in CONTRAM

Card types are used in CONTRAM 5 to specify link properties and hence the network topology. The standard data specifying the usual properties of links are entered through card types 4, 5 and 6. These card types describe the link properties of uncontrolled links, give way links and signal-controlled links respectively. The link properties specified in these card types include the link number, the downstream links connected to the link, the link length, the banned vehicle code specifying those vehicle classes that are prohibited from using the link, the storage capacity of the link and the saturation flow at the downstream end of the link amongst other things. Signal data information is also specified in these card types where appropriate. The link travel time to be used for assignment is specified in these card types as a cruise time or a cruise speed or by a speed/flow curve.

Additional link data such as tolls are specified through additional card types notably card types 14, 15 and 16 which correspond to card types 4, 5 and 6 respectively. Provision is available in card types 14, 15 and 16 to enter elements such as tolls and other costs which may modify the perceived costs of specific links. This information is defined in conjunction with card type 62 where the perceived cost function parameters are defined. Entering toll information in card types 14, 15, 16 alerts CONTRAM to the fact that the toll component has to be defined in the perceived cost function in card type 62. The toll magnitude can also be varied in card type 62. Set numbers enable specific links to be identified for tolling over specified time slices. The units of the perceived cost are specified in card type 61. For example, card type 61 can be used to instruct CONTRAM to output the perceived cost figures in **POUNDS** rather than in **PENCE** to avoid the numbers becoming unwieldy. The reader is referred to the CONTRAM manual for more detailed and specific description of the various other card types used in CONTRAM (Taylor and Leonard, 1989). This section has only outlined those card types that are most relevant to this work and best illustrate how tolls were entered in CONTRAM for this research. Details about standard card types which any CONTRAM 5 user would invariably have to define if they were to run CONTRAM 5, have not been described here.

5.4 Location of Cordons and Scenarios Modelled for the Southampton Network

Two available potential guideline sources were used to help locate the cordon positions and/or screen lines for the network modelling. The first is information on the location of survey points used to capture Origin–Destination information by Arup Consultants when preparing the demand matrix used in this research. The second is information on the location of survey points used to capture annual Modal Split Survey and 12 hour classified counts by the Southampton City Council. Information from these two sources was used to locate the cordon positions. A number of network cordon pricing schemes were modelled. Basically, these pricing schemes consisted of a number of cordon pricing scheme arrangements as described below. Figures 5.1 and 5.2 depict the three main cordon locations. Figure 5.2 also shows the main zonal areas in Southampton.

a. An External Cordon just inside the motorway boundary (Blue line in Figures 5.1 and 5.2). Such a cordon would discourage through trips from entering Southampton and instead use the motorway network around the city's edge; the M27 to the North and Eastern sides of the city and the M271 on the Western side of the city. Southampton water is on the Southern side of the city. Such a cordon on its own would not affect the movement of traffic within the motorway boundary.
b. A Middle cordon (or mid cordon) just inside the boundaries defined by Terbourba Way, Winchester Road and Burgess Road (Red line). Such a cordon on its own would not discourage through traffic from outside Southampton but would discourage traffic within the motorway boundaries from crossing this cordon into the city center. The alternative routes for affected traffic is mainly to use the above named boundary roads to bypass the city and join other roads to travel eastwards, westwards or northwards. However, these roads are themselves normal urban links and not motorway links, and therefore, might not be able to cope with the extra traffic re-routed to them.
c. A cordon around the Central Business District (CBD) (Green line). This would intercept all trips entering the CBD either from within or without the motorway boundary. It, however, has limited effect for traffic within the CBD and for significant traffic outside the CBD but within the Southampton network. The alternative routes for the affected trips are limited due to the radial nature of the network, although Paynes,

Howard, Archers and Lodge Roads may act as boundary roads. As with the mid cordon, these roads are normal urban links that could be overwhelmed by re-routed traffic.

d. A combination of these cordon positions varying up to a maximum of three. May and Milne (2000) used a three cordon system in their studies but were aware of the fact that other patterns of cordons and screen lines as well as other distributions of charges across them could perform differently. To an extent this research, by exploring single cordon systems and a combination of multiple cordon systems, provides some understanding to this issue.

5.5 Modelling Results

In the following sections the network effects of the modelled road pricing scenarios are reported. It was decided to first analyse the CBD cordon in greater detail in order to understand the more obvious trends in the results. This would also help to make comparisons between the performance of different cordon positions and or combinations of cordons, which is undertaken later in the chapter. Choosing to analyse the CBD cordon first, is plausible. Firstly, the CBD is small and more compact than the other cordons making it simpler to analyse. Secondly, congestion is most pronounced in city centres and it is in such congested centres that road pricing is likely to be introduced first. Traditionally, CBD's also tend to be better served by the radial nature of public transport services compared to areas outside the CBD for which public transport may not be as reliable, as regular and as frequent as services into and out of the CBDs (e.g. ROCOL, 2000).

5.5.1 An Analysis of the CBD Cordon

Tables 5.3, 5.4 and 5.5 give a summary of the overall network performance based on a variety of performance indicators for the CBD cordon. The results are for two way charging. Table 5.3 tabulates the results as read from the CONTRAM output or result file. Table 5.4 shows the absolute changes for successive toll levels compared to the uncharged base case scenario, while Table 5.5 shows the corresponding percentage changes. The changes in selected performance indicators are discussed, beginning with the total network vehicle kilometres (VKT).

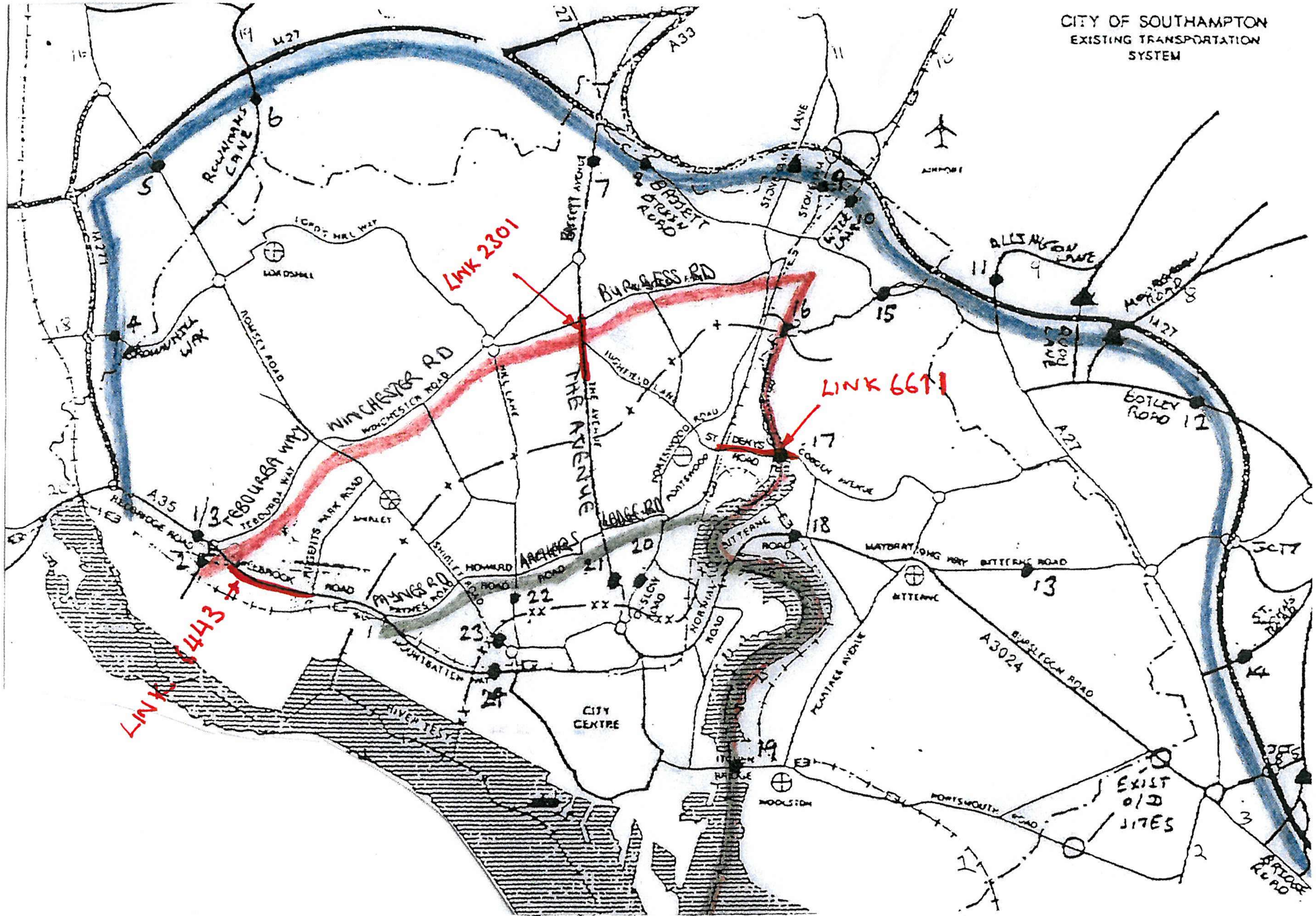


Figure 5.1 Map showing Locations of Proposed Cordon Locations in Southampton

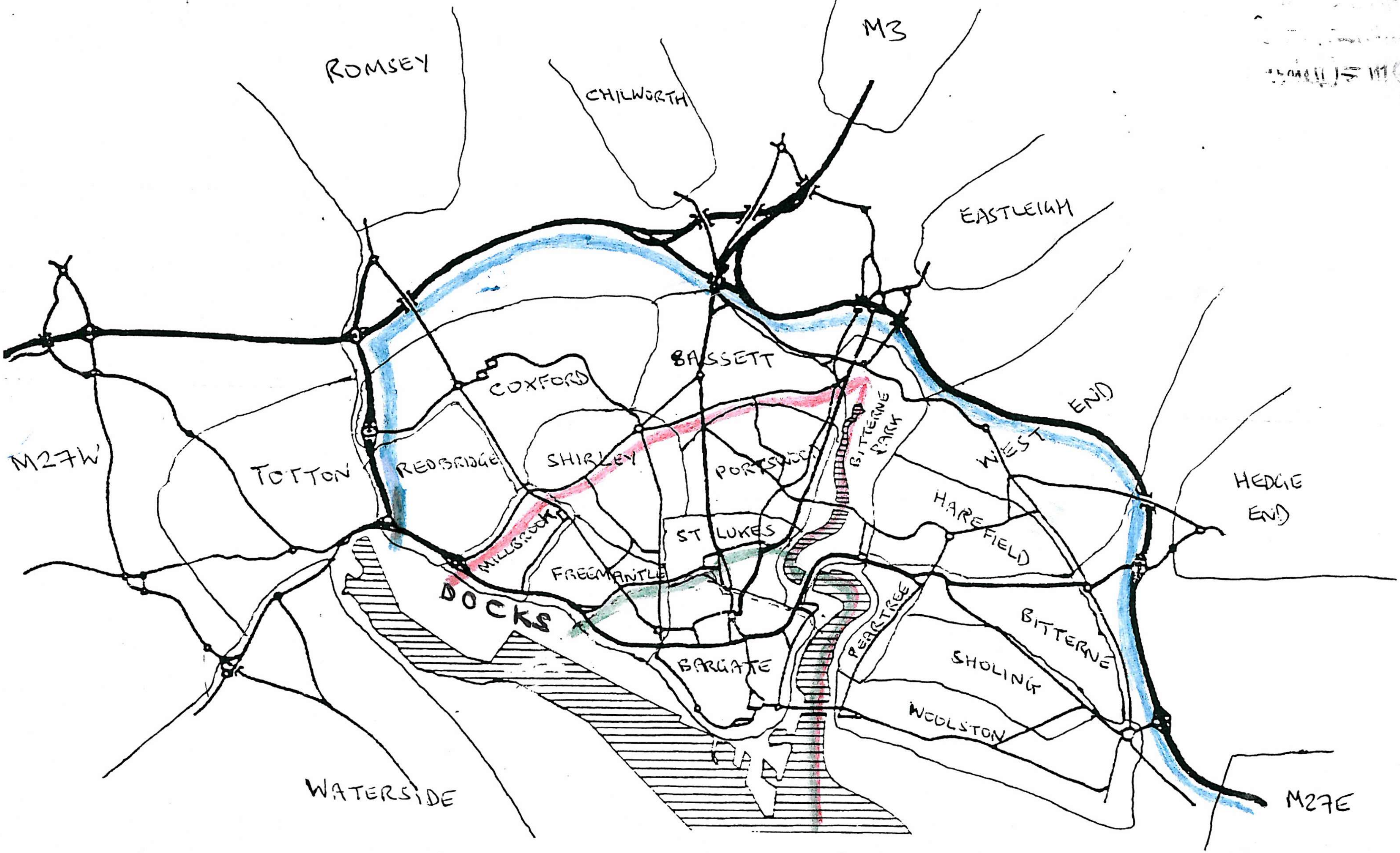


Figure 5.2 Map Showing Cordon Locations and Main Zonal Areas In Southampton

Charge Level to cross cordon in Pence	Packets	Freemoving Vehicle Hours	Flow Delay Vehicle Hours	Queuing Delay Vehicle Hours	Total Network Vehicle Hours	Total Network Vehicle Kmetres	Overall Network Speed (KPH)
0 (Base Case)	110,390	12,566.8	1,990.6	3,563.2	18,120.4	940,623	51.9
20	110,390	12,613.5	2,007.7	3,609.1	18,230.3	944,669	51.8
30	110,390	12,638.6	2,018.2	3,648.2	18,305.0	946,731	51.7
40	110,390	12,664.3	2,037.3	3,712.4	18,414.0	948,564	51.5
50	110,390	12,687.3	2,050.1	3,788.9	18,526.4	950,398	51.3
100	110,390	12,840.4	2,116.0	4,323.1	19,279.5	961,969	49.9
150	110,390	13,010.5	2,183.6	4,989.7	20,183.9	975,198	48.3
200	110,390	13,176.4	2,257.2	5,764.4	21,197.9	987,902	46.6

Table 5.3 CBD Cordon Summary Results

5.5.1.1 CBD Cordon Vehicle Kilometres Travelled (VKT)

The total packets entering and leaving the network in the modelled period remains constant at 110,390 packets for all the charge levels as can be seen in Table 5.3. This confirms the inelasticity of the modelling as well as its consistency since the same demand matrix was run throughout the modelling.

The increases in total network vehicle kilometres (VKT) seems to confirm that the tolls are causing re-routeing at all the charge levels and that this re-routeing effect increases with increasing charge level as some drivers with alternative routes, re-route to avoid the tolled links. The increase appears to be linear. For the CBD cordon the VKT increased by 4,045.6 kilometres or 0.43% at the 20 pence charge level and by 47,278.3 kilometres or just over 5% at the £2 toll level (Tables 5.4 and 5.5). These appear to be reasonable increases and consistent with evidence from the literature (e.g. Tolofari, 1997). Tolofari's corridor modelling of tolls registered up to about 0.6% increases in VKT for tolls varying between 50p and £2.

Charge Level to cross cordon in Pence	Freemoving Vehicle Hours	Flow Delay Vehicle Hours	Queuing Delay Vehicle Hours	Total Network Vehicle Hours	Total Network Vehicle Kmetres	Overall Network Speed (KPH)
0 (Base Case)	0	0	0	0	0	0
20	46.9	17.1	45.9	109.9	4,046	-0.1
30	72.0	27.6	85.0	184.6	6,108	-0.2
40	97.7	46.7	149.2	293.6	7,941	-0.4
50	120.7	59.5	225.7	406.0	9,775	-0.6
100	273.8	125.4	759.9	1159.1	21,346	-2.0
150	443.9	193	1426.5	2063.5	34,575	-3.6
200	609.8	266.6	2201.2	3077.5	47,278	-5.3

Table 5.4 Absolute Changes in Network Parameters for CBD Cordon

5.5.1.2 CBD Cordon Total Network Vehicle Hours and Delays

The results of the total network vehicle hours were also seen to increase with increasing charge level as expected. Under inelastic modelling, the network effects of cordon tolls can be expected to deteriorate with increasing charge level (Smith et al, 1994, Wigan, 1971, Wigan and Bamford, 1973, Tolofari, 1997). The results from the modelling here is consistent with this finding for the results of the CBD cordon as can be seen from Tables 5.3 to Table 5.5. Table 5.5 and Figure 5.3 show that the percentage increase in total network vehicle hours varied between 0.61% at the 20p toll level, to 17% at the £2 toll level. Figure 5.3 suggests that the increase in total vehicle hours is not linear. Instead it is seen to rise slowly at the lower toll levels of up to 50p after which there is a much rapid increase in total network vehicle hours. The rapid growth in total network vehicle hours at higher toll levels appears to arise mainly from an increase in queuing delay vehicle hours rather than from an increase in flow delay and/or freemoving vehicle hours. This can be seen clearly from Table 5.5. Table 5.5 shows that up to the 50 pence toll level, the freemoving vehicle hours, the flow delay vehicle hours and the queuing delay vehicle hours, all register modest and reasonably comparable percentage increases. However, from the 100 pence toll level, the queuing delays clearly register much higher increases than those of either the freemoving or the flow delay vehicle hours. Although the net effect is an increase in total network vehicle hours that is comparable and consistent with those in the literature (e.g. just over 10% for example at the 200 pence toll level), it is clear that at higher toll levels, the re-routing effect begins to put pressure on junction capacity on the boundary routes to which the vehicles priced off switch.

Charge Level to cross cordon in Pence	Packets	Freemoving Vehicle Hours	Flow Delay Vehicle Hours	Queuing Delay Vehicle Hours	Total Network Vehicle Hours	Total Network Vehicle Kmetres	Overall Network Speed (KPH)
0 (Base Case)	110 390	0	0	0	0	0	0
20	110 390	0.37	0.86	1.29	0.61	0.43	-0.19
30	110 390	0.57	1.39	2.39	1.02	0.65	-.39
40	110 390	0.78	2.35	4.19	1.62	0.84	-0.77
50	110 390	0.96	2.99	6.33	2.24	1.04	-1.16
100	110 390	2.18	6.30	21.32	6.40	2.27	-3.85
150	110 390	3.53	9.70	40.03	11.39	3.68	-6.94
200	110 390	4.85	13.40	61.78	17.0	5.03	-10.21

Table 5.5 Percentage Changes in Network Parameters for CBD Cordon

It is to be expected that as more vehicles re-route to the boundary routes due to increased tolls, congestion would grow on these routes. Evidence in the literature suggests that under inelastic modelling, cordon tolls cause the overall network performance to deteriorate at higher tolls since the benefits achieved from the tolled areas are outweighed by the disbenefits at the boundary routes (Smith et al, 1994, May and Milne, 2000). The modelling in this work is consistent with this finding and shows that re-routing due to the implementation of the CBD cordon on the Southampton network, would result in a net increase in total network vehicle hours rather than a net decrease. The increase is most pronounced at higher tolls.

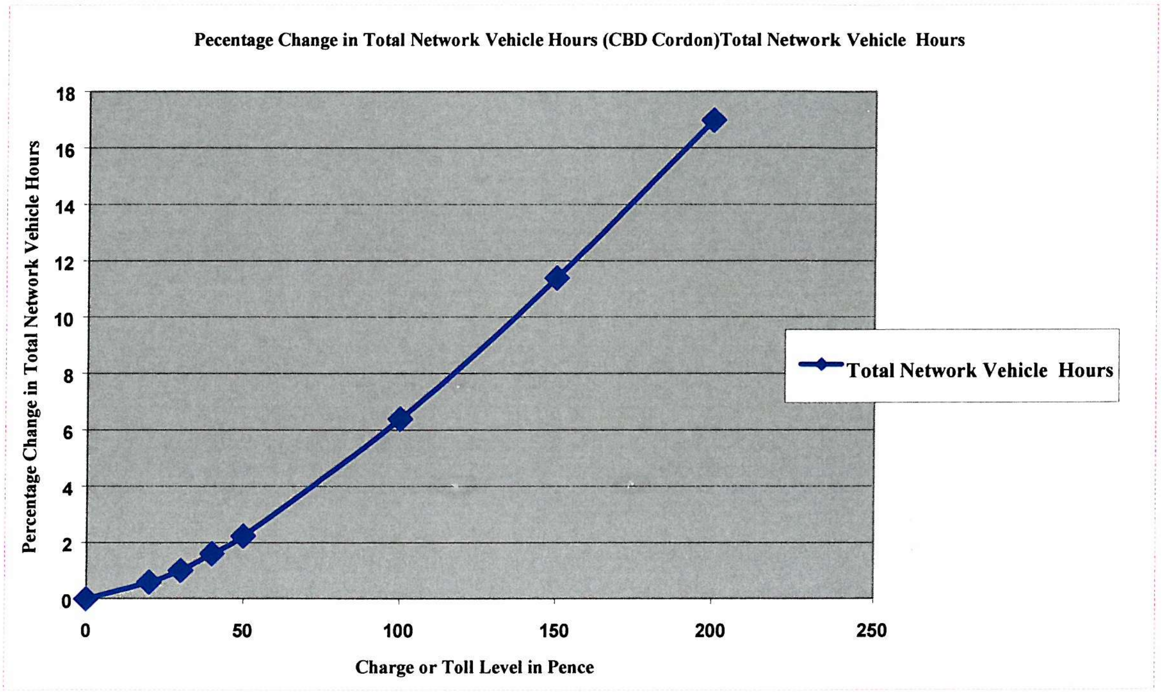


Figure 5.3 Percentage Change in Total Network Vehicle Hours for the CBD Cordon

5.5.1.3 CBD Cordon Overall Network Speed

In CONTRAM, the overall network average speed is the quotient of the total network VKT and the total network vehicle hours (VHS). Under inelastic assignment, it represents the net effect of the expected increases in speed within the charged area, and the expected decrease in speed on the boundary routes/and or outside the cordon. It can be seen from Table 5.3

that the average network speed decreases with increasing toll level as expected. The percentage decrease ranges from about 0.2% at a toll of 20 pence, to about 10.2% at a toll of 200 pence. Like the total network vehicle hours, the decrease in speed is most severe at higher toll levels from 100 pence and upwards. The decrease in speed follows from the increase in total network hours with increasing toll level already reported. The pronounced decrease in average network speed at higher tolls arises mainly because of the rapid increase in the queuing vehicle hours. This increase in queuing vehicle hours and hence in the total network vehicle hours, outweighs the effect of the increase in total network vehicle kilometres. This results in a net decrease in average speed despite an increase in VKT due to the re-routing effect.

5.5.1.4 Perceived Cost or Generalised Cost Changes

Toll Level in Pence	Tolled Link Flows (Veh/Hour)	Total Veh Paying (Veh)*	Revenue in £/Hour	Total Revenue in £
0	10,790.0	21,580.0	0.0	0.0
20	9,587.0	19,174.0	1,917.4	3,834.8
30	9,128.0	18,256.0	2,738.4	5,476.8
40	8,833.0	17,666.0	3,533.2	7,066.4
50	8,606.0	17,212.0	4,303.0	8,606.0
100	8,081.0	16,162.0	8,081.0	16,162.0
150	7,662.0	15,324.0	11,493.0	22,986.0
200	7,358.0	14,716.0	14,716.0	29,432.0

Table 5.6 Tolled Link Flows, Revenues/Hour and Revenues over Modelled Period

*** Total Veh Paying (Veh) = Total Number of Vehicles Paying Toll in modelled period**

Toll Level in Pence	Tot Network Vehicel Hours	Travel Time Costs in £	Toll Component of PC in £	Calculated Total Network PC in £	CONTRAM Output PC in £
0	18,120.4	130,466.9	0.0	130,466.9	130,457.6 (0)
20	18,230.3	131,258.2	3,834.8	135,093.0	135,247.1 (0.1)
30	18,305.0	131,796.0	5,476.8	137,272.8	137,424.2 (0.1)
40	18,414.0	132,580.8	7,066.4	139,647.2	139,774.8 (0.1)
50	18,526.4	133,390.1	8,606.0	141,996.1	142,096.3 (0.1)
100	19,279.5	138,812.4	16,162.0	154,974.4	154,908 (0)
150	20,183.9	145,324.1	22,986.0	168,310.1	167,914.7 (0.2)
200	21,197.9	152,624.9	29,432.0	182,056.9	181,228.8 (0.5)

Table 5.7 Mathematical Check of Calculated Perceived Cost versus CONTRAM Output Perceived Cost (PC) figures

As was explained earlier, the perceived cost function has been used in this research to take into account the effects of cordon tolls. The cost function takes the form of a general cost function in which in the presence of tolls, route choice behaviour is influenced by both the need to reduce travel time and tolls paid. The perceived cost or general costs are defined at link level. In its output, CONTRAM tabulates total network perceived cost (PC) values. The total network perceived cost at any given toll, is the sum of the perceived cost of the individual links over the modelled period. This can be used to check the mathematical correctness of the modelling method used. If the modelling is correct, than the perceived cost figure that is output by CONTRAM, must equal that calculated from first principles. Using first principles, the total network perceived cost can be calculated from:

Perceived Cost (PC) = (Total Network Vehicle Hours)*(Value of Time) + (Tolled Link Flows)*Toll **(7)**

The tolled link flows in vehicles/hour were determined from the flow output of CONTRAM. Since these are hourly flows, the total number of vehicles paying the tolls in the modelled two hour peak period is the product of the hourly flows and the two hour duration over which the tolls are also applied. This information is tabulated in Table 5.6 for all the toll levels and represents the second term in the perceived cost equation above.

The first term of the perceived cost equation simply represents the equivalent monetory costs of the travel time or total network vehicle hours over the modelled peak period. The perceived cost in monetary units is thus the sum of the monetary travel time costs and the toll costs. This information is also tabulated in Table 5.7. The toll component of the perceived cost is also tabulated in Table 5.7. It can be seen that at each toll level, the toll component in Table 5.7 is simply the revenue generated over the modelled peak period as tabulated in Table 5.6. The perceived cost read from the CONTRAM output is also tabulated in Table 5.7 in the last column. The figures in parentheses in the last column of Table 5.7 show the percentage differences between the calculated figure of the perceived cost and that from the CONTRAM output. It can be seen that the differences are very small and range from 0% to 0.5%. These minor differences can be explained by rounding off of parameters such as the total network vehicle hours from its components in the CONTRAM model. There could also be very small differences in the tolled link flows. Average tolled link flows have been used here, while CONTRAM can determine these flows for calculation of the perceived cost, on a link by link basis, from one time slice to another. To all intents and purposes, one can be confident that the toll representation and hence the modelling of the effects of tolls in this work is mathematical plausible.

5.5.1.4.1 Different Interpretation of the Perceived Cost

It is clear from the perceived cost equation (7) above that the monetary implications of the tolls can be interpreted differently by different market segments. To a network manager, the second term represents revenue generated as tabulated in Table 5.6. From this perspective, the perceived cost equation can thus be written as:

Perceived Cost (PC) = Total Network Vehicle Hours)*VOT + Revenue Generated (8)

Apart from managing congestion, the success of cordon tolls would rely on the revenue generated. If hypothecated by network managers such as local authorities, revenues generated from tolls would enable investment in alternative transport modes. This could include improved bus services, investment in cycle tracks and pedestrian facilities as well as the development of park and ride facilities amongst other things. Equation (8) shows the balancing act that network managers would have to achieve in order to achieve both congestion reduction (reduced travel times/total network vehicle hours)and generate adequate revenue for the provision of alternative transport means for those priced off.

Network users particularly those paying the tolls and those priced off interpret the tolls as direct out of pocket costs (OPC) that increase their cost of travel. From this perspective, the equation can be written as:

Perceived Cost (PC) = (Total Network Vehicle Hours)*VOT + Increased OPC (9)

Those able and willing to pay expect to recoup some of this money in improved travel conditions particularly as reduced journey times. Those unable or unwilling to pay may view tolls as 'just another tax' or a way of 'driving them' out of their cars. These drivers would expect that feasible alternatives were provided for them. This is clearly one of the major challenges that network managers implementing road user pricing would have to address since without the revenues expected from road user charging, providing viable alternatives could prove to be a difficult task. The expected imminent introduction of road user charging in London might be expected to answer some of these difficult questions.

5.5.1.4.2 Variation of Perceived Cost with Toll Level

Figure 5.4 shows how the travel time component of the perceived cost varies with toll level. The curve is as expected, the same shape as that of the total network vehicle hours from which it is derived. The travel time component of the perceived cost increases with increasing toll level just like the total network vehicle hours. Figure 5.5 shows how the toll component of the perceived cost varies with toll level. This too is expected to be the same shape as the variation of revenue generated which is discussed in the next section. The resultant variation of the perceived cost with toll level is influenced by the behaviour of its two components and is shown in Figure 5.6. Figure 5.6 shows that the perceived cost appears to increase linearly with toll level. The fact that the perceived cost increases with toll level under inelastic modelling here is consistent with literature evidence (e.g. Smith et al, 1994). The increase in the toll component with toll level can be interpreted as showing that the increase in toll level, more than compensates for the decrease in tolled link flows with increasing toll level. The increase in the travel time component of the perceived cost is probably more worrying since it seems to suggest that the decrease in travel times in the charged area, is offset by the increase in travel time in the uncharged area. This is consistent with the widely held view and concern that road user charging will transfer congestion from the charged areas to the uncharged areas.

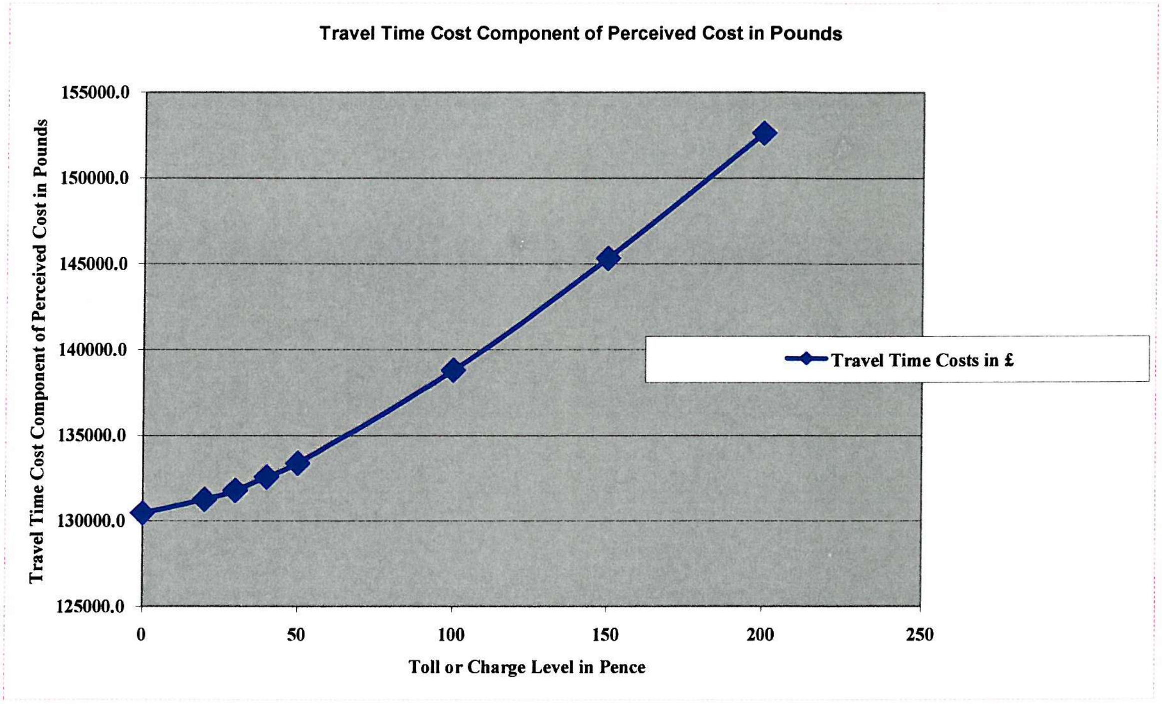


Figure 5.4 Variation of Travel Time Cost Component of the Perceived Cost with Toll Level

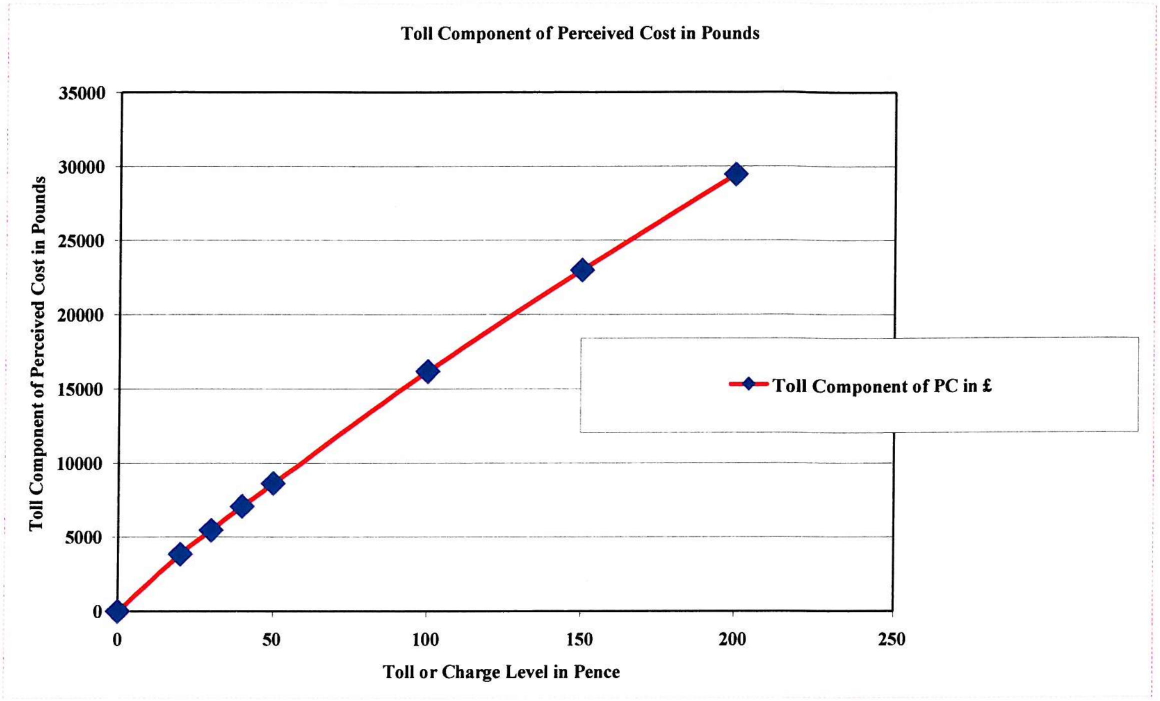


Figure 5.5 Variation of Toll Component of the Perceived Cost with Toll Level

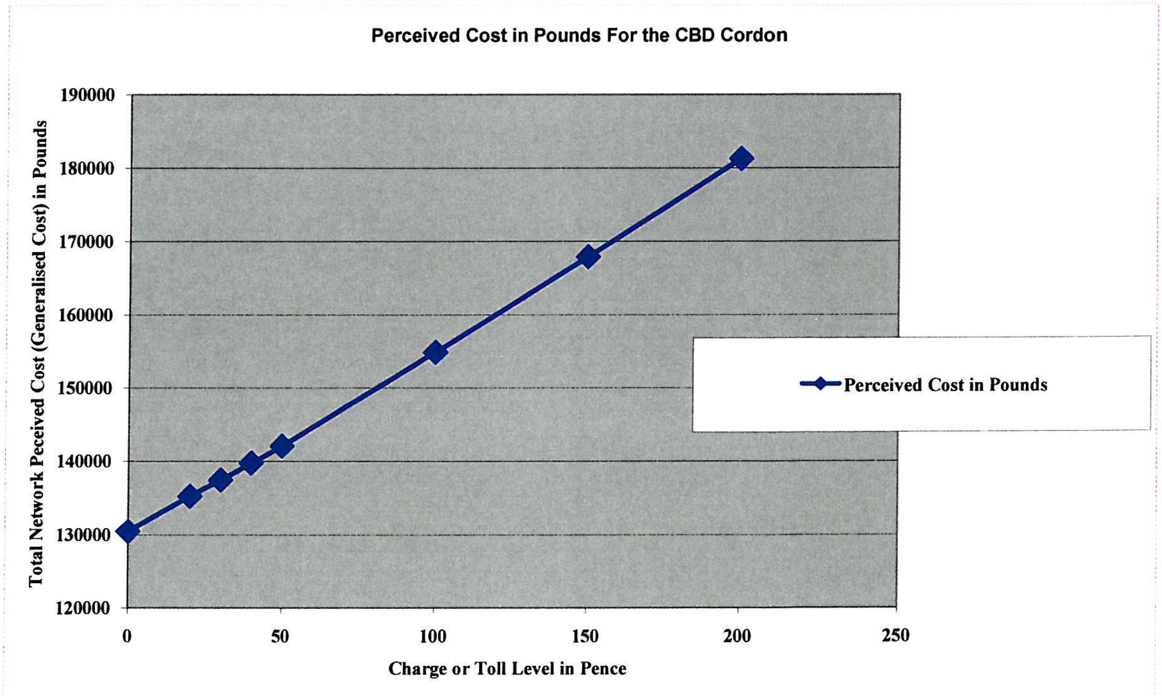


Figure 5.6 Variation of Total Network Perceived Cost with Toll Level

5.5.1.5 CBD Cordon Flow Changes for Different Links and Revenue Analysis

In the sections below, a more detailed look at the flow changes that occur on the tolled links, boundary links, and selected links inside and outside the CBD cordon are considered. These flow changes can help to understand the changes in network parameters such as the revenues and the total network vehicle hours and its components.

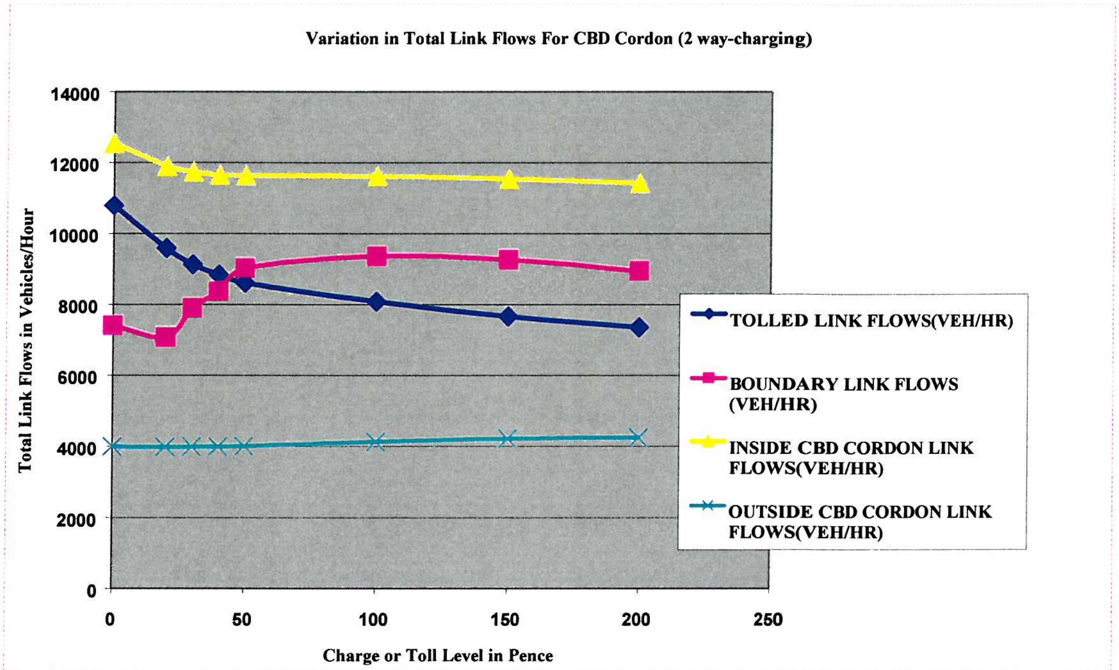


Figure 5.7 Variation in Total Link Flows For the CBD Cordon

The flow changes for the tolled links, boundary links, inside the CBD cordon links and outside the CBD cordon links are depicted in Figure 5.7 above. Generally, the trends are as expected. The flows on the tolled links are seen to generally decrease with toll level as through trips re-route away from the tolled links. The flows on the boundary links are seen to increase with toll level as vehicles priced off from the tolled links re-route to the uncharged boundary links. The total flows on the links inside the cordon are seen to generally decrease with toll level. This is to be expected because those vehicles that were priced off from the tolled links no longer cross the CBD cordon and enter the CBD network. Instead, these vehicles re-route to the boundary or orbital links. In this work the links outside the cordon, have been taken to be those outside of the boundary or orbital links. The boundary links have been taken to be the orbital links immediately on the edges of the cordons. The total flows on the links outside the CBD cordon are seen to increase marginally. The increase could occur because of some trips re-routing to routes further away from the immediate peripherals of the charged cordon. In theory, until a toll is encountered, there is no incentive for vehicles emanating from outside the cordon to change their route, and only when the toll is encountered does the route change occur. This could explain the rather small increase in flows on links outside the cordon. This appears to be consistent with literature evidence that re-routing vehicles are likely to use feasible routes immediately outside the boundaries of the charged cordons when they re-route away from charged routes (e.g. May and Milne, 2000). May and Milne (2000) concluded that under cordon pricing, most diverted vehicles tended to re-route to the orbital or boundary routes rather than spread out over wide areas of the network. This was because the main aim was to avoid paying the tolls and hence reduce their total trip costs. On the other hand, they found that congestion-based charging caused vehicles to re-route and spread out wider over the network including to routes outside the orbital routes. This was because under this pricing regime, the aim was not so much to reduce total travel costs as to minimise delays encountered. They concluded that rat-running was therefore more likely under congestion-based charging than with cordon charging.

Figure 5.8 shows the tolled link flow changes and the hourly revenue generated. The revenues are seen to increase with increasing toll level despite a decrease in flows with increasing toll level. The decrease in flows is more than compensated for by the increase in toll level. However, as can be seen in Figure 5.8, the revenue seems to increase linearly with toll level at lower toll values after which the growth is less linear. This seems to suggest the possibility of revenues levelling off or even decreasing at much higher tolls as flows on tolled links decrease. As was noted earlier, while revenue may be regarded as an added advantage of road user charging by network managers, the view of the public may be different. The different interpretations about revenue were discussed in Section 5.5.1.4.1 when discussing the perceived cost. As expected the revenue curve in Figure 5.8 is the same shape as that of the toll component curve of the perceived cost in Figure 5.5. Smith et al, (1994) argue that in view of the different interpretation of the revenue by network operators and the paying public, the answer probably lay in designing road user charging schemes that delivered the best benefits at low charges.

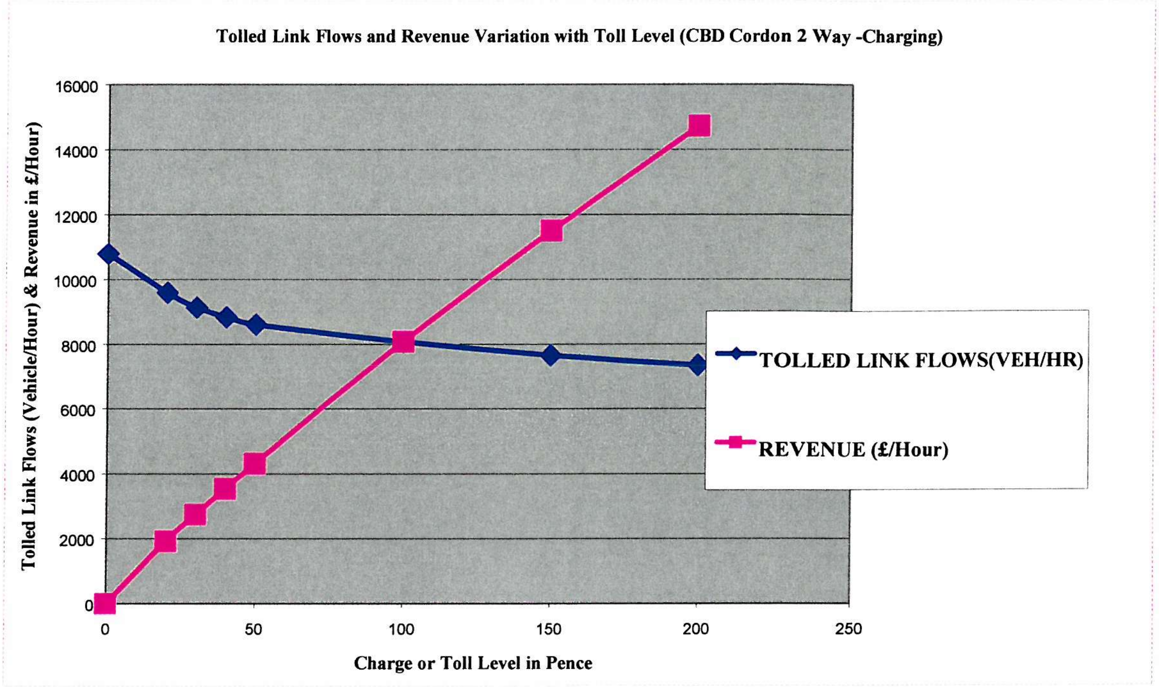


Figure 5.8 Tolled Link Flow and Revenue Variation with Toll Level

5.6 Average Link by Link Change Analysis for the CBD Cordon

CONTRAM is able to output link by link changes of various parameters for analysis. By analysing the link by link parameters, the changes experienced by a vehicle travelling on these links can be appreciated. This is in contrast to the aggregate summary information considered so far which generally gives average network effects. The changes in some link by link parameters are tabulated in Tables 5.8 below.

Link Performance Parameter	Base Case	20 Pence	30 Pence	40 Pence	50 Pence	100 Pence	150 Pence	200 Pence
Mean Link Travel Time (Seconds)	75.8	51.0	50.3	49.8	49.5	49.7	49.6	49.4
Absolute Change (Seconds)	0.0	-24.8	-25.5	-26.0	-26.3	-26.1	-26.2	-26.4
Percentage Change (%)	0.0	-32.7	-33.6	-34.3	-34.7	-34.4	-34.6	-34.8
Average Link Speed (KPH)	30.5	36.7	37.1	37.3	37.4	37.6	37.8	37.9
Absolute Change (KPH)	0.0	6.2	6.6	6.8	6.9	7.1	7.3	7.4
Percentage Change (%)	0.0	20.3	21.6	22.3	22.6	23.3	23.9	24.3
Total Link Delays (Vehicles Hours)	303.4	282.5	217.1	206.8	202.9	202.5	206.5	202.5
Absolute Change (Vehicle Hours)	0.0	-20.9	-86.3	-96.6	-100.5	-100.9	-96.9	-100.9
Percentage Change (%)	0.0	-6.9	-28.4	-31.8	-33.1	-33.3	-31.9	-33.3

Table 5.8 Average Link by Link Changes for CBD Tolled Links

5.6.1 Tolled Link Travel Time Changes

Table 5.8 suggests that the average travel time of a vehicle on tolled links would generally decrease with increasing toll level as expected. However, the decrease is sharpest at the lower toll levels after which there appears to be very little decreases between subsequent successive toll levels. This is most evident in the Total Link Delay parameter also shown in Table 5.8. It can be seen from this parameter that there is a significant decrease in total delays up to about the 50 pence toll level. There after the delays remain virtually unchanged with increasing toll level. This appears to support literature evidence that cordon schemes will attain their best benefits at lower tolls. This is to be expected since tolled links that are operating at or near their saturation could experience large reductions in delays from relatively small reductions in flows. However, as congestion on the tolled links decreased, further decreases in flows would not yield significant changes in travel time between subsequent higher tolls since delays would not reduce appreciably. For the Southampton network, at the current congestion level, the CBD cordon results suggest that the average saving in travel time on the tolled links would be about half a minute (about a 35% decrease) although this could be expected to vary from link to link as can be seen in Figure

5.9 which illustrates the variation in individual tolled link travel times. Factors that may cause variations in link travel time changes include for example:

- The base or original level of congestion of the link as measured by the volume to capacity ratio. Congested links operating at or near their capacities will benefit most as is indeed the purpose of rationing capacity by willingness to pay.
- The extent/number of vehicles diverted from the tolled links. It can be expected that for the more congested links, even small levels of diversions may originally cause significant decreases in link travel times. However, as congestion decreases on the links, more decreases in link flows may not significantly reduce the link travel time any further as less saturated conditions prevail.
- The link length as longer congested tolled links can be expected to register higher decreases in travel time over the whole length of the link even where the decreases per unit length of different links were equal. The speed/flow effects are also more pronounced on longer links than on shorter ones.

A half minute decrease in link travel time would be equivalent to a monetary saving of about 6 pence at the current value of time adopted in this research of about 12 pence/minute or about 720 pence/hour. This appears to suggest that for the Southampton network at current congestion levels, drivers paying to cross the CBD cordon, would on average recoup only about 6 pence of the tolls they paid in equivalent monetary journey time savings. This recouped equivalent monetary travel time savings is only 30% of the value of the lowest 20 pence toll level tested. The observation that the equivalent monetary savings in journey times is likely to be less than the toll paid is consistent with literature evidence (e.g. TRB, 1994). However, the savings may be expected to be somewhat higher for specific O-D pair journey times where other links particularly those downstream of the tolled links (inside the charged area) may also enjoy reduced flows and hence reduced link travel times. This is illustrated later when O-D travel cost changes are considered in section 5.10.1. Table 5.8 suggests that once the initial savings in tolled link travel times have been made at about the 20 pence to 50 pence toll levels, there are very little extra savings at the higher tolls as was earlier observed. This is consistent with literature evidence. For example

(1994), also found this to be the case for both cordon tolls and other charging regimes. In their modelling of the Cambridge network, benefits were seen to peak at an optimum charge of only 50 pence.

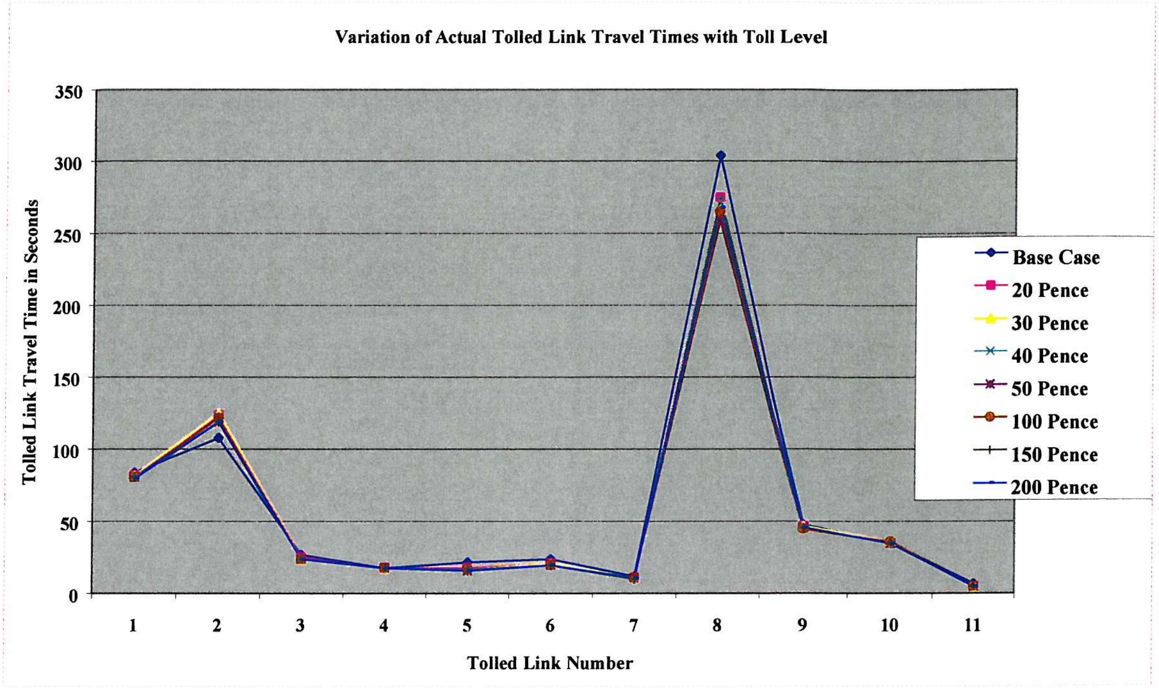


Figure 5.9 Variation in Individual Tolled link Travel Times with Toll Level for the CBD Cordon

It has to be noted that, the decrease in link travel time on the tolled links under inelastic modelling are wholly due to some through trips diverting away from the tolled links and re-routing to alternative uncharged links at the boundary of the cordon or to links outside the cordon. None of this decrease is due to the fact that radial trips such as some External-Internal movements (E-I) and/or some Internal-External (I-E) trips would in practice be suppressed by the tolls through such mechanisms as trip retiming, mode changes and possibly through working from home as could occur with teleworking. This is because some motorists making such radial trips would be unwilling to pay and therefore respond elastically to the tolls rather than continue to travel on the tolled links as is the assumption under inelastic modelling. Therefore, the travel time changes on the tolled links reported under inelastic modelling represent a lower bound value and so underestimate the benefits that would be enjoyed by motorists willing and able to pay the tolls (e.g. May and Milne, 2000, Smith et al, 1994).

5.6.2 Tolled Link Average Speed Changes

It can be seen from Table 5.8 that the average link speed of the tolled links before tolling is 30.5 kilometres/hour. This speed is seen to rise steadily with increasing toll level as expected. The average link speeds are seen to decrease as total link delays also decrease. At the toll level of 200 pence, the average tolled link speed has increased by just over 7 kilometres/hour or by about 24%. The improved conditions on the tolled links benefit significantly from the decrease in total delays. The total delays on the tolled links are seen to decrease from 303.4 vehicle hours before tolling, to 202.5 vehicle hours at the 200 pence toll level. The 100.9 decrease in total delay vehicle hours at the 200 pence level, represents a decrease of just over 33%. Overall, the results are as expected and show that the tolls improve the travel conditions on the tolled links by pricing off some through trips away from the tolled links to the boundary links or to links outside the cordon. This in turn reduce delays and improves tolled link speeds.

5.6.3 Boundary Link by Link Changes

The boundary link by link changes are shown in table 5.9. It can be seen that the average link travel time increases with toll level as expected. The average link travel time was seen to almost double from about 45 seconds in the base case scenario, to over a minute and a half at the 200 pence toll level. The increase in travel time is relatively gradual at the lower toll levels up to about 50 pence, after which there is a sharp increase in the average link travel time as can be seen from Figure 5.10. Figure 5.10 also suggests that the rate of increase in travel time on the boundary routes is significantly higher than the corresponding decrease in travel time on the tolled links particularly at the higher toll levels.

Initially, it can be expected that the increase in flows on the boundary links due to re-routing from the tolled links does not cause the travel times to rise very fast. However, as the diverted flows increase, the boundary links become more congested and the travel time then rises more steeply as the link conditions become more saturated and approach capacity. Even though the increase in diverted flows to the boundary routes may decrease between successive higher tolls as suggested by Figure 5.7, the link conditions may continue to deteriorate as saturated conditions are approached. This in contrast to the tolled links where link saturation decreases with increasing toll level.

Link Performance Parameter	Base Case	20 Pence	30 Pence	40 Pence	50 Pence	100 Pence	150 Pence	200 Pence
Mean Link Travel Time (Seconds)	45.1	47.6	49.7	51.4	53.7	64.3	77.8	96.2
Absolute Change (Seconds)	0.0	2.5	4.6	6.3	8.6	19.2	32.7	51.1
Percentage Change (%)	0.0	5.5	10.2	14.0	19.1	42.6	72.5	113.3
Average Link Speed (KPH)	28.1	26.8	25.9	25.5	25.1	23.4	21.5	20.5
Absolute Change (KPH)	0.0	-1.3	-2.2	-2.6	-3.0	-4.7	-6.6	-7.6
Percentage Change (%)	0.0	-4.6	-7.8	-9.3	-10.7	-16.7	-23.5	-27.0
Total Link Delays (Vehicles Hours)	117.6	124.3	146.1	164.9	189.9	269.4	355.0	426.8
Absolute Change (Vehicle Hours)	0.0	6.7	28.5	47.3	72.3	151.8	237.4	309.2
Percentage Change (%)	0.0	5.7	24.2	40.2	61.5	129.1	201.9	262.9

Table 5.9 Average Link by Link Changes for CBD Boundary Links

The boundary link by link average speed changes can similarly be explained. The boundary link speeds are seen decrease with increasing toll level. The decrease appears to be more rapid at higher tolls from about 100 pence. The total delays also show a gradual increase between the base case and the 50 pence toll level, after which they increase rapidly as congestion increases on the boundary links. This again reinforces the fact that improvements in the charged area are at the expense of deteriorating conditions on the boundary links. The lower base case average speed of 28 km/hr for the boundary links compared to base case speed of 30.5 km/hr for the tolled cordon links, generally reflects the difference in link standard between the two groups of link rather than that the boundary links are more congested. Tolled links include amongst them some of the main dual arterial links into the city, whilst most of the CBD cordon boundary links are typical lower speed urban links. The high percentage increase in total delays on the boundary links is consistent with literature evidence. For example, modelling by Gower and Mitchell (1998) found delay increases of up to 176% on routes to which vehicles diverted as a result of motorway tolls in congested urban environments. These delay increases occurred at tolls of 4 pence/kilometre. This is equivalent to a fixed toll of about 40 pence for a 10 kilometre trip. This research has found percentage delay increases of about 129% at toll levels of 100 pence.

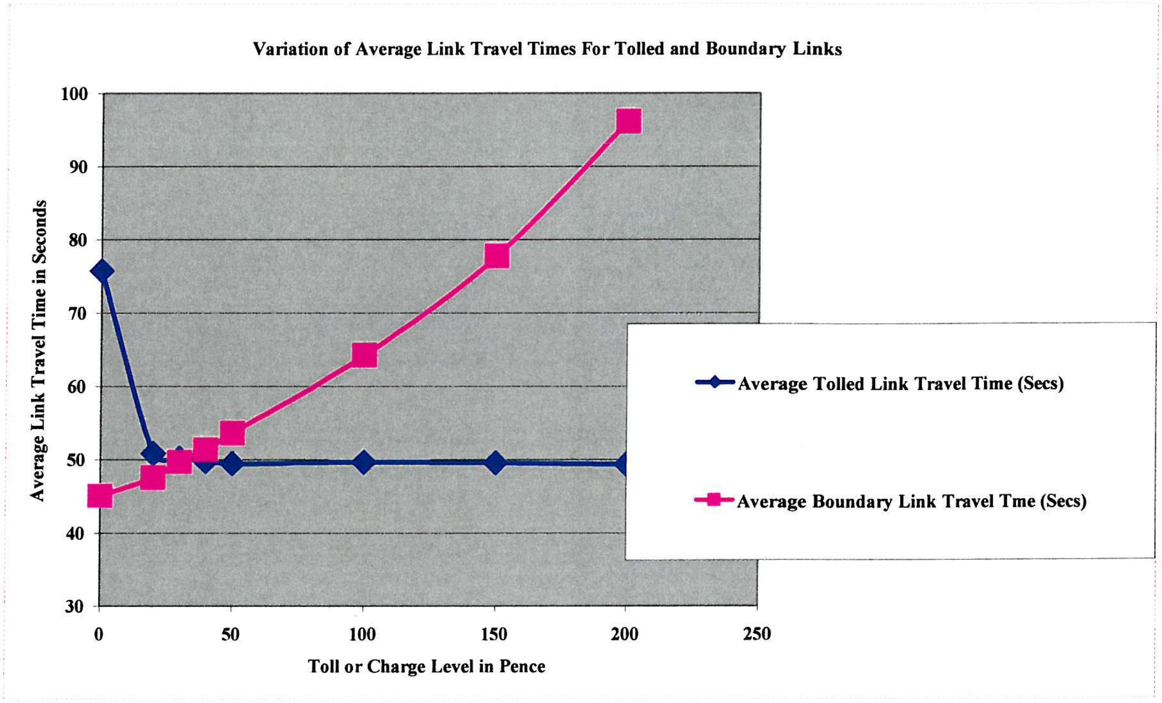


Figure 5.10 Variation of Average Link Travel Time with Toll Level on the CBD Tolled and Boundary Links

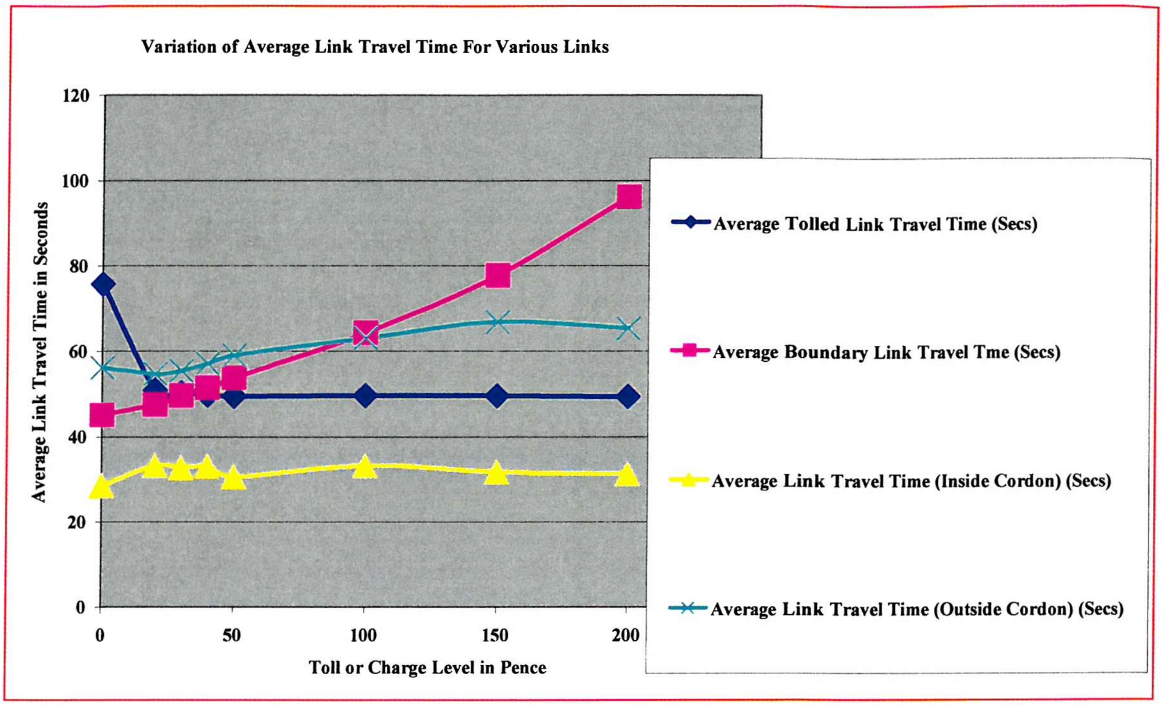


Figure 5.11 Variation of Average Link Travel Times For Various CBD Cordon Links

5.6.4 Inside Cordon and Outside Cordon Link Changes

Figure 5.11 summarises and compares the changes in travel times for the CBD tolled links, the boundary links, some selected links inside and outside the CBD cordon. The figure appears to show that although there is evidence of link travel times reducing inside the cordon, some of these reductions are quite marginal as seen by the almost flat nature of the link travel time curve representing the links inside the cordon. This seems to suggest that some links inside the cordons would not enjoy significant gains in travel times as a result of tolling especially at current congestion levels. This could reflect the fact that tolling may not significantly affect route choice within the tolled cordons since cordon tolls do not directly affect internal-internal (I-I) trips. Therefore, there may be no incentive for such trips to re-route , and if the traffic tolled off from the tolled links did not use some of these links, then little to no changes may occur on some links inside the cordon. However, it might be expected that in real life, the reduction in travel times on the tolled links will improve the network conditions in the charged area. This might cause some suppressed car trips to take advantage of these improvements and therefore be attracted onto the network.

The issue of the potential for road pricing to induce new trips is an area of research in its own right and is not the main interest of this research.

Figure 5.11 also seems to suggest that there might be some increases in travel times on links outside the cordon apart from the boundary links. The modelling in this work calculated travel time increases of up to 16.5% on links outside the CBD cordon for the Southampton network. The average link speeds were found to decrease by about 2 kilometres per hour or by 6.5%. As Figure 5.11 shows, the increases in travel time for links outside the cordon do not appear to be large especially in comparison with those on the boundary links. While it is to be expected that some through trips would re-route to links further away than the immediate peripherals of the cordon, the results suggest that this is not very significant at current congestion levels. It is also to be expected that most through trips, might not do so until they encounter the tolled links since toll avoidance is the underlying cause of re-routing under cordon tolls. It is therefore not surprising that a significant number of links outside the cordon may not experience significant changes in their level of service. These same observations were noted earlier under a more aggregate analysis and were noted to be consistent with literature evidence about the re-routing effects of cordon tolls.

5.7 Some Conclusions from Analysis of the CBD Cordon

Although the network effect of tolls appears to depend on the toll level, the adverse effects were less pronounced at the lower toll levels than at higher tolls. In line with literature evidence, the benefits arising from improvements on the tolled links, were at their optimum at lower toll levels, up to about 50 pence in this research. However, little or no further benefits accrued on the tolled links at higher toll levels. At higher tolls the overall network performance as measured by total network vehicle hours was seen to deteriorate as expected. Boundary link delays increased more rapidly at higher tolls than delays reduced on the tolled links. As a result, boundary links showed significantly larger increases in travel time than the travel time reductions on the tolled links. Average travel time increases of up to a minute and a half were calculated on the CBD cordon boundaries. The tolled links on the other hand only showed average decreases in travel time of about half a minute. This suggests that more disbenefits resulted on the boundary routes than benefits occurred on the tolled links or the charged area in general. Therefore the evidence in this work is consistent with the widely held view that improvements in the charged area would be at the expense of deteriorating conditions outside the charged areas.

Although there were generally some decreases in travel times for links inside the charged cordon (other than the tolled links) the changes did not appear to be significant compared to the reductions on the tolled links. This could be explained by the fact that unless the vehicles priced off affected specific links inside the cordon, a number of links inside the cordon might not experience large decreases in their travel times or delays. Since trips inside the cordon do not directly encounter the tolls, route changes may occur only for those trips for which improved and/or shorter routes become available as an 'after effect' of reductions in travel times or delays on the tolled links.

Similarly, although in general, links outside the cordon (other than the immediate boundary routes) showed increases in flows and hence in travel times, these were not as large as the increases on the boundary routes immediately on the outskirts of the charged cordon. This could be because there may be no incentive for vehicles to re-route until the toll is encountered. This suggests that route changes before the toll is encountered may not be significant and drivers may potentially continue to use their original routes outside the cordon until just before the toll is encountered. Therefore, unless conditions on the nearest available free routes were infeasible, vehicles tolled off from the tolled links can be expected to use the boundary routes before resorting to even longer routes further away from the cordon boundaries. This may explain why the boundary or orbital routes appear to suffer the worst changes in link level of service compared to links outside the cordon that are further away from the boundaries. The observation that re-routing appears to be onto the boundary links than links further away, is consistent with literature evidence about what may be expected of route changes under cordon tolls (May and Milne, 2000).

5.8 Comparison of the Single Cordon Schemes:

May and Milne (2000) noted for example that the results of their modelling could be specific to the network tested although the general trend of the results was likely to be more generic. Also, their results were based on a scenario of three cordons only, although it was realised that the effects could be different if different cordon arrangements/positions and/or combinations were tested. Further, their work concentrated on comparing the network effects of different charging regimes of cordon tolls, time based charging, distance based charging and delay based charging. While their results ranked delay based charging as the most efficient method, it was realised that cordon tolls were probably the most likely to be implemented because of their simplicity. It was also concluded that cordon charging was also least likely to cause rat-running since the amount of charges were known to drivers in advance. On the other hand, in trying to avoid congested links or junctions, congestion based or delay based charging could result in more rat-running even though in theory this charging regime was most efficient at reducing congestion. It was, however, also considered that because drivers were unlikely to have perfect knowledge, they might not be able to predict the incidence of congestion sufficiently to take advantage of the benefits theoretically predicted for congestion charging by the assignment model. Therefore, cordon pricing regimes still warrant further consideration since they offer the most likely start to the implementation of road user charging. The results that follow are based on work done in this research in which a variety of cordon positions were considered using the Southampton network. Basically, the results compare the performance of the different cordon positions tested using the same parameters that were used in analysing the CBD cordon. Scenarios in which a combination of such cordon positions leading to multiple cordon schemes of up to three cordons were also tested. In addition the potential implications of each of the cordon scenarios on important aspects such as revenue generation and the potential implications for elastic behaviour were considered.

5.8.1 Flow and Revenue Changes for the Different Cordon Positions

It was decided to first consider the flow changes since it is predominantly these flow changes that cause the resultant performance of the network in response to the tolls. Table

5.10 shows the flows intercepted by each of the separate cordons for tolls ranging from 20 pence to 200 pence compared to the base case scenario without charging. It can be seen from the table that the CBD cordon at 10,790 vehicles/hour, intercepts the least number of vehicles before tolling as expected.

			Total Tolled Link Flows in Vehicles/Hour					
Cordon	**Base Case**	**20 Pence**	**30 Pence**	**40 Pence**	**50 Pence**	**100 Pence**	**150 Pence**	**200 Pence**
CBD	10790	9587	9128	8833	8606	8081	7662	7358
MID	17613	14803	13748	12830	12135	10729	10098	9566
EXTERNAL	21753	19142	18543	18036	17600	15993	14835	14274

Table 5.10 Variation of Total Flows on Tolled Links by Toll Level and Cordon Position

		Total Flows Re-routed/Diverted fromTolled Links in Vehicles/Hour						
Cordon	**Base Case**	**20 Pence**	**30 Pence**	**40 Pence**	**50 Pence**	**100 Pence**	**150 Pence**	**200 Pence**
CBD	0	1203	1662	1957	2184	2709	3128	3432
MID	0	2810	3865	4783	5478	6884	7515	8047
EXTERNAL	0	2611	3210	3717	4153	5760	6918	7479

Table 5.11 Diverted or Re-routed Flows from Tolled Links by Toll Level and Cordon Position

The external cordon at 21,753 vehicles/hour, intercepts the most number of vehicles in the base case scenario. This is followed by the mid cordon, which intercepts 17,613 vehicles/hour. In all three cordon positions, the flows intercepted are seen to decrease with increasing toll level as drivers able to do so, re-route away from the tolled links to alternative free routes. Alternatively, the flows diverted from the tolled links are seen to increase with toll level as expected for all three cordon positions as shown in Table 5.11. It is interesting to note that despite the external cordon intercepting the most number of trips in the base case scenario, it is the mid cordon, which diverts the most number of vehicles as can be seen in Table 5.11. This trend is seen to occur at all the charge levels tested. This could be explained by the fact that most cross-city trips in Southampton with origins and destinations outside the Southampton network, already use the orbital motorway system on the peripherals of the city (Southampton Provisional Local Transport Plan 2000/1-2004/5). The mid cordon intercepts those trips that would otherwise travel through it if no mid cordon tolls were implemented. Since in general, the boundary links at the peripherals of the mid cordon are as typical of urban links as any of the links through the mid cordon, there is no incentive for drivers to use the boundary links any more than they use the radial links. This is unlike the external cordon, where the motorway links offer a far more superior option for through trips than cross-city links.

The fact that the external cordon, still intercepts the most number of trips at all charge levels shows that there is a significant number of radial trips into Southampton from external zones. This could have implications for the provision of alternative transport options if longer trips are to respond elastically to measures such as road user charging. The high number of trips intercepted by the external cordon, suggests that, congestion and potentially vehicle kilometre based pollution could be alleviated if some trips with origins outside Southampton and destinations inside it (long E-I trips) responded elastically. However, evidence from the literature suggests that longer trips are likely to have lower elasticities than shorter trips and hence most of the long trips can be expected to continue to be done by the SOV unless viable alternatives were available. May and Milne (2000) for example, compared the network effects of various charging regimes for Cambridge, York and Leeds. They found that the benefits (measured as reductions in travel time and vehicle kilometres) were lower in Leeds partly because this city was larger, trips longer and elasticities smaller. The Leeds network had more long distance traffic passing through it.

		Total Revenue Generated by Toll Level and Cordon Position in £/Hour						
Cordon	Base Case	20 Pence	30 Pence	40 Pence	50 Pence	100 Pence	150 Pence	200 Pence
CBD	0	1917.4	2738.4	3533.2	4303	8081	11493	14716
MID	0	2960.6	4124.4	5132	6067.5	10729	15147	19132
EXTERNAL	0	3828.4	5562.9	7214.4	8800	15993	22252.5	28548

Table 5.12 Variation of Revenue Generated by Toll Level and Cordon Position

The revenue generated by each of the cordons is seen to increase linearly with toll level as expected. This is shown in Table 5.12 above. As expected from the flow information shown in Table 5.10, the external cordon generates the highest revenues at all toll levels in direct proportion to the flows intercepted or crossing the cordon, while the CBD cordon generates the least revenue. The external cordon generates about two times the revenue generated by the CBD cordon and about one and half times the revenue generated by the mid cordon. It also generates about 84 % of the revenue generated by the CBD and mid cordon combined. Although the external cordon intercepts the most number of trips and hence generates the most revenue, its potential to induce elasticity for trips inside the Southampton network is limited. This is because trips within the Southampton network would not be affected by the external cordon tolls and to all intents and purposes, drivers may continue to travel by car as before. A significant proportion of the radial trips crossing the cordon are longer trips that would benefit from the improved conditions on the tolled links rather than be inconvenienced by the increased travel costs due to the tolls. For such long trips, a toll of 200 pence, may still seem a better option to travellers than the cost of public transport, whose fares are likely to be higher than 200 pence, service frequency and reliability poor and out of vehicle waiting times higher than those of the SOV. Therefore, the toll component may not significantly increase the total travel costs for such longer trips as would be the case with shorter journeys. This is a major criticism of cordon tolls since short trips crossing the cordon would bear the brunt of the tolls more than longer trips. It would appear that for the Southampton network, the external cordon would be the best in terms of revenue generation, but not for congestion alleviation within the Southampton network.

5.8.1.1 Flow and Revenue Changes at Higher Tolls

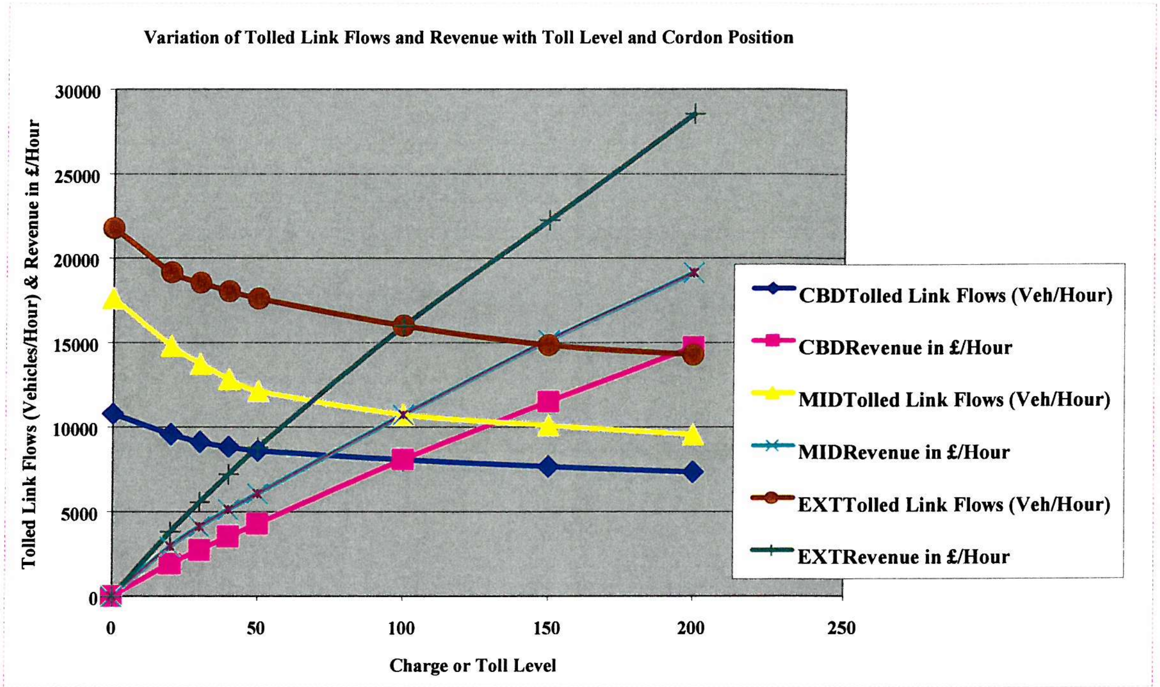


Figure 5.12 Variation of Total Flows on Tolled Links and Revenue by Toll Level and Cordon Position

Figure 5.12 shows that although the tolled links flows (intercepted flows) decrease with increasing toll level for all the cordon positions, the decrease in flows is most pronounced up to about the 100 pence toll level, after which there appears to be a less rapid decrease in flows intercepted. This would seem to suggest that the flows might possibly level off at some higher toll value as no further vehicles are re-routed from the tolled links. This seems to be confirmed by Figure 5.13 which shows that the flows diverted from the tolled links despite initially showing a sharp increase, are seen to flatten off at higher toll levels as the number of vehicles diverting between successive higher toll levels decreases. Theoretically, it should be possible to reach a point when no further diversions occur. This should occur when all the through trips crossing a cordon are re-routed away from the tolled links to the orbital or boundary links. In reality, it is unlikely that such a state will be reached since capacity limits on key junctions would result in excessive queuing delays making re-routing infeasible. Some form of elastic response particularly for shorter trips may be expected to come into play at the higher toll levels.

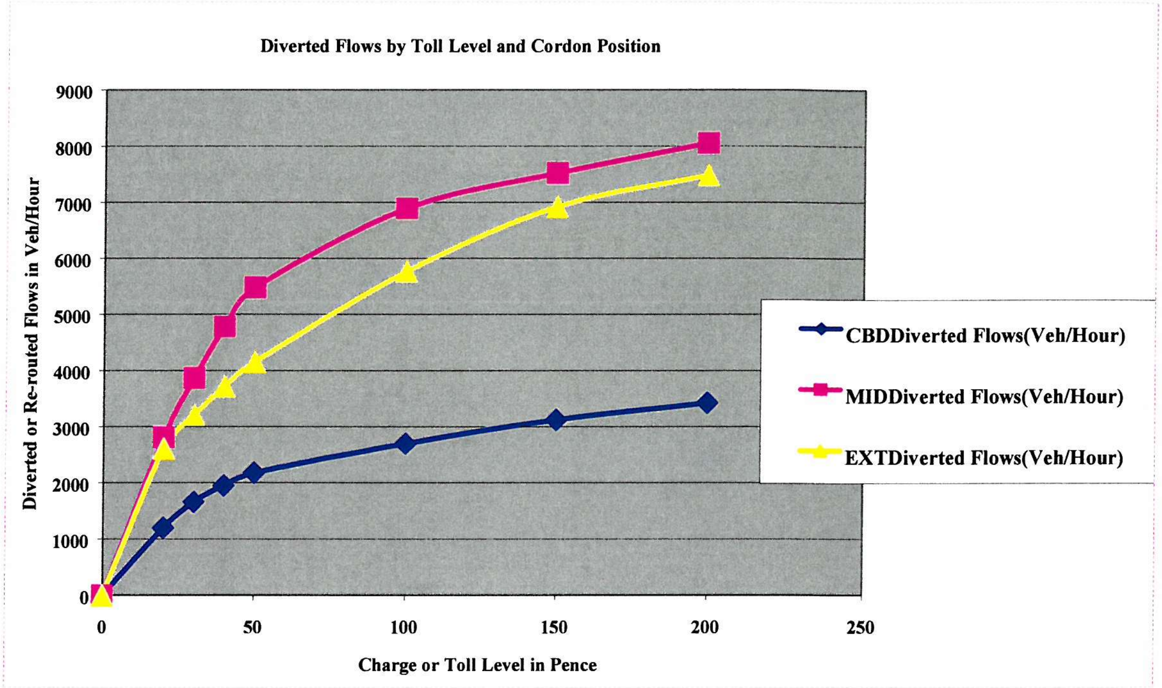


Figure 5.13 Variation of Diverted or Re-routed Flows with Toll Level and Cordon Position

Following the discussion above, it can also the expected that the revenues generated may potentially level off at some higher toll level, as the decrease in intercepted flows become such that the increase in toll levels is unable to compensate for the decrease in the number of paying vehicles. However, over the range of tolls considered in this research, Figure 5.12 seems to suggest that the increase in toll levels is sufficient to offset the decrease in flows with increasing toll level. Therefore the revenues are seen to increase with toll level over the whole range of charges considered, for all the three cordon positions. This is consistent with May and Milne's (2000) finding that under fixed or inelastic demand, cordon pricing revenue was seen to rise almost in proportion to the charge level. The authors concluded that this continued and proportionate increase in revenue with toll level suggested that there was little propensity for traffic to divert to avoid the cordon charges. The results in this research are consistent with this conclusion. This is particularly so at higher charge levels because queuing delays rise faster on the boundary links, than delays are reduced on the tolled links or charged areas. Therefore drivers are better off paying the tolls than re-routing at higher toll levels under inelastic demand. Realistically, it may be expected that some radial trips would respond elastically to the increase in tolls because they were unable or unwilling to pay the higher tolls especially considering that the incremental savings in travel times would not rise significantly above those already enjoyed at the lower toll levels.

5.8.1.2 Brief Summary About Flow and Revenue Comparison by Cordon Position

For the Southampton network, the CBD cordon was found to intercept the least number of trips. This was followed by the mid and external cordon respectively in order of increasing number of trips intercepted. The fact that the CBD cordon intercepted the least number of drivers may mean that its potential to change drivers' behaviour would be limited. This is because most drivers particularly those outside the CBD cordon would be able to execute their trips as before since they would not encounter the CBD cordon. It was also argued that despite intercepting the most trips, the external cordon was unlikely to cause most drivers to respond elastically. This was mainly because in contrast to the CBD cordon, the external cordon would be unable to influence the behaviour of drivers inside it rather than outside it. Further, the longer trips intercepted by the external cordon were likely to be less sensitive to tolls than the shorter trips intercepted by mid and CBD cordons. The mid cordon intercepted more trips than the CBD cordon but less than the trips intercepted by the external cordon. However, it also diverted the most number of trips. The mid cordon position enables it to influence trips inside the Southampton network better than either the external cordon or the CBD cordon. Although it may seem that by diverting more trips than the other two cordons, the mid cordon may encourage re-routing more than it encourages elastic responses, the mid cordon is better placed to affect a significant proportion of trips within the Southampton network than the external cordon. Since trips within the Southampton network will be shorter than those intercepted by the external cordon, the mid cordon is better placed to influence the shorter within Southampton trips, which as literature evidence suggests are more likely to show elasticity than the longer trips intercepted by the external cordon.

The analysis undertaken in this work suggests that the trips intercepted by each of the cordons decreased with increasing toll level, although there was evidence to suggest that the decrease in the number of intercepted trips reduced between successive charge levels. This appears to be so from Figure 5.12 where the flow curves are seen to flatten with increasing toll level, and from Figure 5.13.where it can be seen that at higher toll levels the trips diverted curves are also seen to flatten off. However, within the range of tolls tested, the revenue generated continued to increase with toll level, suggesting that the increase in toll level more than compensated for the decrease in flows on the tolled links with increasing toll level. The modelling showed that the external cordon generated the most revenue at all toll levels, followed by the mid and CBD cordons respectively.

Although the CBD cordon appears to be the least likely cordon to encourage elastic behaviour mainly because it intercepts much fewer trips than either the mid or external cordons, it however, also contains some of the most congested and sensitive areas of the network (e.g. high pedestrian activity). It also benefits from the more radial nature of public transport services and is better placed to offer more viable travel alternatives than the other two cordons. Further, because of its smaller and compact geographic size, the capital and enforcement costs of a CBD cordon, would make it the most likely to be implemented with potential for expansion later (e.g. ROCOL, 2000).

5.8.2 Comparison of Total Network Vehicle Kilometres

Table 5.13 tabulates the actual model output, absolute differences and percentage changes in VKT for the three single cordons. The results show that the VKT increase with toll level for all the three cordon locations. This information is also depicted in Figure 5.14 where it appears that there is more or less a linear increase in VKT with toll level.

Cordon	Performance Parameter	Base Case	20 Pence	30 Pence	40 Pence	50 Pence	100 Pence	150 Pence	200 Pence
CBD	VKT	940,623	944,669	946,731	948,564	950,398	961,969	975,198	987,902
	Absolute Change (VKT)	0	4046	6108	7941	9775	21346	34575	47278
	Percentage Change (%)	0.0	0.4	0.6	0.8	1.0	2.3	3.7	5.0
MID	VKT	940,623	946,457	951,900	957,593	964,721	994,684	1,016,556	1,043,743
	Absolute Change (VKT)	0	5834	11277	16970	24098	54061	75933	103119
	Percentage Change (%)	0.0	0.6	1.2	1.8	2.6	5.7	8.1	11.0
EXTERNAL	VKT	940623	945147	947485	951196	956185	982033	1005596	1016255
	Absolute Change (VKT)	0	4524	6862	10573	15561	41409	64973	75632
	Percentage Change (%)	0.0	0.5	0.7	1.1	1.7	4.4	6.9	8.0

Table 5.13 Summary Results for Total Network Vehicle Kilometres Travelled (VKT) for Single Cordons

The increase in VKT for all the three cordons is testimony to the re-routing occurring as a result of the tolls. As expected, the CBD causes the least increase in VKT since it intercepts the least number of vehicles and also diverts the least number of vehicles away from itself. Further, its smaller radius also means that the extent of the diversions around it are smaller than for both the external and mid cordons. Despite that the mid cordon would be expected to cause smaller diversions than the external cordon because of its smaller radius, the results show that it is the mid cordon that causes the largest increase in VKT for all the three cordons. This would appear to be because the mid cordon diverts the most number of vehicles at all toll levels compared to the other two cordons as was seen earlier. It would appear that the smaller diversion lengths that could be expected of the mid cordon compared to the external cordon, are more than compensated for by the larger number of vehicles diverted by the mid cordon compared to the external cordon.

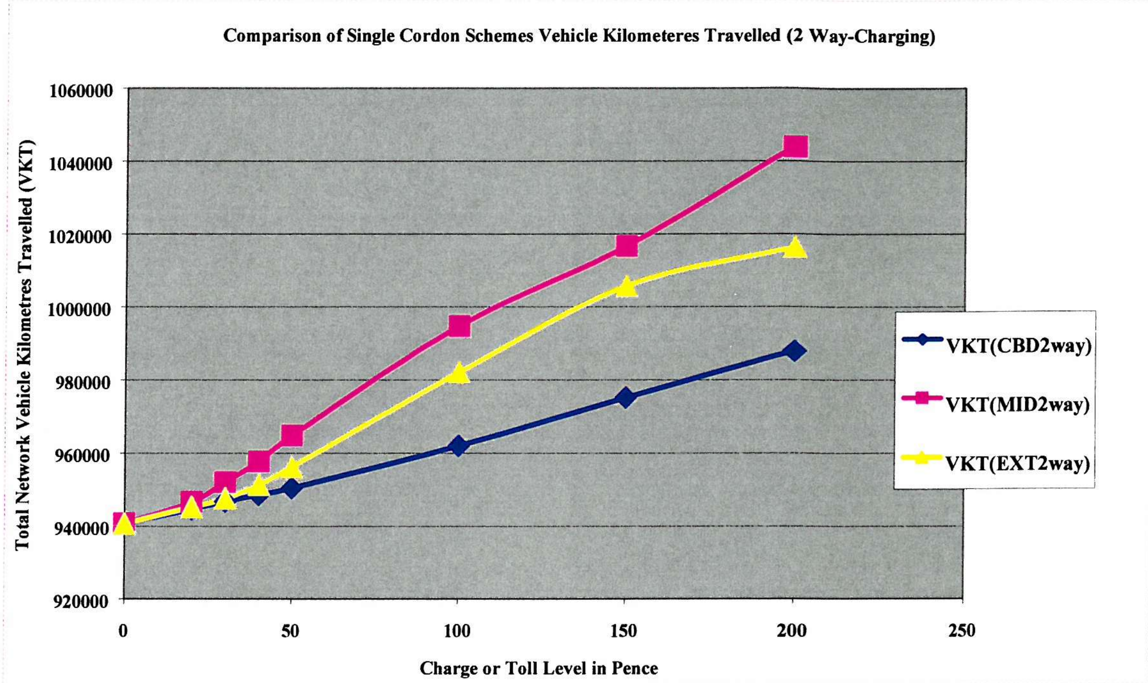


Figure 5.14 Variation of Total Network Vehicle Kilometres Travelled with Toll Level For Single Cordon Schemes

The CBD cordon results in a 5% increase in VKT, while the mid cordon and external cordons cause about 11% and 8% increase respectively. These increases are consistent with literature evidence. Additionally, the fact that all the cordons causes some re-routeing, is consistent with May and Milne (2000) who found that the pricing regimes they tested; i.e. per distance charging, per unit time of travel charging, congestion based charging and cordon charging, all caused re-routing away from the charged links. The authors concluded that because environmental benefits were related to reductions in VKT, it seemed that road user charging and in particular, the re-routeing mechanism which increased these VKT, may not significantly alleviate the overall adverse environmental effects of transport apart from the charged area. However, as was pointed out in Chapter 2, Tate and Bell (2000) argued that re-routing traffic away from highly populated activity centres, to the less populated city peripherals, may at least have some positive health benefits since the number of people exposed to harmful emissions would be reduced. Further, the greater dispersion and lower population activity at the city peripherals would neutralise the effects of any minor increases in emissions as a result of re-routing. Although the TDM work considered by Tate and Bell was a gating strategy, it is widely accepted that road user charging would similarly alleviate congestion from centres in which it was applied and divert traffic to longer uncharged routes. In this respect the effects of both TDM strategies are quite similar, although one may expect differences in the magnitude of the diversions. Proponents of road user charging argue that direct user charging is likely to be the most 'coercive' TDM measure (e.g. Cullinane, 1992, Gärling et al, 2000) although this remains an area of research interest considering that little is known about the elasticity estimates of different TDM measures. Economists argue that direct user charging is the most efficient way of alleviating congestion since travel costs are better matched or related to the congestion caused by vehicles. The revenue potential of direct user charging, however, appears to be undisputed (e.g. ROCOL, 2000, Cheese and Klein, 1999).

5.8.3 Summary and Comparison of Total Network Vehicle Hours

Cordon	Performance Parameter	Base Case	20 Pence	30 Pence	40 Pence	50 Pence	100 Pence	150 Pence	200 Pence
CBD	Total Network Vehicle Hours	18,120.4	18,230.3	18,305.0	18,414.0	18,526.4	19,279.5	20,183.9	21,197.9
	Absolute Change (VHS)	0.0	109.9	184.6	293.6	406.0	1159.1	2063.5	3077.5
	Percentage Change (%)	0.0	0.6	1.0	1.6	2.2	6.4	11.4	17.0
MID	Total Network Vehicle Hours	18,120.4	18,155.2	18,359.9	18,625.6	18,976.4	20,642.8	22,239.3	24,203.6
	Absolute Change (VHS)	0.0	34.8	239.5	505.2	856.0	2522.4	4118.9	6083.2
	Percentage Change (%)	0.0	0.2	1.3	2.8	4.7	13.9	22.7	33.6
EXTERNAL	Total Network Vehicle Hours	18120.4	18,394.7	18,619.9	18,866.7	19,079.0	20,516.4	22,548.2	23,732.0
	Absolute Change (VHS)	0.0	274.3	499.5	746.3	958.6	2396.0	4427.8	5611.6
	Percentage Change (%)	0.0	1.5	2.8	4.1	5.3	13.2	24.4	31.0

Table 5.14 Summary Results for Total Network Vehicle Hours for Single Cordons

Table 5.14 shows that the total network vehicle hours increase with increasing toll level for all the cordon positions as expected. The increases were smaller at the lower toll levels but increased rapidly as the toll level increased. Under inelastic modelling, the network effects of cordon tolls can be expected to deteriorate with increasing charge level (Smith et al, 1994; Wigan and Bamford, 1973; Tolofari, 1997). The results from the modelling here is consistent with this finding for all the three cordon positions. Therefore the increase in total network vehicle hours with increasing tolls is consistent with literature evidence. For example Smith et al, (1994) concluded that too high a charge had a very adverse effect on the overall network performance. This was because traffic would be forced to user longer and less congested routes. The decrease in vehicle hours in the charged area was not able to offset the increase in vehicle hours as a result of using the much longer routes. It appears that, the increase in delays at junctions on boundary routes is a main cause of the higher increases in total network vehicle hours at higher tolls, as can be seen from Figure 5. 15 which shows that total network queuing delays increase rapidly at higher tolls. Smith et al, (1994) concluded that cordon tolls were poor in improving network performance if the demand matrix was inelastic. The results here are consistent with this finding.

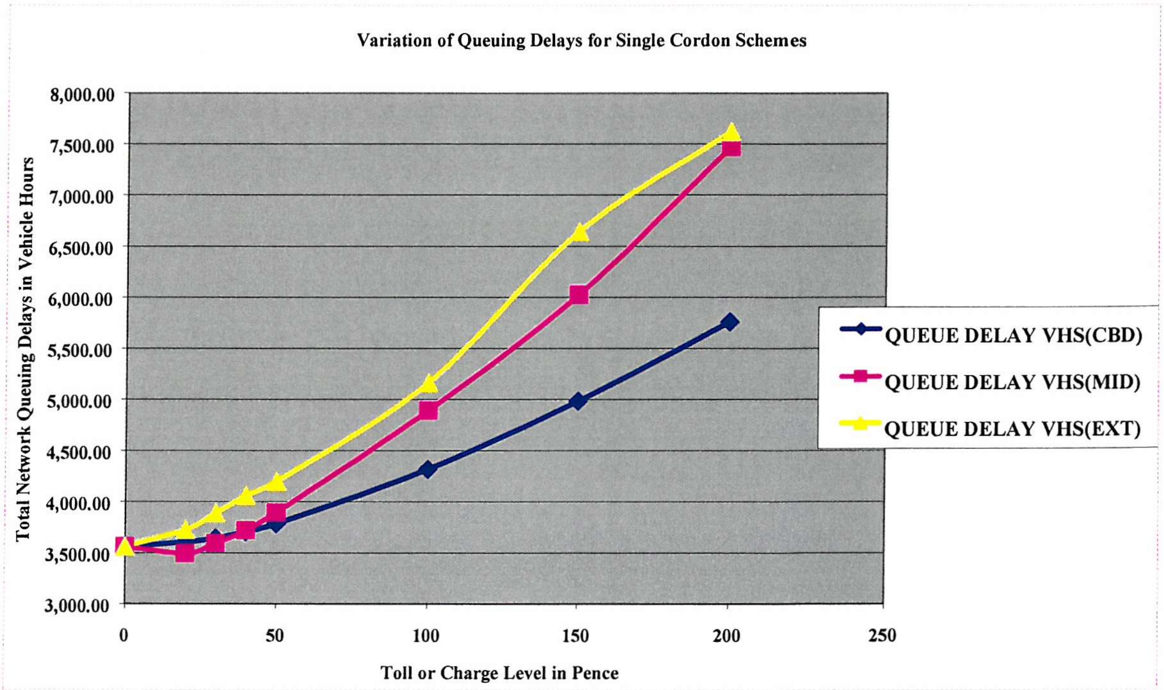


Figure 5.15 Variation of Queuing Delays with Toll Level for Single Schemes

In this work, the CBD cordon caused percentage increases in total network vehicle hours ranging from about 0.6% at a toll of 20 pence, to 17% at a toll level of 200 pence. The corresponding percentage increases for the mid and external cordons were about 0.2% to 33.6% and 1.5% to 30.9% respectively. In all the three cordon positions, the percentage increases are quite consistent with literature evidence for toll levels up to about 50 pence. For example, the work by Gower and Mitchell (1998) considered per kilometre tolls of up to 4 pence per kilometre. This would estimate to a fixed toll of only 40 pence for a trip of 10 kilometre length. The percentage increase in total network vehicle hours at 4 pence per kilometre was 6.4%. This compares reasonably to the range of percentage changes found in this work at about the 100 pence toll for the CBD cordon (6.4% increase), 50 pence toll level for the mid cordon (4.7% increase) and 50 pence toll level for the external cordon (5.3% increase) The percentage increases for higher tolls appear to be outside the range in the literature. This appears to be due to the rapid increase in queuing delays at higher tolls, particularly from about 50 pence to 100 pence as can be seen from Figure 5.15. This seems to suggest that below these charges, the boundary routes are able to accommodate the traffic re-routed to them. However, junction capacity becomes inadequate at higher tolls as more vehicles re-route away from the tolled links onto the boundary routes. The implications could be that re-routing is unlikely to be a feasible option high tolls since the time spent queuing at the orbital routes would be excessive. Although there is evidence of even longer routes being used at higher tolls as seen by the increase in VKT (Table 5.13 and Figure 5.14), capacity limits at key junctions on boundary routes, may be expected to cause some trips not to re-route but to respond in some elastic manner such as peak spreading, foregoing the trip or trip suppression or by changing destination. Shorter orbital trips, may be expected to respond this way in real life since the delays experienced would constitute a large proportion of their travel time than would be the case for longer orbital trips. Further, shorter trips are more likely to be better served by public transport than longer trips.

5.8.4 Summary and Comparison of Overall Network Average Speed

For all the cordon positions, the overall average network speed is seen to decrease with increasing toll level as can be seen in the summary Table 5.15. At the lower toll levels the speeds for all the three cordons are comparable. However, the CBD cordon has the highest speeds at the higher toll levels. Its overall network speed at the 200 pence toll level is 46.6 kph, a 5.3 kph decrease from the base case speed of 51.9 kph. This represents a 10.2% decrease in overall network speed. The mid cordon has the next better performance in terms of overall network speed. The overall network speed at the 200 pence toll level is 43.1 kph, a drop of 8.8 kph on the base value, and equivalent to a 17% drop in overall network speed. On the other hand the external cordon has the worst performance of the three cordons when it comes to overall network speed. The speed at the 200 pence toll is 42.2 kph, a drop of 9.1 kph or 17.5%. The higher increase in VKT for the mid cordon compared to those of the external cordon, more than compensates for the higher increases in total network vehicles registered by the mid cordon. This results in the mid cordon's overall network speed being higher than that of the external cordon. The reason why the CBD has the better speeds at higher toll levels appears to be because it results in the least increase in delay vehicle hours at these high tolls. This arises because the CBD cordon only diverts about 50% of the vehicles diverted by the mid cordon for example, but to boundary links of comparable standard and base congestion level as those of the mid cordon boundary links. The resulting lower total network vehicle hours are enough to cause the overall network speed of the CBD cordon to be the highest even if it registers the least increase in VKT. The higher increases in mid cordon VKT is unable to compensate for its higher increase in total delays and hence its higher total vehicle hours. This causes the mid cordon speed to be lower than that of the CBD cordon.

Cordon	Performance Parameter	Base Case	20 Pence	30 Pence	40 Pence	50 Pence	100 Pence	150 Pence	200 Pence
CBD	Overall Network Speed(Kph)	51.9	51.8	51.7	51.5	51.3	49.9	48.3	46.6
	Absolute Change (Kph)	0.0	-0.1	-0.2	-0.4	-0.6	-2.0	-3.6	-5.3
	Percentage Change (%)	0.0	-0.2	-0.4	-0.8	-1.2	-3.9	-6.9	-10.2
MID	Overall Network Speed(Kph)	51.9	52.1	51.8	51.4	50.8	48.2	45.7	43.1
	Absolute Change (Kph)	0.0	0.2	-0.1	-0.5	-1.1	-3.7	-6.2	-8.8
	Percentage Change (%)	0.0	0.4	-0.2	-1.0	-2.1	-7.1	-11.9	-17.0
EXTERNAL	Overall Network Speed(Kph)	51.9	51.4	50.9	50.4	50.1	47.9	44.6	42.8
	Absolute Change (Kph)	0.0	-0.5	-1.0	-1.5	-1.8	-4.0	-7.3	-9.1
	Percentage Change (%)	0.0	-1.0	-1.9	-2.9	-3.5	-7.7	-14.1	-17.5

Table 5.15 Summary Results for Overall Network Speed in Kilometres per Hour (Kph)

5.8.5 Summary and Comparison of Perceived Cost Changes

Figure 5.16 shows the variation of perceived cost for the single cordon schemes. The differences in perceived cost for the three single cordons is influenced by the relative contributions of the total travel time costs and the toll cost component. Therefore the CBD cordon perceived cost is the smallest as expected since this cordon has the least total network vehicle hours and the least toll cost component or revenue generated. Although it was seen that the mid cordon had larger total network vehicle hours than the external cordon, the large toll cost component (equal to revenue generated) of the external cordon perceived cost compared to that of the mid cordon, ensures that the external cordon perceived cost is larger than that of the mid cordon. Therefore, from a road user point of view, the external cordon causes the largest increase in total network costs, particularly because of the large out of pocket costs paid as tolls. This is followed by the mid and CBD cordons respectively. The perceived cost suggests that it is possible to raise substantial

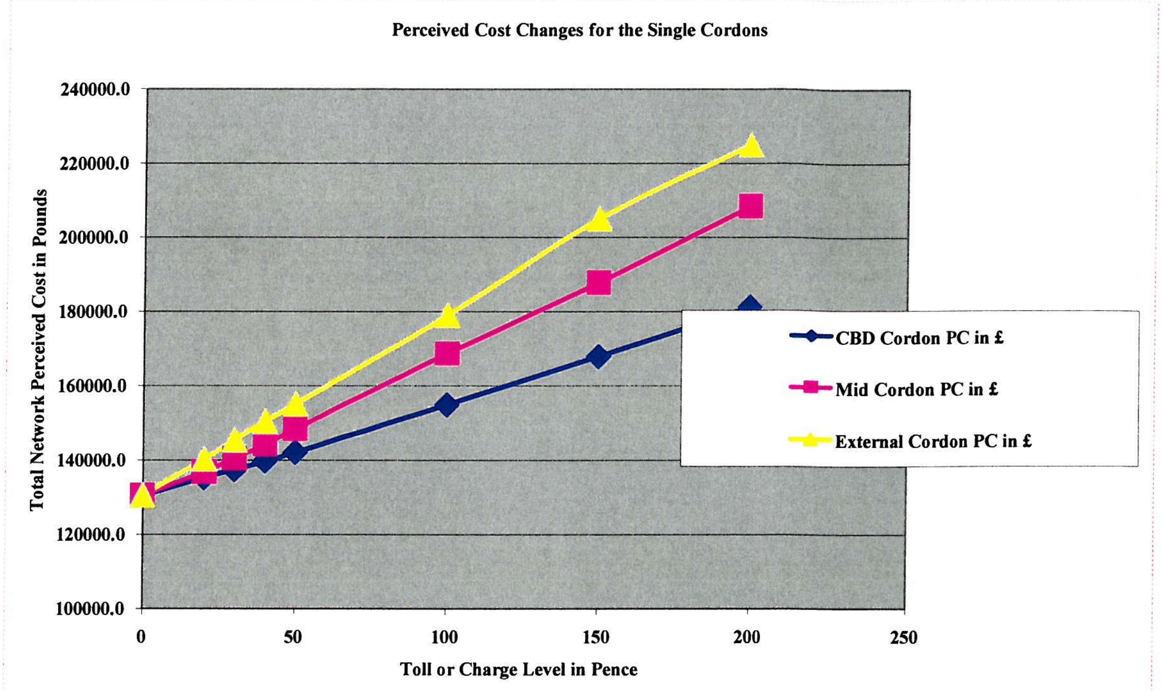


Figure 5.16 Variation of Total Network Perceived Cost with Toll Level for Different Single Cordons

revenue for the Southampton network without affecting most of the trip movements within Southampton by applying the external cordon. As was explained earlier, the external cordon is unlikely to reduce congestion within Southampton through elastic responses although some improvements will arise because the remaining through External -External (E-E) trips would divert to the motorway system. However, most of the longer radial E-I trips can be expected to show little elastic behaviour as literature evidence suggests.

5.8.6 A Summary on the Comparison of Single Cordon Schemes

The CBD cordon had the least increase in total network vehicle hours, suggesting that it had the best performance from an inelastic modelling perspective. The mid cordon had the worst performance based on total network vehicle hours. The external cordon, raised the most revenue although it was argued that it would have little effect on trips within the Southampton network.

It was shown under single cordon schemes that there were differences in flows intercepted by each of the different cordons. The CBD cordon had the least coverage and intercepted the least number of trips. Therefore its potential for elasticity was considered to be potentially low since many drivers outside it would not be affected by this cordon. The external cordon intercepted the most number of trips but many trips within the Southampton network would be unaffected by its presence. Therefore the potential of the external cordon to change travel behaviour other than by re-routing, was also limited. The mid cordon was argued to be the cordon that had the most potential to cause elastic behaviour even though evidence suggests that a CBD cordon is one that is most likely to be implemented (e.g. ROCOL, 2000). The summary above shows that different cordons can be expected to perform better on different criteria. This is consistent with literature evidence (e.g. May and Milne, 2000).

5.9 Multiple Cordon Schemes

It can be envisaged that pricing schemes may be implemented in stages in which outer cordons could be added after the initial implementation of a CBD cordon. Implementing multiple cordon schemes increases the coverage of cordon tolls making it difficult for drivers to void the tolls or not to come into contact with a cordon. Therefore, multiple cordons can complement the different single cordon schemes. A number of multiple cordon schemes were considered. This included a combination of the mid and CBD cordons (MIDCBD), the external and CBD cordons (EXTCBD), the mid and external cordons (MIDEXT) and a combination of all the three cordons (THREE). One of the issues raised in the Hong Kong studies was the potential for a set of lower priced multiple cordons to perform better than a single higher priced cordon (Dawson, 1986). To model this scenario, it was assumed for instance that only a vehicle crossing all three cordons would incur the full toll level of say £ 2.00. A car crossing a single cordon would only incur a third of this toll, while one crossing two cordons would incur two thirds of the maximum toll. Effectively, at any given toll level such as 50p, 100p or 150 p, only a car crossing all three cordons would incur the full toll level. This effectively provided a scenario of lower charged multiple cordons and was designated 'effective three cordon scenario' or

(EFFTHREE). The results of the combined cordons are reported in the tables below which also include results of the single cordons for comparison.

			Total Tolled Link Flows in Vehicles/Hour					
Cordon	Base Case	20 Pence	30 Pence	40 Pence	50 Pence	100 Pence	150 Pence	200 Pence
CBD	10790	9587	9128	8833	8606	8081	7662	7358
MID	17613	14803	13748	12830	12135	10729	10098	9566
EXTERNAL	21753	19142	18543	18036	17600	15993	14835	14274
MIDCBD	28403	23327	22758	21548	20536	18540	16836	15409
EXTCBD	32543	28848	27869	27032	26461	24339	22832	21397
MIDEXT	39366	34108	32466	31252	30298	27717	25480	23403
THREE	50156	43634	41538	40069	38881	34890	31943	29769
EFFTHREE	50156	47358	46291	45323	44371	41013	38881	37070

Table 5.16 Variation of Tolled Link Flows with Toll Level for Combined Cordon Schemes

Table 5.16 shows that multiple cordons generally intercept more vehicles than the single cordons from which they are derived. It is to be expected that in general the flows intercepted by the multiple cordons approximate to the sum of the flows intercepted by the corresponding single cordons from which they are derived. Table 5.16 shows this to be the case. It is interesting to note that the combined mid and CBD cordons (MIDCBD scenario) are seen to intercept flows that are similar to or marginally higher than those of the external cordon alone. This seems to suggest that the MIDCBD cordon scenario can potentially raise revenues (see Table 5.18) comparable to those from the external cordon alone while also offering the potential for elastic behaviour since a significant proportion of drivers within the Southampton network would encounter these cordons. This scenario therefore appears to offer the revenue potential of the external cordon and the potential TDM capabilities of the mid and CBD cordons combined. This is further seen from Table 5.17 where it can be seen that this combined scenario diverts nearly twice the flows diverted by the external cordon alone, with potential to reduce congestion in the Southampton network better than the external cordon alone, or for that matter, the CBD and mid cordons separately.

		Total Flows Re-routed/Diverted fromTolled Links in Vehicles/Hour						
Cordon	Base Case	20 Pence	30 Pence	40 Pence	50 Pence	100 Pence	150 Pence	200 Pence
CBD	0	1203	1662	1957	2184	2709	3128	3432
MID	0	2810	3865	4783	5478	6884	7515	8047
EXTERNAL	0	2611	3210	3717	4153	5760	6918	7479
MIDCBD	0	5076	5645	6855	7867	9863	11567	12994
EXTCBD	0	3695	4674	5511	6082	8204	9711	11146
MIDEXT	0	5258	6900	8114	9068	11649	13886	15963
THREE	0	6522	8618	10087	11275	15266	18213	20387
EFFTHREE	0	2798	3865	4833	5785	9143	11275	13086

Table 5.17 Variation of Diverted Flows with Toll Level for Combined Cordon Schemes

		Total Revenue Generated by Toll Level and Cordon Position in £/Hour						
Cordon	Base Case	20 Pence	30 Pence	40 Pence	50 Pence	100 Pence	150 Pence	200 Pence
CBD	0	1,917.40	2,738.40	3,533.20	4,303.00	8,081.00	11,493.00	14,716.00
MID	0	2,960.60	4,124.40	5,132.00	6,067.50	10,729.00	15,147.00	19,132.00
EXTERNAL	0	3,828.40	5,562.90	7,214.40	8,800.00	15,993.00	22,252.50	28,548.00
MIDCBD	0	4,665.40	6,827.40	8,619.20	10,268.00	18,540.00	25,254.00	30,818.00
EXTCBD	0	5,769.60	8,360.70	10,812.80	13,230.50	24,339.00	34,248.00	42,794.00
MIDEXT	0	6,821.60	9,739.80	12,500.80	15,149.00	27,717.00	38,220.00	46,806.00
THREE	0	8,726.80	12,461.40	16,027.60	19,440.50	34,890.00	47,914.50	59,538.00
EFFTHREE	0	9,471.60	13,887.30	18,129.20	22,185.50	41,013.00	58,321.50	74,140.00

Table 5.18 Variation of Revenue Generated with Toll Level for Combined Cordon Schemes

Another point of interest is that of the 'effective three cordon' scenario (EFFTHREE). This scenario is seen to intercept the highest flows at all toll levels than other scenarios. This is because the arrangement effectively charges lower tolls for drivers crossing each cordon. For instance, a car crossing all three cordons at the toll level of 200 pence would pay £6 under the 'THREE' cordon scenario, but would only pay £2 under the 'EFFTHREE' scenario. Therefore the propensity to divert can be expected to be lower under the 'EFFTHREE' scenario. The consequent outcome is high revenue generation at effectively low tolls. Such a scenario can be expected to cause those unable or unwilling to pay to re-route rather than to respond elastically since the lower diverted flows appear not to cause excessive delays on the boundary routes. In fact the queuing delays (see Figure 5.17 on page 164) and the total network vehicle hours (see Table 5.20 on page 163) for this scenario are as low as those attained by the CBD cordon on its own even if it diverts about four times the flows diverted by the CBD cordon (see Table 5.17 on page 160) at a toll level of 200 pence. This is because the CBD cordon diverts virtually all re-routed vehicles to the CBD cordon boundary routes resulting in rapid increases in delays on these boundaries as junction capacity is expended. The 'EFFTHREE' cordon scenario diverts vehicles to boundary routes on all the three cordons without excessively overloading boundary routes on any one single cordon. The potential of the 'EFFTHREE' cordon scenario to change the behaviour of drivers other than by re-routing can be expected to be appreciable in travel markets of low values of time since toll values are relatively low, but intercepted flows high. Unlike the external cordon scenario, this combined cordon scenario does intercept drivers within the Southampton network, although at low effective tolls, making it ideally suited to pricing off those with very low values of time. Another interesting point about the 'EFFTHREE' combined cordon scenario is that despite its high revenue potential (and hence high toll cost component), its total perceived cost is relatively low compared to other combined cordon scenarios (Table 5.22). This is because of its lower travel time cost increases under inelastic modelling compared to other combined cordons. The total network perceived cost of the 'EFFTHREE' case is similar to that of the mid cordon and just higher than that of the CBD cordon even if its total network vehicle hours are similar to those of the CBD cordon. The higher toll cost component of the 'EFFTHREE' scenario makes its total perceived cost to be higher than that of the CBD cordon. In reality, the toll cost component is higher for the 'EFFTHREE' case not because travellers pay high toll levels, but because more travellers effectively pay lower tolls.

Charge Level (Pence)	VKT(CBD)	VKT(MID)	VKT(EXT)	VKT(MIDCBD)	VKT(EXTCBD)	VKT(MIDEXT)	VKT(THREE)	VKT(EFFTHREE)
0	940,623	940,623	940,623	940,623	940,623	940,623	940,623	940,623
20	944,669	946,457	945,147	971,358	948,546	949,675	952,134	943,229
30	946,731	951,901	947,485	954,489	952,567	956,550	960,798	944,852
40	948,564	957,593	951,196	962,732	959,351	966,204	971,660	946,593
50	950,398	964,721	956,185	971,358	965,202	974,914	984,369	950,042
100	961,969	994,684	982,033	1,018,798	1,000,671	1,017,661	1,040,768	963,610
150	975,198	1,016,556	1,005,596	1,057,752	1,029,143	1,049,602	1,071,893	984,369
200	987,902	1,043,743	1,016,255	1,086,786	1,049,473	1,059,997	1,086,650	1,009,170

Table 5.19 Multiple Cordon Total Network Vehicle Kilometres (VKT)

Charge Level (Pence)	VHS(CBD)	VHS(MID)	VHS(EXT)	VHS(MIDCBD)	VHS(EXTCBD)	VHS(MIDEXT)	VHS(THREE)	VHS(EFFTHREE)
0	18,120.40	18,120.40	18,120.40	18,120.40	18,120.40	18,120.40	18,120.40	18,120.40
20	18,230.30	18,155.20	18,394.70	19,748.70	18,556.10	18,393.20	18,658.60	18,201.60
30	18,305.00	18,359.90	18,619.90	18,769.00	18,838.70	18,775.60	19,258.70	18,257.80
40	18,414.00	18,625.60	18,866.70	19,259.50	19,223.40	19,301.40	20,047.10	18,354.80
50	18,526.40	18,976.40	19,079.00	19,748.70	19,574.80	19,805.10	20,815.50	18,502.70
100	19,279.50	20,642.80	20,516.40	22,734.10	21,893.40	23,040.50	25,672.30	19,491.00
150	20,183.90	22,239.30	22,548.20	26,066.40	24,516.60	26,554.40	30,203.50	20,815.50
200	21,197.90	24,203.60	23,732.00	29,466.00	27,160.50	30,069.80	33,514.70	22,587.50

Table 5.20 Multiple Cordon Total Network Vehicle Hours (VHS)

Charge Level (Pence)	SPEED (CBD)	SPEED(MID)	SPEED(EXT)	SPEED(MIDCBD)	SPEED(EXTCBD)	SPEED(MIDEXT)	SPEED(THREE)	SPEED(EFFTHREE)
0	51.9	51.9	51.9	51.9	51.9	51.9	51.9	51.9
20	51.8	52.1	51.4	49.2	51.1	51.6	51.0	51.8
30	51.7	51.8	50.9	50.9	50.6	50.9	49.9	51.8
40	51.5	51.4	50.4	50.0	49.9	50.1	48.5	51.6
50	51.3	50.8	50.1	49.2	49.3	49.2	47.3	51.3
100	49.9	48.2	47.9	44.8	45.7	44.2	40.5	49.4
150	48.3	45.7	44.6	40.6	42.0	39.5	35.5	47.3
200	46.6	43.1	42.8	36.9	38.6	35.3	32.4	44.7

Table 5.21 Multiple Cordon Overall Network Speed (KPH)

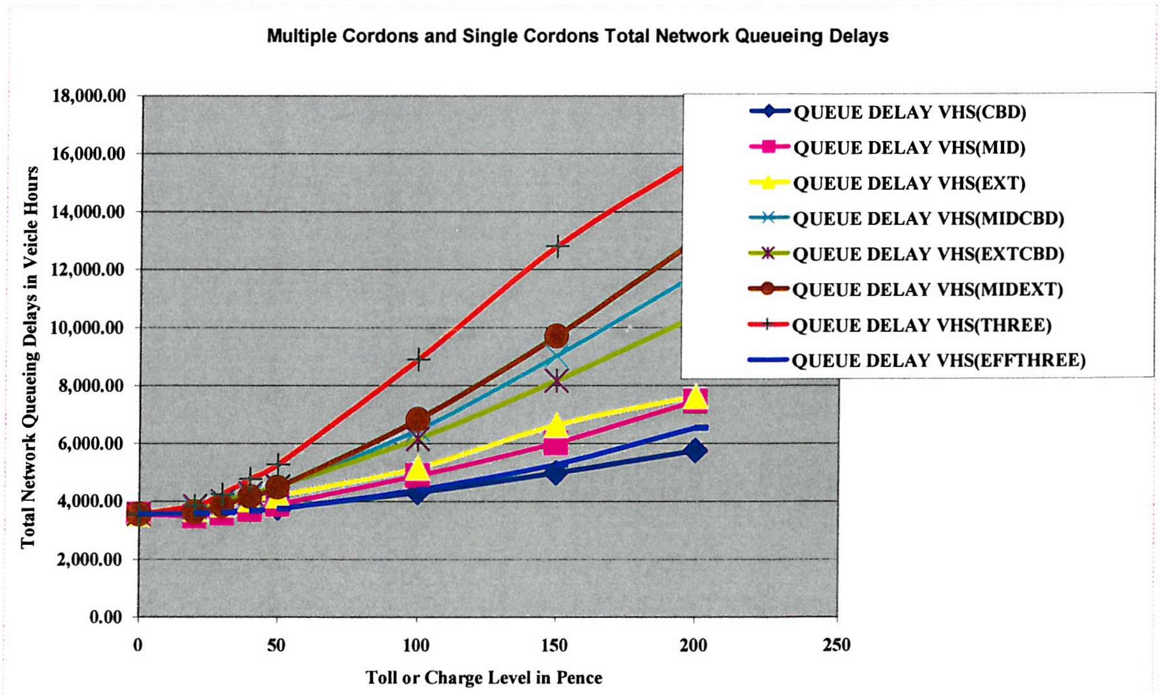


Figure 5.17 Variation of Total Network Queuing Delays for Multiple Cordons

Charge Level (Pence)	PC in £ (CBD)	PC in £ (MID)	PC in £ (EXT)	PC in £ (MIDCBD)	PC in £ (EXTCBD	PC in £ (MIDEXT	PC in £ (THREE	PC in £ (EFFTHREE
0	130,457.60	130,457.60	130,457.60	130,457.60	130,457.60	130,457.60	130,457.60	130,457.60
20	135,247.10	136,778.40	140,306.10	158.591.60	145,531.00	146,450.10	150,795.10	137,486.30
30	137,424.20	140,478.60	145,400.50	146,678.10	152,759.10	154,950.00	161.706.20	140,377.60
40	139,774.80	144.217.20	150,432.90	152,818.60	160,371.40	164,067.00	173.516.00	143,425.90
50	142,096.30	148.392.10	155,056.30	158.591.60	167,644.40	172,746.80	184.839.10	147.525.10
100	154,908.00	168,606.90	179,046.80	191.537.50	205,678.80	219,667.60	244.750.10	165.215.90
150	167,914.70	187,716.20	204,987.70	223.553.00	242,932.10	263,467.10	296,560.80	184,839.10
200	181,228.80	208,406.50	224,912.10	253,266.20	276,918.00	302,470.60	336,198.20	208,356.80

Table 5.22 Total Network Perceived Cost for Multiple Cordon Schemes

5.9.1 A Summary about the Performance of Multiple Cordon Schemes

Not surprisingly, the multi-cordon schemes appeared to perform less well than single cordon schemes when using total network vehicle hours as the performance indicator (Table 5.20). This is because multiple cordons intercepted and diverted more trips, causing boundary links to experience rapid increases in total network vehicle hours at higher toll levels. The increase in total network vehicle hours at higher toll levels was mainly due to increased queuing delays and hence limited capacity on key junctions on the boundary links. The only exception was the 'EFFTHREE' combined scenario which had total network vehicle hours comparable to some single cordons as was explained earlier. Multiple cordons also caused higher increases in VKT as expected compared to single cordons (Table 5.19). However, the increases in total vehicle hours for multiple cordons (Table 5.20), made their overall network speed to be lower than those of single cordon schemes particularly at higher toll levels (Table 5.21)

Multiple cordons generated more revenue than single cordon schemes (Table 5.18). This was as expected because multiple cordons intercepted more vehicles than single cordon schemes. The 'EFFTHREE' combined cordon scenario in particular, raised more revenue than any of the cordon scenarios tested. This was because although it intercepted as many trips as the 'THREE' cordon scenario at the base scenario, its effective lower toll levels enabled it to intercept more trips than any other cordon scenario when tolls were implemented.

The total network perceived costs were higher for multiple cordons than for single cordons because multiple cordons caused more increases in total network vehicles hours and so resulting in increased travel time costs. They also caused the higher increases in the toll cost component of the total perceived cost. The result is that travel costs were generally higher under multiple cordons than under single cordon schemes. The implications are that more elastic behaviour can be expected under multiple cordons than under single cordons. This is because more trips are intercepted. Longer trips can also be expected to pay more tolls under multiple cordons, making them more likely to show elastic behaviour than if they only paid at one cordon. Capacity limits on boundary routes are more likely to make re-routing infeasible on multiple cordons as delays would be very high at higher toll levels. This would also cause some drivers to respond elastically. More shorter trips would also be affected by multiple cordons, and so cause these trips to possibly respond elastically. The potential for wider coverage of pricing schemes to cause elastic behaviour is consistent with literature evidence (e.g. Lari and Buckeye, 1997, Tolofari, 1997). It was argued that the 'EFFTHREE' scenario had the potential to generate high revenues while also pricing off those with very low values of time. Where the travel market was more affluent, lower priced multiple cordons may be more of a revenue generation measure than a TDM measure despite its potential to intercept many trips.

5.10 Capacity Limits and Pricing: Implications for Potential Elastic Behaviour

Trip suppression or elastic responses to cordon tolls could potentially arise from two main reasons: Increased monetary travel costs and capacity limits on key junctions as re-routing to boundary routes increased. Short trips crossing a cordon would be most affected. In the absence of pricing, congestion would be the 'policy' that would cause elastic responses. Trips using key congested routes would be the most likely to be elastic. In the presence of cordon tolls, the response mechanisms are best summarized by Table 5.23. It can be seen

ORIGIN/DESTINATION	Internal Destination (I)	External Destination (E)
Internal Origin (I)	No Toll No Change in Route	Have to Cross the Cordon No Change in Route
External Origin (E)	Have to Cross the Cordon No Change in Route	Routes May Change

Trip Making Pattern/Movement	Potential Response under Inelastic Matrix	Potential Response Under Elastic Matrix
I-I	No Change in Route	Reduced congestion may induce new trips No incentive for trip suppression
E-I	No Change in Route but pay toll on crossing cordon	Toll may encourage trip suppression mechanism such as retiming, mode change, forgo trip, etc.
I-E	No Change in Route but pay toll on crossing cordon	Toll may encourage trip suppression mechanism such as retiming, mode change, forgo trip, etc.
E-E	Route may change from cross-city route to orbital routes	Main response likely to be re-routeing although some travellers may retime, change mode, forgo trip, change destination etc.

Table 5.23 Potential Effect of Cordon Charging on Different Trip Movements

from the table that trips within the cordon would not encounter tolls and might not change their travel behaviour. Under inelastic modeling, radial trips using the tolled links would have no option but to continue using the tolled routes. In reality, some drivers using the tolled trips would be unable or unwilling to pay the tolls, and would therefore respond elastically. Shorter trips crossing the cordon would be more likely to respond elastically than longer trips. This is because the proportion of the toll costs compared to the total travel costs would be larger for shorter trips than for longer trips. For instance a short trip whose travel time before tolling, was 5 minutes, would have travel time costs of 60 pence at the value of time of 12 pence/minute used in this research. If a toll of 200 pence reduced the travel time by 2 minutes, the new travel costs would be 236 pence. This would consist of 36 pence in travel time costs and 200 pence in tolls. Although there is a 2 minute decrease in travel time, the short trip would experience a net increase in travel costs due to the toll. The new travel costs would be nearly four times the base travel costs of 60 pence. Under elastic modeling, those drivers unwilling to pay the toll for a 2 minute saving in travel time, would be priced off. A longer trip whose base travel time before tolling was say 15 minutes, and also enjoyed a 2 minute decrease in travel time after paying a 200 pence toll would see their travel costs nearly double from 180 pence (15 minutes*12 pence/minute) to 356 pence (13 minutes*12 pence/minute 200 pence). It can therefore be appreciated that the increase in travel costs as a result of the tolling, would be more disproportionate for shorter trips than for longer trips.

Orbital trips on the other hand have the option to re-route. However, this research has shown that at higher toll levels, queue delays increase rapidly due to capacity limits on junctions on the boundary routes. It can be expected that some orbital trips, would respond to the increase in delays through elastic mechanisms, than experience large delays even if they were not paying any tolls. Therefore, in the presence of direct pricing, capacity limits on boundary routes may influence drivers to respond elastically than by re-routing. Shorter orbital routes may be expected to be more likely to respond elastically than longer orbital trips because shorter trips would experience a disproportionate increase in delays compared to longer trips. As with priced off radial trips, the provision of alternative travel options is a challenge that network operators would have to address.

5.10.1 O-D Pair Travel Cost Changes for some E-I trips under Inelastic Modelling

In order to illustrate the increase in travel costs that would be experienced by some radial trips unable to change route under a cordon pricing, the mid cordon was chosen for illustration. The mid cordon enabled the study of O-D pairs within Southampton, i.e. all links are represented for these O-D pairs since the whole trip or a substantial part of it occurs within the Southampton network. This is unlike for the external cordon where part of a trip may occur in a part of the network outside the Southampton network and therefore not accurately and fully represented in the Southampton network.

Radial trips with an origin outside the mid cordon and a destination inside it, and/or vice versa, (E-I and/or I-E trips) have to cross the cordon under inelastic modelling. Only through trips are diverted to alternative boundary routes. The diversion of through trips from the tolled links can be expected to reduce tolled link travel times and so benefit radial trips using these tolled links. Table 5.24 illustrates the trip travel time changes of some radial (E-I) movements before and after tolling using some key tolled links as part of their route. The tolled link (number 6443) used by these movements is on the key western approach into the city using the Redbridge Road/Millbrook Road West into the city (see Figure 5.1 and 5.2). Tolled link (number 6611) is one of the eastern approach river crossings (Cobden Bridge) while link number 2301 is on the busy A33 Avenues route from the northern approach. These are all very busy and congested roads especially in the peak period. The results in Table 5.24 show that the tolling results in O-D trip travel time decreases varying from just over a minute to just over three minutes for these O-D pairs. These travel time improvements are simply illustrative and not necessarily universal. It is possible that some O-D pairs may experience higher travel times. Travel time decreases varying between 5 and 25 minutes have been reported in the literature depending on amongst other things, the level of congestion and trip length (e.g. Mekky, 1995, 1996,1997).

O-D Pair	Trip Description	Trip Type	Tolled link Used	Base Case Travel Time (minutes)	TravelTime with Mid Cordon Toll of 200P (minutes)	Change in Travel Time (minutes)
5259 to 9056	Totton Central to Bargate/West Park Road (CBD)	E-I	Link 6443	15.6 (187.2)	114.4 (372.8)	1.2 (185.6)
5260 to 9062	Totton South to Bargate/Carlton Place (CBD)	E-I	Link 6443	12.4 (148.8)	10.7.0 (328.4)	1.7 (179.6)
5263 to9015	Waterside to Bargate/Queens Park (CBD)	E-I	Link 6443	19.6 (235.2)	16.7 (400.4)	2.9 (165.2)
5215 to 9066	Sholing to Bargate/Queensl and (CBD)	E-I	Link 6611	19.0 (228)	15.8 (389.6)	3.2 (161.6)
5183 to 9062	Harefield to Bargate/Carlton Place (CBD)	E-I	Link 6611	15.3 (183.6)	13.4 (360.8)	1.9 (177.2)
5159 to 9094	Bassett to Portswood	E-I	Link 2301	6.5 (78.0)	5.3 (263.0)	1.2 (185.0)

Table 5.24 Illustration of Changes in O-D Travel Times for Selected Trip Movements under a CBD Cordon Toll of 200 pence

The figures in parentheses represent the trip perceived cost values in pence. For example, the base case travel time from origin 5259 to destination 9056 is 15.6 minutes. This is equivalent to a perceived cost of 187.2 pence at the value of time of 12 pence/minute used in this research. After applying a toll of 200 pence the new travel time is 14.4 minutes. The perceived cost after tolling is the sum of the new travel time costs and the toll, hence the 372.8 pence. The net effect is an increase in perceived cost of 185.6 pence. The difference in the O-D perceived cost the before and after cases (i.e. 185.6 pence in the above mentioned example), represents that part of the toll that is not recouped in equivalent travel time savings. The 1.2 minutes decrease in travel time for O-D pair 5259 to 9056, is equivalent to about 14 pence and is that part of the toll that is recouped in equivalent travel time savings. It is clear from this illustration that the effect of the toll is to cause the travel costs to rise and that the savings in travel time are less than the toll paid. As Table 5.24 shows, the equivalent travel time savings can be expected to vary by O-D pair. In the illustration above, the money recouped as travel time savings varied between 14 pence (e.g. O-D pair 5259 to 9056) and 38 pence for O-D pair 5215 to 9066. It is the increase in perceived cost that will cause some radial trips to respond elastically in real life than pay the toll and enjoy travel time savings that are lower than the toll paid. The inelastic modeling assumes that radial trips will continue to travel since re-routing is not an option. In reality, some radial trips will be priced off by the tolls. This thesis has argued that the exact way in which these behavioural changes would occur as a result of the increase in travel costs is not fully understood and therefore, that, simple methods are required to estimate the potential network effects of such decisions. A 'what if' approach to estimating the behavioural changes was adopted based on literature evidence as is done in Chapter 6.

5.11 Conclusions and Summary

This chapter has reviewed the re-routeing effects of road user charging from the literature. Most of the evidence is from linear or facility pricing (e.g. Mekky, 1995; 1996, 1997; Tolofari; 1997; Golob, 2001; Tretvik, 1993). In such schemes, parallel tolled roads have been built alongside the existing congested roads. This enables those able to pay for reduced travel times to travel on the tolled roads and those unable and unwilling to pay to continue to use the free routes (e.g. Highway 407, Melbourne City Link; SR–191 in California). Since private investors are involved in these projects, revenue generation inevitably assumes an important role alongside the fundamental objective of reducing congestion on existing facilities by offering alternative parallel charged routes. Prices on the tolled routes are also used to regulate flows on the tolled routes so that the level of service (LOS) on the tolled routes remains better than that on the free routes. It appears that there has been little or no resistance to tolls in such schemes because the old parallel route remains available for those unwilling to pay. Such tolled roads have provided understanding on the extent to which travelers were willing to pay for travel time savings by re-routing from congested free routes with high travel times, to tolled routes offering faster speeds, reduced travel time delays and lower overall travel times. Journey time savings of 5 minutes to 25 minutes have been reported for those switching from the free routes to the tolled routes (e.g. Mekky, 1995, 1996, 1997; Tretvik, 1993). This aspect of tolled roads has provided valuable evidence on the trade off between travel time and money (value of time) (e.g. Tretvik, 1993; Mekky, 1995). These toll roads have also provided evidence on the effect of increased tolls on tolled facilities, with those on the margins being priced off from the tolled routes to the free routes.

However, the re-routeing effects of the classical case for road user charging, in which existing 'free' roads have direct charges introduced are less clear. This is more so for area wide pricing schemes in urban areas. In these schemes, re-routeing to avoid the tolls is often a ‘driver initiative’ rather than the objective of the network operator. The consequences on the network of such reassignment may range from very modest overall network reduction in vehicle hours rarely exceeding 5% (although this may be higher within the charged area) to altogether a deterioration in the overall network performance. This is because of possible transfer of charge-avoiding traffic to unsuitable roads. Cordon tolls in particular, have the potential to transfer congestion to the roads just outside the tolled cordon; the so called 'boundary' effect. Some researchers (e.g. May and Milne, 2000; Tolofari, 1997; Gower and Mitchell, 1998) have highlighted this problem. Boundary route delay increases as high as 100% have been reported in the literature. In the case of May and Milne (2000) the overall network effects of such increases were not very detrimental to the network with net gains sometimes being obtained in network performance at low tolls. This was because of the availability of substantial spare capacity on these outer orbitals. Research by Gower and Mitchell (1998), however, has shown that this is not always the case especially as such re-routeing effects have the potential to cause queues to build up at junctions as the toll level increases resulting in a net decline in network performance. Net total network journey time increases of up to 6.4% and total delay increases of up to 42% were estimated by their modelling. Although there was some concern about the extent to which this was a genuine outcome rather than a modelling shortcoming, repeating the modelling on a different network showed that this was indeed a potential genuine effect.

Modelling of different cordon toll scenarios in this research has similarly shown that for an inelastic matrix, re-routeing effects can indeed result in adverse overall network performance in so far as the total network delays and total network vehicle hours were concerned. It was found out that the network performance were particularly worse at high charge levels because delays increased rapidly as the capacity of junctions was expended on the boundary routes. Single cordons were seen to cause less increases in vehicle hours than multiple cordons because they intercepted and diverted less traffic than multiple cordons. However, low charged multiple cordons were found to have vehicle hour increases similar to those of single cordons, but to generate the most revenue. For the single cordon schemes, the CBD performed best in terms of total network vehicle hours, while the mid cordon caused the largest increase in total network vehicle hours. It was argued that although the external cordon intercepted the most number of trips at all charge levels, its potential was more that of revenue generation than behavioural change since most trips within the Southampton network would not be affected by it. Generally, different cordons or cordon combinations had their strong and weak points and therefore performed better than others when evaluated on certain parameters areas and worse when evaluated on others. The differences in performance of different cordon scenarios when considered on different criteria is consistent with literature evidence. May and Milne (2000) for example, found that different pricing regimes performed differently against different performance indicators, and therefore argued that guidance was needed on the most appropriate objective functions for measuring network performance.

Multiple cordons generally performed worse than single cordons when evaluated on total network vehicle hours. However, multiple cordons generated more revenue than single cordons because they intercepted more trips. The perceived costs of multi-cordons were also generally higher than those of single cordons. One can therefore argue that the worse performance of multiple cordons when evaluated on total network vehicle hours and on perceived costs, is an indication of their potential to cause elastic responses in real life. Thus the extent of the network deterioration under the fixed matrix assumption, can be interpreted as a measure of the potential for elastic behaviour under such adverse network costs. Although results in this research suggest that combined cordons are better placed to encourage both elastic behaviour and also generate more revenue than single cordons, practical considerations such as costs and potential opposition by the public, may favour the initial implementation of single cordons such as those around the central business districts of cities (e.g. ROCOL, 2000).

Analysis of some O-D pairs showed that travel time savings in excess of three minutes were possible for the Southampton network. However, the travel time savings were less than the tolls paid. The fact that perceived costs were higher after tolling than before tolling, even for O-D pairs experiencing reduced travel times also confirms this. The finding that equivalent monetary travel time savings for those able to pay would be less than the direct charges paid, is consistent with literature evidence.

In the next chapter the potential network effects of elastic responses such as peak spreading and trip suppression are considered for the Southampton network as a whole. Such scenarios aim to establish an upper bound figure for the potential network effects of responses to TDM measures such as road user charging. Scenarios in which specific O-D pairs are suppressed are also briefly considered following the findings from this chapter. It was argued in this chapter that radial trips into charged areas would be unable to re-route and so some drivers using tolled links were likely to respond elastically in real life, than pay the tolls as is the case with inelastic modeling.

6 ESTIMATING THE NETWORK EFFECTS OF ELASTIC IMPACTS

6.1 Introduction

In this chapter some modelling scenarios of a 'what if' nature based on assumptions about the road pricing scheme, and the behavioural impacts that might arise, are defined. The scenarios are tested using the Southampton network. Road pricing is used here as a TDM measure that can potentially result in the specified travel behavioural responses and hence changes in network performance.

The literature is quite unanimous that where re-routeing opportunities exist, travellers will, where ever possible, first change their route rather than retime their trips, change their mode or destination or fore go their trip (e.g. Bonsall et al, 1998; Eurotoll Project Report, 1999 @ http://www.hhh.umn.edu/centers/slp/conprice/euro.htm; Hayes et al, 1999). There is some evidence in the literature, however, to suggest that where such re-routeing opportunities do not exist, or are infeasible, other impacts other than re-routeing may take place (e.g. Hayes et al, 1999; Adcock, 1998; Hecker and Schnittger, 1997; Hug et al, 1997). This could arise due to a variety of reasons including network structure or configuration. The City of Bergen is a classical example. The city is cited in a valley surrounded by mountains. Radial routes lead into the city and only 10% of the population live inside the cordon area while 90% live outside it. The valley nature of the city with radial routes leading to the city imply that no re-routeing opportunities exist and travellers not willing to pay have to change their destination, retime their trips, change mode or not travel at all. In Trondheim the impacts were predominantly trip retiming while in Oslo destination changes of discretionary trips was evident. These responses were mainly consistent with the design of the schemes. These examples show that travellers do respond to pricing measures in ways other than re-routing alone. Other examples include the Bristol ELGAR demonstration trials where incentives for using public transport were offered. Making public transport free to trial participants made mode change to public transport no more expensive than re-routeing to avoid the charges (Adcock, 1998; Hayes et al, 1999). Also evidence from the time dependent Sunday/weekend pricing scheme on the A-1 freeway outside Paris, showed that little or no diversionary impacts had occurred. Instead trip retiming was the major impact. This appeared to have been due to the inferior nature of the free parallel arterials compared to the motorway as well as the scheme design which encouraged retiming (TRB, 1994). These examples are thus illustrative of the possibility of pricing schemes in causing elastic responses.

6.1.1 Core Questions Addressed

This chapter, seeks to shed light on a number of key questions about the potential network effects of specific behavioural responses to TDMs such as road user charging rather than on the prediction of these impacts. Core questions include:

What would the network effects be if travellers responded by:

1. peak spreading?
2. trip suppression?
3. through a combination of behavioural changes?

The need for answers to questions 1 to 3 addressed in this chapter is supported by Harvey (1994) who noted that apart from the question whether there is indeed a price elasticity in urban transportation, there was a need for answers to the nature, magnitude, and distribution of benefits from pricing in general and from the implementation of individual measures in specific contexts. Examples from the literature as illustrated above show that travellers do respond elastically to TDM measures such as road pricing especially where alternatives are made available and/or disincentives to the SOV are put in place. There is therefore some elasticity in urban transportation even though this is in the inelastic range; -0.10 to –0.15 at the low end to –0.30 to –0.5 at the upper end depending on the charge, current costs of travel and the capacity of alternative roads and transit systems (TRB, 1994, Bhatt,1994b, Goodwin, 1992, Oum et al, 1992). As to the question of the nature, magnitude and distribution of benefits, Harvey noted that although arguments based on intuition shed light on the direction of change under TDMs such as pricing, little tangible evidence existed to the exact question of the magnitude of benefits from these measures. This was in part due to the wide range of potential behavioural responses and to the uncertainties relating to specific aspects such as the spatial, technological and demographic contexts of the schemes. This made it difficult to provide generic answers.

To circumvent the problem of dealing with the possible myriad of responses, this research has assumed the nature of the response by posing the question 'what if travellers responded in such a way?'. This is not altogether an unreasonable assumption because evidence suggests that a TDM measure usually results in a primary behavioural response and a series of secondary responses (e.g. Johnston and Rodier, 1994; Harvey, 1994). The primary response is the predominant one and can be expected to influence the magnitude of the network effects. Thus a differential pricing scheme will mainly result in retiming and hence peak spreading although some secondary responses such as mode changes or trip suppression may also be evident. By making assumptions about the road user scheme, difficult and uncertain modelling issues such as technological, socio–demographic and economic variations, and spatial coverage can also be circumvented. The Southampton network is used as a case study.

6.1.2 General Assumptions for the Elastic Modelling

Consider the simple equation:

$T_{ijk} = f\,(c_{ijk})$ where:

f is a decreasing function of cost and $T^0{}_{ijk} = f\,(c^0{}_{ijk})$ where

$T^0{}_{ijk}$ is unrestrained base year demand in time slice k given base year costs $c^0{}_{ijk}$ in time slice k.

It can be expected that the travel market that can potentially respond to a TDM measure such as road user charging is that which is directly affected by such a scheme i.e. experiences an increase in c_{ijk}. A motorist is affected by a pricing scheme if they spatially encounter (O_i -D_j) such a scheme at the times of day at which it is in operation. Thus a CBD cordon may affect certain O_i–D_j movements but not others and only those O–D movements affected can be expected to potentially respond. For example, one conclusion about the impact of the Trondheim Toll Ring on travel behaviour was that the impact of the toll ring seemed greatest on those who lived outside and worked inside the toll ring

(Meland and Polak, 1993). This was considered a consequence of both the spatial structure and the directionality of charging. The market that can potentially respond can therefore be expected to increase with increased geographic coverage of the scheme (e.g. Lari and Buckeye, 1997; Tolofari, 1997) and this can potentially approach 100% of the O–D movements if the scheme is so appropriately designed. Within the affected O–D movements the propensity to respond and how depends on the elasticity of each individual or broadly the elasticity of specific market segments of that total travel market. Since this travel market can be considered to be heterogeneous, there will be variations in this elasticity according to the market segment, with some market segments being totally inelastic and therefore continuing to travel as before, while some market segments will be totally elastic and therefore be priced off the network. The distribution of elasticity estimates within the travel market will thus influence the magnitude of the travel market that changes their travel behaviour. However, data on detailed disaggregate elasticity estimates or the distribution of these elasticity values within the travel market are scarce in the literature (e.g. Brown et al, 1993; Ghali et al, 1998). Often, aggregate elasticities are assumed (e.g. Smith et al, 1994; Milne, 1997). There are, however, those who argue that the adoption of aggregate elasticity estimates underestimates the potential for fiscal measures as TDMs leading to the misinterpretation that such measures are a poor policy lever of arresting traffic congestion (Pucher and Rothenberg, 1979; Chan, 1991).

Because CONTRAM is an inelastic assignment model and is unable to capture or represent these issues, it is necessary that assumptions are made about these issues in the modelling. Since the task here is to estimate the potential upper bound network effects, it can be expected that a scheme affecting most or all of the O–D pairs will result in the most possible reduction in travel demand (T_{ij}) because each O–D pair will experience an increase in (c_{ij}). Schemes with less geographic coverage can be expected to reduce travel demand to a lesser extent and hence yield network effects between those of the base case scenario and those defined by this upper bound limit for a given network at a given congestion level.

Additionally it can be assumed for simplicity that the socio–economic characteristics of the areas i.e. zones is similar. This implies that the proportion of poor, rich and medium and hence the distribution of values of time is the same in all areas. The effect of this assumption is that similar suppression levels can be applied to all zones and thus simplifying the modelling task. In reality certain zones have higher proportions of low income earners, high income earners or mid income earners (e.g. Smith et al, 1998). Thus the most suppression can be expected from low income earners and the least from high income earners. The distribution of these groups within each zone would affect the extent of suppression within each zone while the spatial orientation of the zones into poor, mid and rich could affect the 'spatial' patterns of response and hence travel as a result of direct user charging. Other factors that could affect the extent to which specific zones are sensitive to the charging scheme is the dominance or lack of dominance of a specific mode (e.g. Soberman and Miller, 1998). For example zones with a high dominance of PT use will contribute little to further car trip suppression. Zones with a high car dominance may potentially contribute more to car suppression but may be constrained by lack of alternative modes or because such markets tend to be wealthier, they may tend to be inelastic. The resources available for this study did not extend to the collection or availability of the data that would be required to explore these issues.

6.2 Peak Spreading

The next sections are a review of issues on departure time choice since it is this retiming response that often leads to peak spreading. Later the network effects of assumed peak spreading levels are estimated using CONTRAM.

6.2.1 Issues in Modelling Departure Time Choice

Departure time choice is second to route choice as the most common driver behavioural change (Van Vuren, 1995b; SACTRA, 1994; Delons, 1997). Interest in modelling departure time choice and hence peak spreading is high (e.g. De Palma et al, 1997; van Vuren et al, 1999; Yamamoto et al, 2000a,2000b).

6.2.2 Factors affecting propensity to change departure time choice

Peak spreading implies a change in the temporal distribution of demand due to a variety of reasons as people change their departure times. In the general case departure time changes arise out of a desire by travellers to minimise the amount of time they spend in congested traffic conditions. This view is generally consistent with the DOT's definition, that 'the term peak spreading refers to a reduction in the proportion , though not usually the absolute quantity of traffic in the most congested part of the peak period, with corresponding increases immediately before and after the height of the peak' (DOT, 1996). But it could also occur as a result of transport policy measures such as differential road pricing or regulatory measures such staggered working hours. It is necessary to point out here that peak spreading in this work refers to 'active' peak spreading where travellers make active decisions to retime their trips as opposed to the 'passive' case where increased congestion in mid peak periods affects traffic flows in subsequent periods (e.g. Hounsell, 1991; van Vuren, 1995b).

The factors that can influence the propensity for departure time choice changes have been reported by Chin (1990), Hendrickson and Plank (1984) and De Palma et al, (1997) amongst others. These factors can be divided into demand based factors and network based factors.

Demand based factors include:

- Institutional factors such as;
  Official work start times–were these are constrained, opportunities are also limited
  Staggered working hours, flexi time and compressed work weeks and other alternative working schedules (AWS) are regulatory measures that increase the opportunities for departure time choice –more than 50% of employees have been known to switch their work schedules to earlier start times in response to alternative work hour programmes Chin (1990).
- Socio-Demographic factors such as: type of occupation, trip purpose, income and the trade off between travel time and work arrival time, uncertainty in arrival time, age, family status, sex, long versus short commuting times, household–workplace location relation etc.

- Socio–economic variables such as income, employer travel assistance e.g. company car and expenses.
- Mode factors such as car availability, mode used (car users have more flexibility while bus users dependent on bus schedules), and mode service levels

Network based factors include:

- Schedule delay
- Travel cost
- Journey time and journey time variability
- Differential toll charges
- Differential parking charges
- Time dependent parking availability
- Congestion level
- Length (time) of congested conditions

Given the different variables affecting departure time choice, the task of predicting the temporal distribution of demand is not a simple one. Nevertheless, there is evidence in the literature of the occurrence of trip retiming. However, this evidence, which reports of shifts of up to 50% or more rarely reports evidence on associated network benefits.

6.2.2.1 Concepts and Cost Functions in Peak Spreading

The cost constraints that are usually considered in the modelling cost functions as influencing departure time choice in the literature are (Allam & Alfa, 1992):

1.The cost associated with early arrival (i.e. time spent spent at work before work start time).

2.The cost associated with late arrival. Both these times are usually considered as penalties. It is generally considered that the late arrival penalty is more onerous than the early arrival penalty because the late arrival may extend into what is supposed to be time at work.

3.The cost of travel time from the origin to destination.

It is assumed that travellers have an indifference window within which they would prefer to arrive. This maybe a unique time or a band within which no penalties are incurred (e.g. Alfa, 1986; van Vuren, 1999).

Some modellers have only considered the costs in (3). Some modellers fix or constrain the arrival time and only consider the cost of early arrival and the cost of travel time. Most modellers have considered a linear combination of (1), (2) and (3).

Alfa (1986) derived a general cost function of how a traveller perceives travel cost if they have to arrive at the destination within a required time window of destination target time (DTT). The equation was derived for a single O–D pair connected by one route with a bottleneck in between and was of the form:

$$C(t) = C_w(w(t)) + C_e(t_D - t_a(t))^+ + C_r(t_a(t) - t_D)^+ \qquad (1)$$

Where

$C(t)$ = total perceived cost to the traveller;

$w(t)$ = delay at a bottleneck and may include line haul times – it basically represents the travel time between O to D;

t_D = target or desired arrival time at the destination (DTT);

$t_a(t)$ = is the actual arrival time at the destination;

C_w ,C_e, C_r = are coefficients or weightings attached by the traveller to the respective terms- namely travel time, early arrival time and late arrival time.

The cost for arriving early is thus equal to $C_e(t_D – t_a(t))$ since the actual arrival time $t_a(t)$ is earlier than the targetted arrival time t_D.

The cost for lateness is thus equal to $C_r(t_a(t) - t_D)$ since the actual arrival time $t_a(t)$ is later than the targetted arrival time t_D.

Hendrickson and Kocur (1981) derived a cost function for the case of a bottleneck with tolls as:

$$UC(t) = a_0 + a_1 r(t) + a_2 s(t) + a_3 p(t) + f(t) \qquad (2)$$

where

- $UC(t)$ = user cost
- t = arrival time at bottleneck
- $r(t)$ = queuing time at bottleneck (min)
- $s(t)$ = schedule delay or early arrival time
- $p(t)$ = late time
- $f(t)$ = monetary toll or fare per traveller in cents
- a_0 = fixed time and money costs of travel to work in cents and includes user costs associated with vehicle ownership, vehicle operating costs and the uncongested travel to the bottleneck facility
- a_1 = user cost of queuing time in cents/min
- a_2 = user cost of schedule delay or early arrival in cents/min
- a_3 = user cost of lateness in arrival at work in cents/min

In the user cost equation, early arrivals incur a schedule delay or early penalty given by:

$$s(t) = \begin{cases} B - t_w & \text{if } t_w < B \\ 0, & \text{otherwise} \end{cases} \qquad (3)$$

Also late arrivals incur a lateness penalty given by:

$$p(t) = \begin{cases} t_w - B & \text{if } t_w > B \\ 0, & \text{otherwise} \end{cases} \qquad (4)$$

B = work start time

t_w = arrival time at work.

Note that t_w in equations (3) and (4) above by Hendrickson and Kocur (1981) is the same as $t_a(t)$ in equation (1) by Alfa (1986).

Appropriate modifications to equation (1) should yield the user cost for the cases of:

(a) On time arrival at work in a no toll situation as is currently common

$$UC(t) = a_0 + a_1 r(t) + a_2 s(t) \tag{5}$$

(b) Late arrivals permitted but with a penalty in a no toll situation

$$UC(t) = a_0 + a_1 r(t) + a_2 s(t) + a_3 p(t) \tag{6}$$

To apply these models, it is necessary to determine the coefficients a_1, a_2 and a_3. This is usually not a straight forward task.

In their model of peak spreading Allam and Alfa (1992) assumed a linear cost function of the form:

$$C_i = A(TT_i) + B_l(DT_i + TT_i - W_e)^+ + B_e(W_b - DT_i - TT_i)^+ \tag{7}$$

C_i = the cost to vehicles leaving for work in time interval i

TT_i = the travel time for vehicles leaving in time interval i

DT_i = the assumed departure time for vehicles leaving in time interval i

W_b = is the earliest desired arrival time

W_e = is the latest desired arrival time

A = coefficient expressing the relative weights of the cost of travel

B_e = coefficient expressing the relative weight of the cost of early time at work

B_l = coefficient expressing the relative weight of the cost of late arrival at work

The superscript + implies that only positive values are considered otherwise the value is taken as 0. In other words, if one is late, the fist term $B_l(DT_i + TT_i - W_e)^+$ applies and if one is early the second term $B_e(W_b - DT_i - TT_i)^+$ applies.

The costs associated with time of arrival are not necessarily linear but can have complex distributions such as parabolic variations. As has been mentioned earlier, modellers have tended to include schedule delay (early or/and late arrival penalty) and travel costs (with or without tolls) in the utility function of departure time choice. Chin (1990) also included a 'Total cost divided by Household income' in order to provide a household income effect on travel cost given the relative effects of different departure times. Given the different variables affecting departure time choice, the challenges and uncertainties to the modelling departure time choice and hence peak spreading are put into perspective. Nevertheless, there is evidence in the literature of trip retiming and for countries whose societies have high levels of car ownership and use, such modification to travel behaviour have long been considered a more likely response than trip suppression mechanisms such as modal changes which were significantly pronounced in Singapore and the Hong Kong trials for example (Dawson, 1986; Hayes et al. 1999). However, this evidence, which reports of shifts of up to 50% or more rarely or fails to provide evidence on the extent of the network benefits thereof. Therefore an understanding of the potential on network performance of peak spreading is thus vital.

6.2.2.2 Predicting the Temporal Distribution of Demand

Once the temporal distribution of costs are known using the cost function, the problem becomes one of determining the Volume V_i' in time slice i. Modelling thus, concentrates on predicting the temporal distribution of demand from the cost structure. This can be done in a number of ways depending on the assumptions of how travellers perceive this cost and how the cost affects their decision. Alfa (1986) considered three such ways or modelling principles:

- Deterministic User Equilibrium (DUE) Model: analogous to Wardrop's first principle of route choice, this approach assumes that at equilibrium no traveller can reduce their total cost by changing their departure time. This model assumes that users have perfect knowledge of system costs i.e. travellers have perfect knowledge of delay in the system at each time during the peak period. This assumption is clearly an oversimplification since travellers may have inaccurate and distorted perception of travel time and because of the stochastic variation in travel time over different days for the same time of the day. This approach has been applied by for example Hendrickson and Kocur (1981) and by Allam and Alfa,1992).
- Stochastic User Equilibrium (SUE) Model: this recognises the inaccuracies and distortions in in travelers' perceptions of travel costs. Stochastic models are more realistic than the deterministic approach for simulating commuter decisions in selecting departure time choice. The model gives as output, the probability (P_t) that a traveller chooses to depart from O at time t. The stochastic approach is computationally more cumbersome than the deterministic approach. This approach has been applied by e.g. (Alfa and Minh, 1979).
- System Optimal (SO) Approach: This is analogous to Wardrop's second principle of route choice and assumes that commuters select their departure times in a manner such that the total cost to all commuters is minimised. This prescriptive approach is unlikely in practice since commuters do not generally behave as suggested by such a system optimal approach.

The above approaches are by no means the only principles employed to predict the temporal distribution of peak traffic demand. The DOT's manual for example outlines a number of methods for incorporating peak spreading into urban traffic models i.e. methods for predicting the temporal distribution of traffic demand during the peak period. These emanate either from the literature or from contract work done on behalf of the department or both. The methods are briefly described below. Further details are described by van Vuren et al, (1995b).

- The one used by Stebbings (1988) at the Greater Manchester Transportation Unit (GMTU). In this method, a linear relationship was derived between the percentage of overall peak period traffic occurring in the peak hour, and daily or peak period traffic growth. Therefore, ratio of peak hour traffic to peak period traffic is the dependent variable of this linear relationship. The independent variable is the daily or peak period growth factor. The major disadvantages of the GMTU method is that the resulting relationships are not applicable outside Greater Manchester. Local relationships are needed outside Greater Manchester, and these may not be linear. The method may lead to unrealistic peak hour proportions when extrapolated into the future.
- A methodology based on work done for the TRL by Hounsell (1991). In addition to exploring the GMTU method, Hounsell also investigated a method based on studying past traffic growth trends in short periods within the peak period, relative to the growth in the peak period as a whole. As with the GMTU approach, Hounsell's method suffers from the disadvantage that relationships are not necessarily transferable from one location to another. The method also suffers from that trends in the past, are assumed to be applicable to the future.
- A relationship developed by Goodwin and Coombe (1991) while at Halcrow Fox. The method was developed using data from a number of towns with different levels of congestion. It is suitable for general application rather than specific to one place. In the method, a relationship was developed between the peak period ratio (defined as the ratio of the flows in the adjacent two half-hour periods to the flow in the peak hour) and the average peak hour speed in the modelled network. The disadvantages of the method are that it is based on empirical cross-sectional analysis between a limited number of sites and no long term data. The method also assumes that each peak period is two hours long. The relationships involved would have to be re-calibrated to accommodate longer or shorter peak periods.
- Count Based Models. As with the GMTU method, count based models estimate a functional relationship the between peak hour to peak period ratio and explanatory variables for congestion in the network, using local count data. However, they employ a negative exponential relationship rather than a linear relationship

between the dependent and explanatory variables. The explanatory variable is the ratio of the peak hour volume to capacity ratio (v/c). A disadvantage of the method is that it provides information about the reduction in demand in the busiest hour, but not about the shoulder to which this traffic is traffic is transferred.

- In Proportionate Models, Stated Preference or other techniques are used to determine the proportion of drivers who when faced with a pre-specified level of congestion would set off earlier, rather than later. A utility function is built incorporating such a mechanism. This is a method still undergoing further research.
- Multi–Period Equilibrium Models aim to model the choice of time period in an overall peak period by relating increasing congestion and increasing travel times to a shift from the desired time period to an earlier or later period with less congestion. There is a penalty associated with this shift. This penalty expresses drivers' reluctance to shift from their desired time periods. Multi-period models are similar to the shadow network approach explained earlier in Section 3.4.1. They employ extended networks, which in this case represent alternative departure times. A disadvantage of these models is that historic data covering a number of years during which drivers were known to shift their time of travel is required to calibrate the models. Such data may not be available.
- Incremental Logit Models of Departure time Choice can be based on either absolute cost differences or on cost ratios. The concept behind these incremental logit models is that changes in travel costs per time period are assumed to influence the spread of demand over the peak period. An observed base year profile is taken as the base year profile is taken as the reference profile and after assignment gives rise to base year costs per O-D pair in each time period. These base year costs form the pivot from which the target year profile can be determined given target year costs. Whereas the model based on absolute cost differences would shift long distance trips first, the model based on cost ratios places a greater emphasis on short distance travel. A disadvantage of incremental logit models is that local specific parameters need to be determined by calibrating the logit models using a

trial and error approach using count data at least three years apart (see Chin et al, 1995).

- A more recent methodology was described by van Vuren et al, (1999) based not on discrete but continuous shifts in demand. The method is based on equilibrium scheduling theory in which the combined generalised cost of arrival time and travel time is equal for all travellers within each separate demand segment of a given O-D pair. The method accommodates the possibility that travellers have an indifference band around their preferred arrival time. Arrivals within this band do not incur any schedule disutility. Preferred arrival time data is required for this method. Such data is not usually available since it is common for travel surveys to collect information on actual time of arrival of a trip than to collect information on preferred arrival times.

Although each of the methods outlined above are evidence of advancement in the understanding of predicting the temporal distribution of demand, there are a number of disadvantages that have been highlighted above about these methods as well. Needless to say that the need for extensive data, which may span a number of years is obviously one such problem.

The DOT also recognised the potential for employing manual or automated methods of applying factors to the demand matrix in order to adjust the proportion of the peak period traffic allocated to specific time slices of the peak period (DOT, 1996). For the purposes of evaluating the potential of peak spreading to improve the performance of the network, such a methodology is attractive because more effort maybe placed on the objective of network analysis rather than on the predictive task. The literature may be used to provide guidelines as to the criteria for allocating this temporal demand of traffic to simulate peak spreading. In theory such a methodology does not constrain the modeller as to the possible demand profiles since the modeller might assume any plausible peak profile on the basis of a 'what if' approach as is adopted in this work.

6.2.2.3 Peak Spreading Representation in CONTRAM

The review of the generalised cost or utility function showed that three primary cost components affect peak spreading:

- the cost associated with early arrival;
- the cost associated with late arrival;
- the cost of travel time and fixed costs plus direct charges from origin to destination.

The literature notes that there is uncertainty as to the weighting of these costs and hence in calibration of the utility or cost function and hence in ascertaining the demand profile. Another uncertainty is the relationship between these costs and the number or proportion who choose to travel in the given time period and also whether these costs are linearly related or not. To avoid these uncertainties this modelling assumes the demand profile based on guidelines in the literature rather than predict it (e.g. Yamamoto et al, 2000a,2000b; De Palma et al, 1997, van Vuren , 1999)

Three main profiles might result:

1. If the early arrival penalty is weighed equally to the late arrival penalty, there is an equal chance that as many travellers choose to travel earlier as those that choose to travel later.
2. If, however, the penalty for late arrival is more onerous than that for early arrival, most travellers changing their departure time may be expected to travel in the pre peak shoulder. In a stated preference survey reported by Yamamoto et al, (2000a,2000b) to evaluate responses to hypothetical tolls on freeways with alternative free surface streets, 6.8% of the 409 respondents said they would travel on the charged road before the pricing (travel earlier) compared to 1.5% later. This seemed to suggest in this study that leaving earlier was preferred to leaving later although the authors did not state why this was so for this particular group of respondents.

3. If, however, as might be expected for discretionary trips, the early arrival penalty may be worse than the late arrival penalty, then one would expect most choosing to switch to travel in the post peak shoulder or post peak period.

A fourth dimension affecting all three aspects above is the magnitude of the shift from the current habitual day to day travel pattern of the traveller. For example Johnston ,(1991) and Zupan, (1994) suggested that there is a trade off between travel duration and the travel period in which the trip is undertaken. The fact that travellers do not undertake their journeys very early or very late when most roads can be expected to be unutilised shows that travel duration minimisation alone is not the overriding criteria but also the utility associated with travelling at one's desired travel period. De Palma et al, (1997) concluded from revealed and stated preference surveys in Brussels that, the fact that shift workers with the option for flexi time were no different in their departure time behaviour than other commuters was because habit and or other issues of convenience were more important than travel time savings. The implication and suggestion in the literature is that shifts in departure time choice of half an hour to one hour are possible while those beyond this maybe difficult to achieve (e.g. Ristau et al, 2000).

CONTRAM with its time slice nature allows trips to be shifted by small time periods into adjacent time slices. This is an improvement over simply spreading trips from the peak hour to say the pre peak shoulder or the post peak shoulder since in reality departure time choice is continuous rather than discrete because travellers can choose to delay or start their journeys by any period of time typically one minute or more (e.g. van Vuren, 1998; 1999). In CONTRAM shifts of the order of a typical time slice duration can be executed. This will be typically 5 to 30 minutes long (Taylor and Leornard, 1989).

In the O–D matrix adopted here, it was assumed that the commuters were equally likely to shift their departures times either forwards or backwards but within the boundaries of the two hour modelled peak period i.e. 0730 to 0930. This recognised the fact that most trips in this period would be arrival constrained but may also not be willing to shift to a much earlier time following the argument by Johnston (1991) on the trade off between travel duration and trip timing. Factors were then applied in CONTRAM by first suppressing various levels of the peak hour demand (0800 to 0900) using reduction factors and then redistributing this demand relatively equally to the pre (0730 to 0800) peak hour shoulder and the post (0900 to 0930) peak hour shoulder. This technically meant that the maximum shift possible would be a traveller shifting from the middle of the peak hour (0830) to either the beginning of the pre peak hour shoulder (0730) or to the end of the post post peak hour shoulder (0930). This is equivalent to a maximum shift of one hour which is well within the two hour practical shift suggested by the literature (Ristau et al, 2000)

In the actual modelling, however, the shifts achieved were smaller. This was because it was assumed that travellers shifting from the height of the peak hour would shift immediately to either the end of the pre peak shoulder or to the beginning of the post peak shoulder. This would be equivalent to a maximum shift of about 30 minutes. This would give elasticity estimates well within those suggested by the literature.

The level of peak hour suppression assumed varied up to 20% and was increased in magnitudes of 5% for simplicity. The maximum 20% suppression level assumed in this modelling even for other elastic mechanisms was consistent with literature evidence (e.g. Turner et al, 1999; Hayes et al, 1999, Ristau et al, 2000) and in the demonstration projects CONCERT, LERTS, ELGAR and TRON2. The highest tariffs tested in TRON2 and LERTS seemed to even suggest that suppression levels greater than 20% for regular car users were unlikely (Hayes et al, 1999).

6.2.2.4 Actual Demand Profile Manipulation

The base case temporal distribution of demand for the Southampton Matrix is given in Table 6.1. Assumed peak spreading scenarios in which various levels of car trips are suppressed in the peak hour and 'redistributed' to the peak shoulders are shown. The factors were applied to the O–D matrix using a spreadsheet. Since in theory peak spreading does not reduce the total demand but redistributes it in time, it is important to ensure that the same number of packets or vehicles in the various peak preading scenarios are retained equal to the number of packets in the base case profile. However, because the cell values in

CONTRAM have to be integers, rounding off was inevitable. This was found not to be the case at times, and by a trial and error means, the multiplying or reduction factors were modified upwards or lower until this condition was met.

The runs were repeated for congestion levels 10% and 20% above the base demand level i.e. 1.1D and 1.2D.

Pre Peak Hour Shoulder			Peak Hour	Post Peak Hour Shoulder					
Factors by which to multiply Time Slice				Vehicle Nos in T/S(2-9) for 100 Vehicles in Period 0730 to 0930					
T/S Boundary	0700 - 0730	0730-0800	0800-0900	0900-0930	0.5Hr	0.5Hr	1Hr	0.5Hr	
Pk Spd Lvl(%)	T/S1	T/S2-3	T/S4-7	T/S8-9	**T/S1(fixed)**	T/S2-3	T/S4-7	T/S8-9	T/S 10
0	1	0	0	0	**20.88**	23.66	55.58	20.76	n/a
5	1	1.06	0.95	1.06	**20.88**	25.1	52.8	22.1	n/a
10	1	1.12	0.90	1.14	**20.88**	26.4	50	23.6	n/a
15	1	1.17	0.85	1.20	**20.88**	27.8	47.2	25	n/a
20	1	1.23	0.80	1.27	**20.88**	29.2	44.5	26.3	n/a

Table 6.1. Peak Spreading Profile scenarios runs in CONTRAM

6.2.3 Assumptions about The Road User Charging Scheme

Firstly, it is assumed that a zonal charging scheme is in operation inside the whole area bounded by the M27 to the east and north, the M271 to the west and Southampton water to the south. In such a scheme, users crossing this cordon are charged. Further, users travelling within the cordoned area are also charged. It is assumed that these charges are based on the principle of reducing congestion and unlike the Norwegian cities, are high enough to cause responses of an 'elastic nature'. Also, it is assumed that the charges are differential over the charged peak periods in this case the 0730 to 0930 AM period for which we have data for the Southampton model. It is assumed for simplicity that the PM peak period is to all intents similar in its profile and duration as the AM peak. The maximum charges are assumed to occur in the peak hour 0800 –0900. (Time Slice 4-7). As a network wide pricing scheme, it is assumed therefore that every potential car user will be affected should they wish to travel by car and re-routeing is therefore not a feasible option. The magnitude of the charges are assumed to be high enough to cause 'elastic responses' consistent with the literature i.e. peak hour suppression levels of up to about 20%.

It is also assumed that the technology to implement such charges is in place and to all intents and purposes the charges are collected electronically. This ensures that toll gates or other manual means do not result in 'service queues' at charge points and that a working enforcement system is in place. Clearly, these are very simplifying assumptions in order to test the potential network effects of the assumed behavioural changes. A major problem of area wide schemes as evidenced by experiences in Singapore, Hong Kong ERP Trials, Trondheim toll ring in Norway for example is the potential for certain O-D movements to evade the charge points. It is assumed again that the necessary screen lines have been identified to make it impossible to avoid paying the charges.

For the Southampton network, these assumptions are reasonable. The network is predominantly radial with limited route choice options and well known bottlenecks (e.g. the Itchen Toll bridge, the Northam Bridge and Cobden Bridge. Therefore it is not difficult to envisage a scheme with no feasible options for re-routing operating on the Southampton network.

Evidently such a scheme is 'idealist' and to all intents and purposes defines the maximum potential benefits that could potentially arise from the Southampton network due to a pricing scheme that is designed to encourage peak spreading. In this context it does provide a means of quantifying the potential network effects based purely on efficiency, with no resource constraints, political or public acceptance or equity concerns.

6.3 Results of Peak Spreading

The results below are for the first case scenario where travellers were equally likely to shift their travel earlier or later.

Figure 6.1 Percentage Change in Total Network Vehicle Hours For Base Case

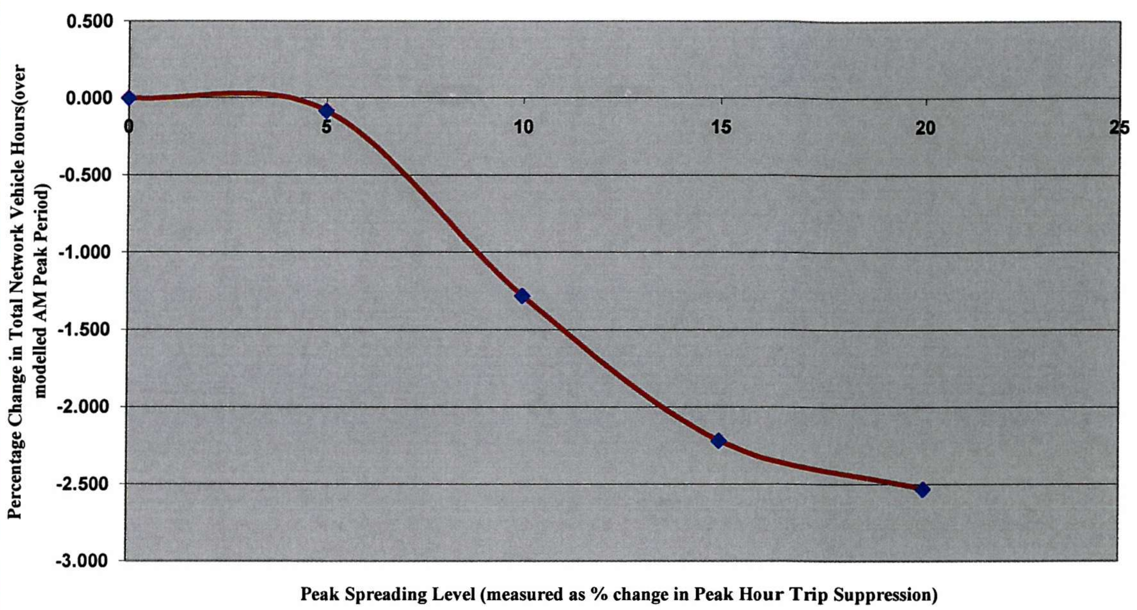
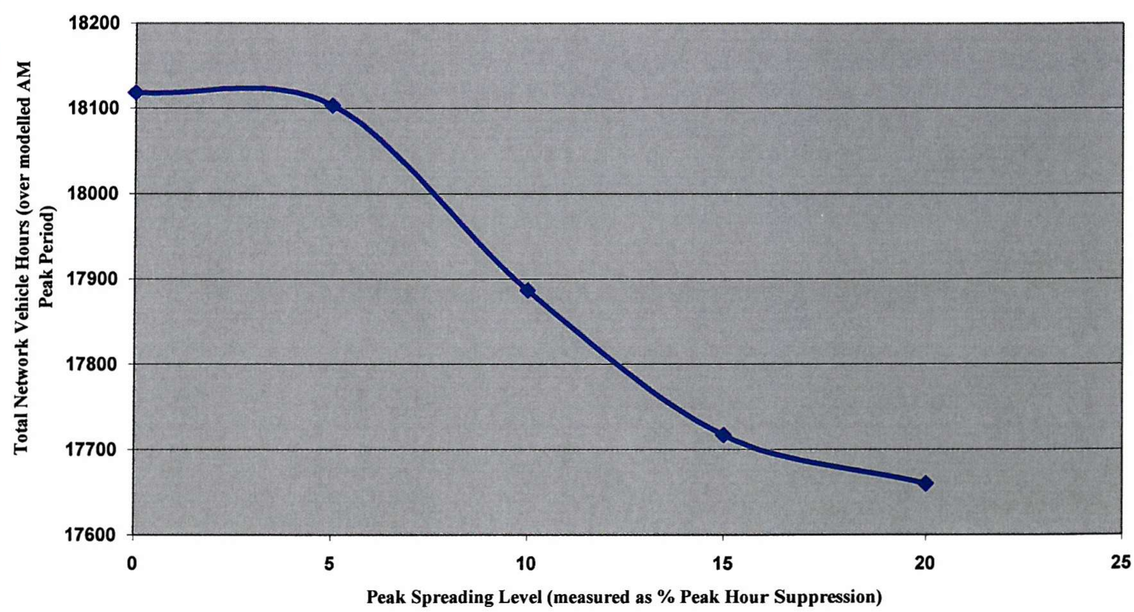
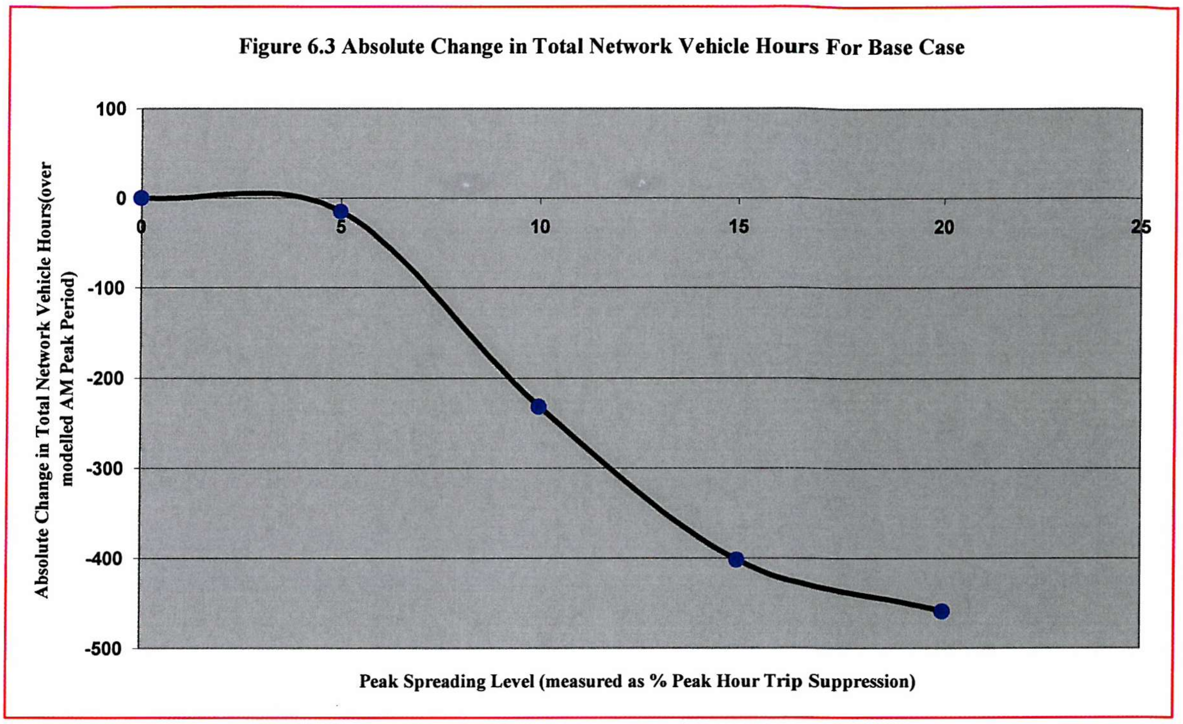


Figure 6.2 Change in Total Network Vehicle Hours (for 1D Base Case)





Figures 6.1 to 6.3 depict the changes in Total Network Vehicle Hours as the peak profile is flattened potentially due to differential peak pricing applied over the AM Peak Period 0700 to 0930. Since in principle, the actual number of vehicles is unchanged but simply spread over a wider time period, the decrease in Total Network Vehicle Hours is actually due to peak spreading. The total load on the network is unchanged in absolute terms but is simply spread out more over the modelled AM Peak Period.

Figure 6.1 shows that the percentage change in total network vehicle hours over the modelled period is just over 2.5% at the 20% suppression level. This is quite a small percentage change. Figure 6.2 shows that without peak spreading, the Total Network Vehicle Hours are just over 18 100 Vehicle Hours for the Southampton network. There is a small decrease in Total Network Vehicle Hours at 5% peak spreading. However, a relatively sharp decrease occurs between 5% and 15% peak spreading after which very little change appears to occur when peak spreading beyond about 18% is applied as seen by the flattening of the curve. This seems to suggest that for the Southampton network at this base case (1D or the based case Demand O-D matrix) congestion level, the most benefits (measured as a decrease in Total Network Vehicle Hours) accrue when peak spreading of

10-17% is applied. Very little benefits appear to accrue at the minimal 5% peak spreading level and also beyond the 18% level too. The minimal benefits at the 5% level could be explained by the fact that at this level of peak hour trip suppression, the 'load redistribution' is too low to yield tangible benefits. However, beyond this level and up to about 17%, the decrease in peak hour loading and its 'redistribution' to the peak shoulders is large enough to cause a significant improvement in the overall network level of service or performance. However, beyond 17%, although the peak hour continues to register some benefits, this is at the expense of the deteriorating conditions in the peak shoulders. This shows in a reduced net improvement for the overall network.

6.3.1 Absolute Changes in Total Network Vehicle Hours

Figure 6.3 gives the actual magnitude of decrease in Total Network Vehicle Hours. The Total Network Vehicle Hours decrease by about 15 Vehicle hours at 5% peak spreading to about 460 vehicle hours at 20%. This is equivalent to a decrease ranging from about 0.1% to 2.5% as shown in Figure 6.1.

If indeed 20% peak spreading were achieved for the Southampton network at this base case congestion level, the equivalent savings in value of time (VOT for an average car = 720.5 pence/hour or 12 pence/minute {see Section 5.3 for VOT adopted)) would approximate to £3 314.30 in the AM peak period or to £6 628.6 for both the AM and PM period assuming for simplicity that the two peak periods were reflections of each other. This assumption might give somewhat slightly larger estimates of the potential revenue because the majority of education trips for example, are made from the home during the AM peak period. However, most of these trips mainly return home in the inter-peak period rather than the PM peak period (e.g. Raha, 1997). For a 250 day working year the equivalent net annual savings in travel time would be £0.828M and £1.657M respectively. The literature suggests that it is mainly those unable to pay i.e. the 'poorer' motorists (e.g. commuters at the margins) who will be priced from the charged peak hour to the uncharged peak shoulders. If this indeed happened, the equivalent monetary savings in travel time could potentially be higher for the business community (working car) (and/or commuters with higher values of time) since their VOT is over thrice that of the average car (Transport Economics Note, 2001). The assumption is that it is such trips with higher values of time that will mainly be the winners of the improved network operation conditions in terms of decreased travel time in the 'desired' peak hour. Generally, the results suggest that for the Southampton network, the percentage reduction in the total network vehicle hours due to peak spreading would be quite small at normal congestion. However, the equivalent monetary value of time savings would appear to be appreciable especially if the 20% peak spreading scenario were to be achieved.

6.3.2 Temporal Variations in Benefits

The aggregate analysis above in Section 6.3.1 has considered the overall network effects over the whole modelled period. However, one would expect peak spreading to result in improved network conditions in the peak hour and reduced but not necessarily adverse effects in the peak shoulders. A temporal analysis of the distribution of benefits is therefore necessary in order to appreciate these temporal variations in network performance.

There is probably an obvious reason for such an analysis. Drivers prepared to pay and drive in the higher priced peak hour will enjoy the benefits of the improved network conditions in this 'premium travel period' as other drivers are priced off. These will be the main benefactors or winners of such a differential pricing scheme. On the other hand, drivers who already have been travelling in the less congested peak shoulders will notice an increase in network volumes or demand during this time. This could possibly result in a reduced LOS and these drivers will of necessity perceive themselves as losers. Drivers who have been priced off the peak hour to the peak shoulders can also be perceived as losers due to the differential pricing scheme. Such an analysis is consistent with May's (1981) comments when he wrote:

"It is obviously vital that time and operating cost losses incurred by those forced to change mode, route or time of travel do not exceed the benefits to those who experience reduced congestion or an improved environment".

In order to estimate these temporal issues for the base case scenario (1D), it was necessary to analyse the changes in time slice by time slice vehicle hours. The analysis here is confined to the time slices numbers 2-9 covering the period 0730 to 0930 (Table 6.1 in Section 6.2.2.4). It can be seen that the AM peak profile thus consists of a 30 minute pre AM peak hour shoulder (0730 - 0800), an AM peak hour (0800 - 0900) and a 30 minute post AM peak hour shoulder (0900 – 0930).

Figure 6.4 shows that before peak spreading, there are about 8,800 vehicle hours in the peak hour. There are about 3,055 vehicle hours in the pre-peak hour shoulder and just 3,540 vehicle hours in the post peak hour shoulder. It is apparent that there is a more rapid decrease in vehicle hours in the peak hour with increasing peak spreading, than there is an increase in vehicle hours in both the peak shoulders. This is clear from the steeper slope in the peak hour graph compared to the slopes of the other two time periods which appear to remain virtually flat. This can be explained by the fact that the congested peak hour is originally operating nearer the network capacity than the peak shoulders and there is an obvious relief in congestion in this period as soon as trips are suppressed from this period. On the other hand, there is clearly excess capacity in both the peak shoulders such that despite an increase in demand as a result of peak spreading, there is a less rapid increase in the vehicle hours in these time periods. Significantly, the implication is that at this congestion level, the rate of increase of disbenefits in the peak shoulders as a result of peak spreading is not as high as the rate of increase of benefits in the peak hour. Effectively, travellers originally travelling in the peak shoulders are not adversely affected by the 'redistributed' demand. There is thus at this congestion level, more benefits than disbenefits in encouraging peak spreading and this improvement is not achieved at the expense of the peak shoulder travel conditions. This net benefit as was seen earlier is about a 2.5% decrease in total network vehicle hours over the two hour modelled period.

Figure 6.4 Temporal Variation of Total Network Vehicle Hours

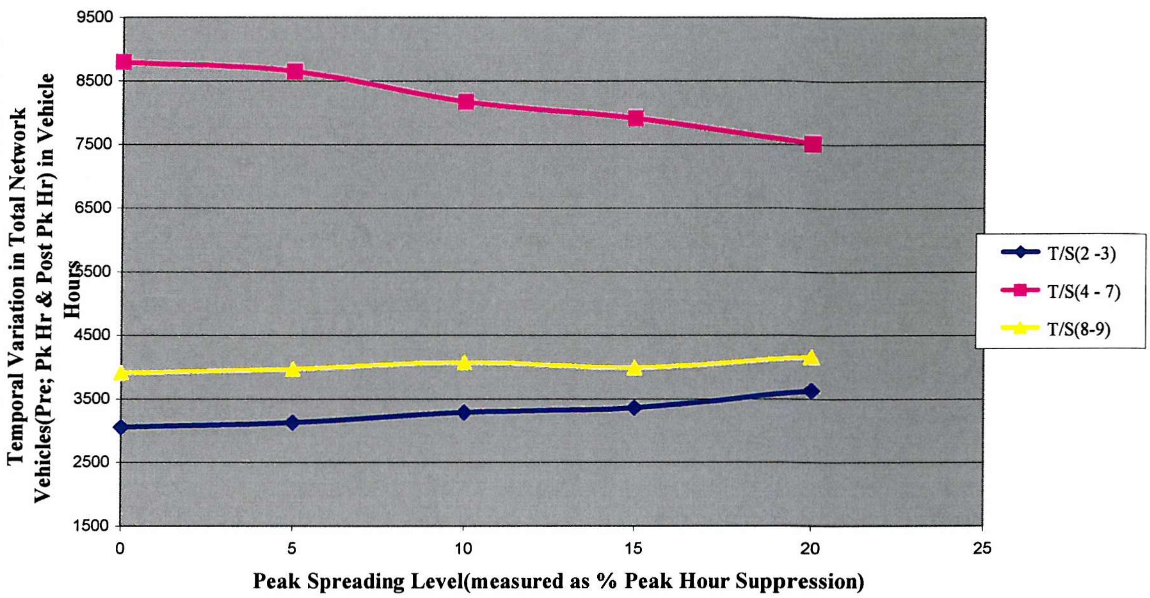
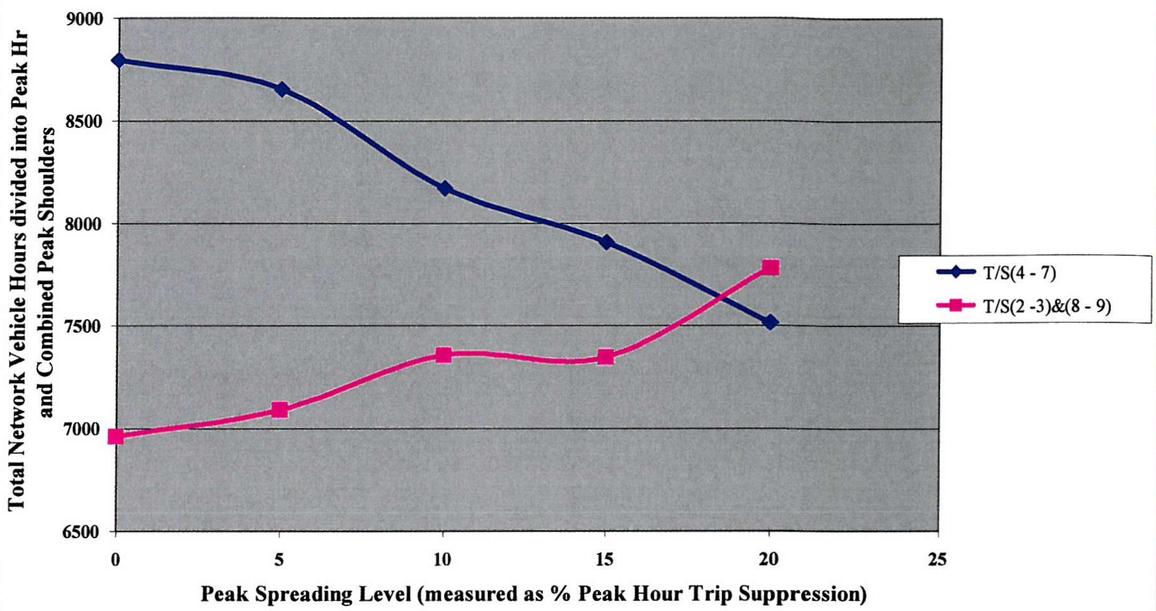


Figure 6.5 depicts the information in Figure 6.4 simply into peak hour versus both the peak shoulders combined. In this way the vehicle hours in the off peak and peak hour can be directly compared. It can also be seen from this Figure too, that the rate of increase in network vehicle hours in the peak shoulders as a result of peak spreading is less that the rate of decrease in vehicle hours in the peak hour. It is interesting though to note that the two graphs intersect at about the 18 % peak spreading level. At this point, the vehicle hours contributed by the shoulder time slices equal those contributed in the peak hour. This point can therefore be used to define the optimum peak spreading level. For peak spreading levels above this point, the decrease in peak hour vehicle hours, are being achieved at the expense of a deterioration in network conditions in the peak shoulders. This does help to explain why there is no appreciable overall network improvement after 18% peak spreading level as depicted in Figures 6.1 to 6.3.

Figure 6.5 Peak Hour v Combined Peak Shoulders Network Vehicle Hours

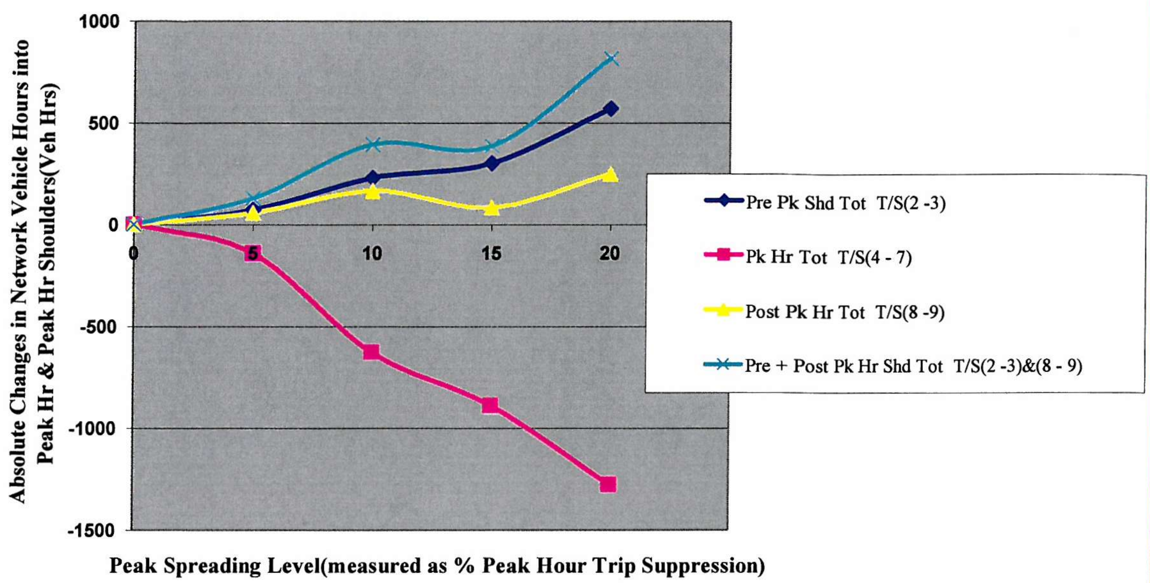


6.3.3 Absolute and Percentage Changes in the Peak Hour and Peak Shoulders

It is now necessary to study the actual magnitude and percentage changes in network vehicle hours over the peak hour and the peak hour shoulders.

Figure 6.6 shows that the reduction in peak hour vehicle hours due to peak spreading varies between about 143 vehicle hours at 5% to about 1,300 vehicle hours at 20% peak spreading. This is equivalent to a percentage reduction range of 2% to 15% as seen in Figure 6.7. Therefore, at this base case congestion level suppressing 20% of the car trips and redistributing them to the peak shoulders can potentially reduce the peak hour network vehicle hours by almost 20%. This is equivalent to value of time savings of at least £9,367 at the 20% suppression level assuming all drivers left have an average car value of time of 720.5 pence per hour. In reality one may expect this equivalent value of

Figure 6.6 Temporal Absolute Changes in Network Vehicle Hours



time savings to be considerably higher since as the literature suggests, it is those motorists with higher value of time that are unlikely to change their travel behaviour by opting to pay up instead. The equivalent annual savings are about £2.4Million in the AM peak period alone assuming a 250 day work day year. From a different view point, this monetary saving is at least the money saved by using the same available infrastructure capacity more efficiently through spreading the network loading instead of providing for infrastructure investment in order to provide extra capacity in the peak hour to achieve the same peak hour vehicle hour savings. An obvious inefficiency of having to provide this extra peak hour capacity, is the very likely under -utilisation of this capacity in the peak shoulders, which as was illustrated in Figure 6.4, already has considerable excess capacity.

As for the peak hour shoulders, Figure 6.6 shows an increase in network vehicle hours of between 71 at 5% peak spreading to 570 at 20% peak spreading for the pre-peak hour shoulder. The equivalent figures for the post-peak hour shoulder are 57 vehicle hours and 250 vehicle hours; - and for the combined peak hour shoulders are 128 and 820 respectively.

Figure 6.7 Temporal Percentage Changes in Network Vehicle Hours

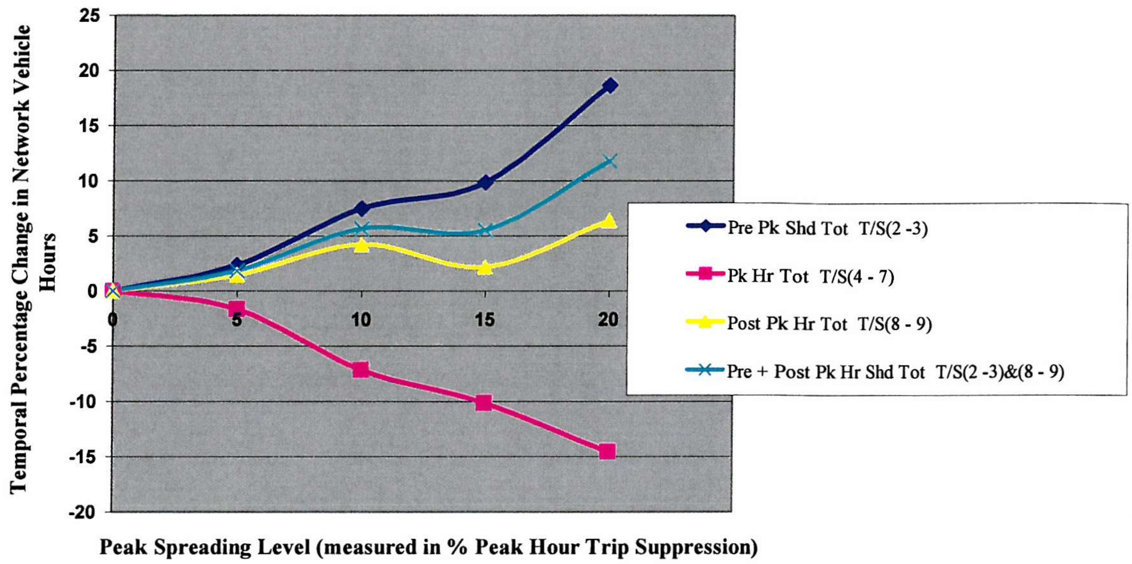


Figure 6.7 shows that this is equivalent to just over a 10% increase in vehicle hours in the combined peak shoulders. While the increase in vehicles hours in the combined shoulders is about £5,900 per day in the AM peak period alone or £1.5 Million per annum, in reality considering that there is still some excess capacity in the peak hour shoulders even after peak spreading (Figure 6.4), this apparent disbenefit represents part of the journey time costs that would be incurred anyway if the network was being used more efficiently. It thus does not represent a need to increase network capacity through infrastructure investment in this time period. Clearly, the argument might change if the differential pricing forces more drivers to shift to the peak shoulders than the capacity available in this time period in order to avoid the road user charge while excess capacity becomes available in the peak hour at the expense of the peak shoulders. Such a situation is undesirable but experience in Singapore showed this to be a possibility. Indeed evidence in the literature suggests that the need to avoid direct charges may weigh more on drivers' response to such charges than the need to save travel time (Burris et al, 2000). The authors found that variable pricing toll discounts offered to electronically paying drivers (i.e. tagged drivers -LeeWay System) but not to other drivers resulted in trip re-timing shifts by the tagged drivers only. Since Lee County, where the study was undertaken on the Midpoint and Cape Coral Bridges in

Florida did not suffer from severe congestion, the resulting traffic changes were considered to have been due to economic factors rather than the need to reduce travel time. Indeed, revealed preference surveys of those eligible for variable pricing discounts showed that 73% retimed their trips primarily to save money than to reduce their travel time. This result is even more compelling considering that the predominant trip purpose was commuting to work.

6.3.4 Winners and Losers: Value of Time Savings and Out of Pocket Costs

6.3.4.1 Peak Hour Winners

Table 6.2 shows that on average, journey time savings perceived by individual motorists able to pay and left travelling in the peak hour could range from negligible at the 5% suppression level, to nearly two minutes at the 20% suppression level. Such time savings can be expected to vary by O-D pair according to the changes in journey times on links used on chosen routes. Based on the average journey times mentioned above, the equivalent value of time savings would range from about 2 pence to just over 21 pence. This would be much lower than the direct out of pocket cost of £2 that could be expected as the typical charge for any car crossing a charged cordon at least once for a city the size of Southampton (e.g. Cheese and Klein, 1999). This would appear to confirm evidence from the literature that the equivalent value of time savings by paying motorists would be lower than the actual direct charge paid by these motorists (e.g. TRB, 1994). Table 6.3 appears to confirm this by showing the gross revenue to be much higher than annual value of time savings. For instance, at the 20% suppression level, AM peak annual gross revenue (used here as a measure of the direct out of pocket costs (OPC) paid as tolls) amounts to £22.1 Million, compared to £2.3 Million equivalent value of time savings enjoyed by the paying motorists. This gives a net equivalent 'monetary loss' of about £19.8 Million to the paying motorist. This point basically implies that for the Southampton network example, revenues generated will be much higher than the equivalent value of time monetary savings enjoyed by the paying motorists, in line with suggested evidence from the literature in general.

	Peak Spreading Level (measured as % Peak Hour Trip Suppression)				
ITEM	Base Case	5%	10%	15%	20%
No of Vehicles before peak spreading	47,750	n/a	n/a	n/a	n/a
No. of vehicles after peak spreading	n/a	47,463	46,317	45,219	44,157
Total Decrease in Vehicle Hours	0	143	626	887	1300
Aggregate VOT (average car) savings in £ (AM only)	0	1,030.31	4,510.33	6,390.84	9,366.50
Average decrease in vehicle hours/vehicle (seconds)	0	11	49	71	106
Average Equivalent VOT savings per vehicle in pence	0	2.2	9.8	14.2	21.2

Table 6.2 Peak Hour Decrease in Vehicle Hours for remaining drivers

	Peak Spreading Level (measured as % Peak Hour Trip Suppression				
ITEM	Base Case	5%	10%	15%	20%
Min. Potential Annual Revenue Generated (as measure of OPC) in £Million	0	23.7	23.2	22.7	22.1
Annual VOT savings (average Car) £Million	0	0.3	1.1	1.6	2.3
Net Monetary 'loss' for paying motorists £Million	0	23.4	22.1	21.1	19.8

Table 6.3 Peak Hour Value of Time (VOT) savings and out of pocket costs for remaining drivers.

The revenue figures in Table 6.3 are obtained by multiplying the number of car vehicles s paying (obtained from Table 6.2) by the toll charge. Therefore £23.7Million is calculated from:

£23.7M = 47,463 vehicles*£2/vehicle*250 days/year*1*10^{-6}

The £0.3M figure for the annual VOT savings is obtained as follows:

£0.3M = £1,030.31(from Table 6.2)*250 days/year*1*10^{-6}

The Net monetary 'loss' for motorists is therefore the difference:

£23.7M - £0.3M = £23.4M

The revenue potential of direct user charging schemes is thus quite evident from this simple analysis despite the much lower equivalent value of time savings. Cheese and Klein (1999) observed that the costs and potential revenue from a road charging scheme would depend on specific design issues such as the number of cordon/entry points, the level of enforcement effort envisaged, the charge, the technology employed in the vehicle, at the roadside and in the system management centre. Their Trafficflow study envisaged running costs of about £10 Million per annum for a city about the size of Southampton (after initial investment of about £18 million or a sixth of the £110 million initial investment expected for a central London scheme). They calculated that the net funds available for investment in local transport over ten years would be £140 million with a DSRC based scheme and £180 million with a paper permit- based scheme (see Table 6.4) or annual funds of £14million to £18 million.

CITY NAME	Central London (C.L.)	City A	City B
POPULATION	600,000 (C.L. only)	400,000	727,000
Vehicles Registered in a 'travel work area'	2.7M	0.5M	0.8M
Envisaged number of cordon crossing points	130	16	35
Envisaged charge to cross cordon into city	£4	£2	£2
Maximum Funds available for investment in local transport with DSRC based scheme (after 10 years)	£530	£140M	£400M
Maximum funds available for investment in local transport with paper permit-based scheme (after 10 years)	£740M	£180M	£470M

Table 6.4 Example of Revenue generation evidence from Road Pricing Schemes (Cheese and Klein, 1999)

The authors argued that the paper based schemes potentially had lower implementation and running costs resulting in higher net revenue. The ROCOL study (2000) also concluded that a paper based scheme would be a possibility in the first term of a London mayor, while more advanced electronic toll collection (ETC) systems would require about 5 - 6 years to put in place (around year 2005/6 from 2000). The Trafficflow study, however, pointed out that a paper based system had limited flexibility than DSRC systems and offered lower potential for use as a traffic or congestion management tool. Indeed, other researchers (e.g. Krammes, 1994) had earlier argued that the medium to long term viability and acceptability of road user charging schemes lay in their ability to integrate the charging schemes with other ITS measures such as driver/traffic information; - the so called "piggy-backing" value added services that would increase the commercial viability of pricing schemes.

If the £10 million annual running costs are assumed in this research for Southampton, the net annual funds would range from about £13.7 million to £12.1 million depending on the suppression level. These funds are consistent with the Trafficflow study reported by Cheese and Klein.

6.3.4.2 Losers in the Peak Hour

The obvious losers in the peak hour are the drivers priced off from this period as a result of differential pricing. Of course some of these drivers may gain in terms of reduced travel times by travelling in the shoulders although a loss arises from being priced off their preferred trip timing. The priced off are the drivers who have exhibited elasticity to the road user charges implemented in the peak hour. In economic terms, these travellers value the utility of their trip as lower than the potential savings in travel time for their journeys. From a behavioural point of view, predicting the proportion of this market segment given limited empirical evidence and hence limited understanding on how this market trades off causal factors such as the need to balance trip duration with trip timing; and the impetus to avoid paying tolls with the need to avoid incurring late arrival penalties for instance, all contribute to making this predictive task difficult and uncertain. This is one of the reasons why this research adopted a 'what if' approach.

Clearly an obvious loss to these drivers is the disutility of having to travel (trip timing) at a period that they would otherwise not, if given the choice. This issue of the trade off between 'trip duration' and 'trip timing' has been raised before in the literature (e.g. Johnston, 1991; De Palma et al, 1997). There seems to be little quantitative evidence though from the literature in understanding this trade off. Nevertheless, this group of travellers are the key to understanding the behaviour of motorists confronted by road user charges of this nature. There is at present, however, a lack of understanding of the factors determining this elasticity in behaviour for travellers and hence in predicting the number or proportion of travellers and their characteristics that are amenable to behavioural changes as a result of road user charging. The magnitude of this market and their trip making patterns would influence the potential network benefits of a pricing policy. If this market were too small (for a given congestion level, given network and trip making pattern), the pricing scheme would be more of a revenue generation scheme than a congestion management one. On the other hand, it has been shown that a highly elastic market may not justify the investment already sunk in existing infrastructure. The results here, and expectedly so, point to a relationship between network 'saturation' and the amount of benefits yielded through relieving the network loading. For a network manager, identifying the required trip suppression in order to achieve optimum network operation is a major first step. At this point the network manager may then decide if the potential network benefits are high enough to warrant proceeding with the proposed scheme. If so, understanding and identifying this potential market possibly through stated preference surveys would be a natural next step.

A potential gain or loss for peak hour drivers forced to shift to the peak shoulders is the change in their travel duration from that they experienced in the peak hour, to that they experience in the pre or post peak hour shoulders. It is possible for this to be either an increase or decrease in travel time depending on the available spare capacity in the shoulder time period of travel. Table 6.5 below shows the average changes in travel time for car vehicles forced to shift to the pre-peak shoulder. It can be seen that such drivers may enjoy average travel time reductions of between one and half to two minutes. These reductions are comparable to but more than the reductions enjoyed by those able to continue travelling in the peak hour. These magnitude of changes in travel duration are consistent with Chin (1990) who reported travel times changes of up to two minutes due to peak spreading in the Singapore Area Licensing Scheme (ALS).

	Peak Spreading Level (measured as % Peak Hour Trip Suppression				
ITEM	Base Case	5%	10%	15%	20%
No of Vehicles in peak hour before peak spreading	47 750	n/a	n/a	n/a	n/ab
No. of vehicles in Pre Shoulder after peak spreading	n/a	34253	34699	34817	35829
Average Vehicle Hours/Vehicle Before Peak Spreading (minutes)	11.1	n/a	n/a	n/a	n/a
Average Vehicle Hours/vehicle after Peak Spreading (minutes)	n/a	8.9	9.1	9.2	9.5
Difference (minutes)	n/a	-2.2	-2	-1.9	-1.6

Table 6.5 Pre Peak Hour Vehicle Hour Changes for Peak Hour 'Priced Off' Travellers

6.3.4.3 Losers in the Peak Hour Shoulders

A main concern in western democracies about implementing road user charging schemes, is the fear of transferring the problem elsewhere. Clearly, a temporally differentiated pricing scheme has the potential to transfer congestion from the highly priced periods to the less priced or non charged periods. This was the case in the initial Singapore experience (in addition to spatial problems due to unforseen re routing to less suitable roads).

Tables 6.6 and 6.7 below suggest that drivers originally travelling in the shoulders may experience travel time increases varying from negligible at the 5% suppression level to just over two minutes at the 20% suppression level as a result of those priced off from the peak hour shifting to the peak shoulders. This seems to suggest that so long as there is available capacity in the peak shoulders, peak spreading may not cause excessive journey time increases to those already travelling in the off peak periods. The increases reported here are also consistent with Chin (1990).

	Peak Spreading Level (measured as % Peak Hour Trip Suppression				
ITEM	Base Case	5%	10%	15%	20%
No of Vehicles before peak spreading	33913	n/a	n/a	n/a	n/a
No. of vehicles after peak spreading	n/a	34253	34699	34817	35829
Total Increase in Vehicle Hours	0	75.7	243	317.7	660.3
Aggregate VOT (average car) disbenefits in £ (AM only)/day	0	509.92	1636.85	2140.02	4447.78
Average increase in vehicle hours/vehicle (seconds)	0	8.0	25.2	32.8	66.4

Table 6.6 Pre Peak Hour Increase in Vehicle Hours for original drivers

	Peak Spreading Level (measured as % Peak Hour Trip Suppression				
ITEM	Base Case	5%	10%	15%	20%
No of Vehicles before peak spreading	47750	n/a	n/a	n/a	n/a
No. of vehicles after peak spreading	n/a	9276	10103	10172	10892
Total Decrease in Vehicle Hours	0	59.4	227.3	209.8	395.7
Aggregate VOT (average car) disbenefits in £ (AM only)/day	0	400.11	1531.09	1413.21	2665.44
Average increase in vehicle hours/vehicle (seconds)	0	23.1	81	74.9	130.8

Table 6.7 Post Peak Hour Increase in Vehicle Hours for original drivers

6.4 Effect of Congestion Level

The variation of the network benefits with increasing congestion level is now considered. Figure 6.8 depicts the absolute change in total network vehicle hours for 1D, 1.1D and 1.2D (ID, is the base case Demand O-D matrix. 1.1D and 1.2D is the base case matrix multiplied by a factor of 10% and 20% respectively) for the peak spreading levels of 5%, 10%, 15% and 20% compared to the base case in each scenario. The equivalent percentage changes are shown in Figure 6.9. 'Noise' in the model output makes the differences between the 1D and 1.1D congestion levels difficult to differentiate. However, it is clear from both graphs that the benefits are much higher for the congested 1.2D level by a multiple of 7 or 8 compared to the base congestion scenario. In fact, the 10% to 14% decrease in network vehicle hours at 1.2D is consistent with modelling results by Ristau et. al, (2000) for the congested Tappan Zee Bridge corridor in New York. This seems to suggest that the benefits from peak spreading will be most significant at high congestion levels and hence for more congested networks than for less congested ones. This is to be expected by analogy to single link 'cost–flow curves'. Fundamentally, these results confirm the fact that where congestion reduction is the aim, then benefits will only be more significant in more congested networks than in less congested ones (e.g. Wigan and Bamford, 1973; Decorla-Souza, 1993). Bamford and Wigan concluded from a simulation model of road charging schemes that there was a sharp rise in benefits as the general level of congestion rose, and that these benefits appeared to be sensitive to p.c.u. demand elasticity but up to a certain elasticity value dependent on the congestion level. The lowest congestion level produced very small benefits that seemed not to change with demand elasticity. Dercola-Souza noted from a pricing strategy modelling results that congested areas could expect more benefits than less congested ones. In this comparison, the less congested urban area achieved a 2.5% reduction in vehicle miles travelled (VMT) while the more congested one produced a 5% reduction. These findings of course seem to suggest that TDM measures such as pricing schemes are more pertinent at higher congestion levels. This is consistent with marginal cost theory. However, from a traffic management view, it may still be beneficial to apply such measures at current congestion levels despite the relatively low network benefits. The rationale would be to use these measures to potentially reduce the growth of traffic and thus delay the onset of higher congested conditions. This would be a preventive rather than a prescriptive measure. Therefore despite the low benefits, at current congestion levels, TDM measures may still have a role to play. In addition the potential revenue which if hypothecated for investment into alternatives to the SOV is still considerable even at these lower congestion levels.

Figure 6.8 Absolute Change in Total Network Vehicle Hours with Congestion level

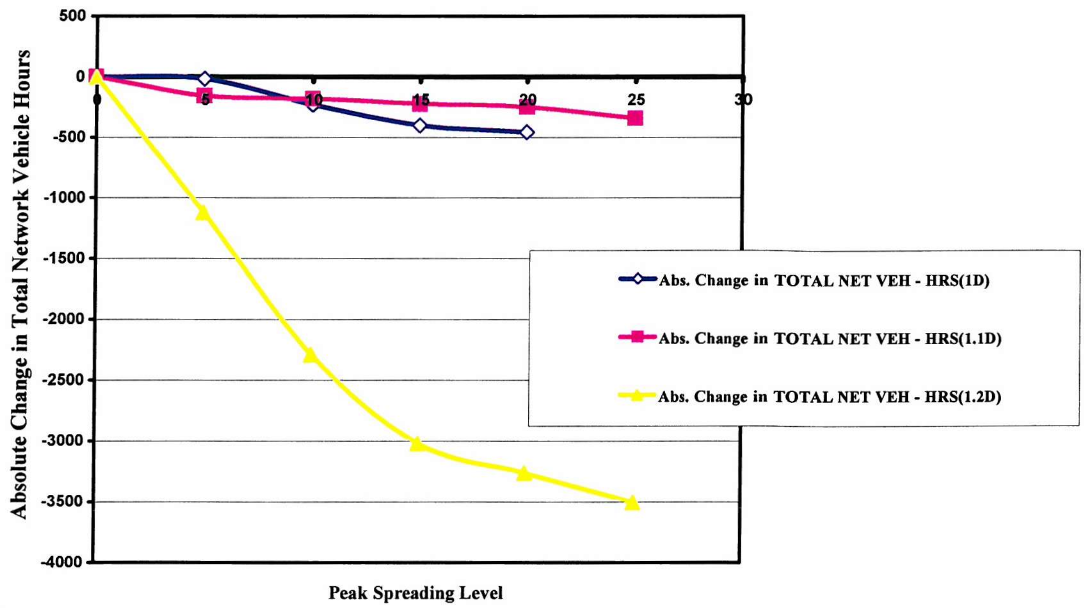
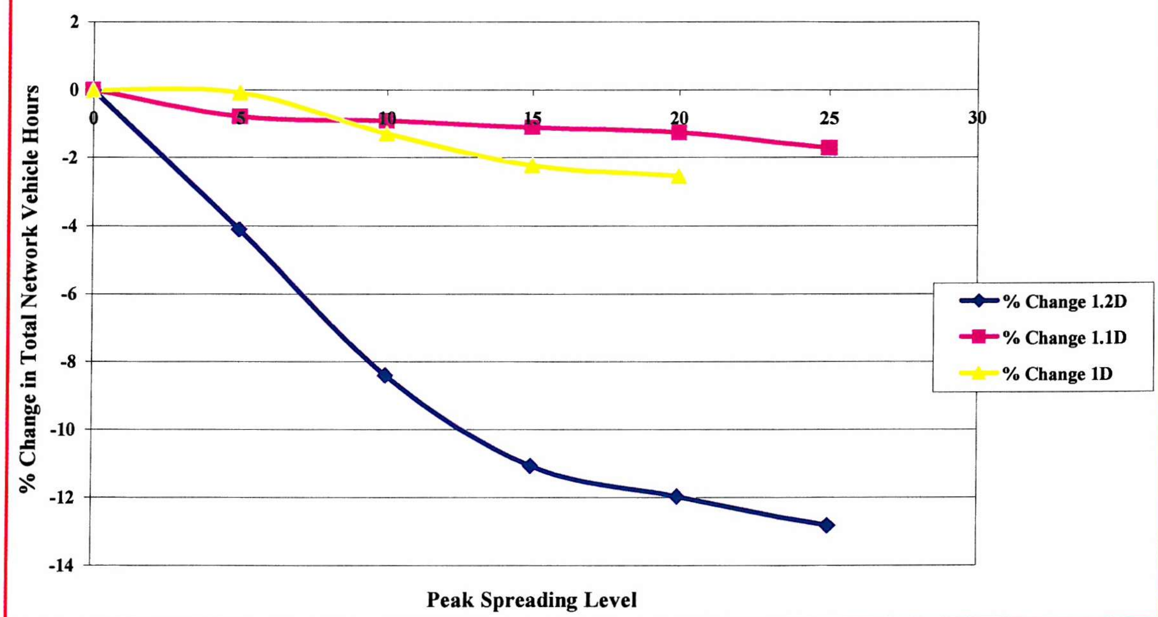


Figure 6.9 % Change in Total Network Vehicle Hours with Congestion Level



6.5 Further Analysis from a selection of parameter indicators

A clearer understanding of the network changes due to peak spreading can also be acquired from Tables 6.8, 6.9, 6.10 and 6.11. These employ a number of network parameters to show the changes in these parameters as the peak spreading level is increased. The tabulations are again made for the three congestion levels1D, 1.1D and 1.2D. The current network loading of the Southampton network can be considered to lie between the 1D and 1.1D congestion levels. The 1.2D congestion level represents a significantly higher state of congestion of the Southampton network as might occur at a future date.

6.5.1 Total Vehicle Hours and its Components

From Table 6.8 it can be seen that at 1D the free moving component of the vehicle hours constitutes 69% of the total vehicle hours, while the flow delay constitutes 11% and the queuing delay 20%. As congestion increases from 1D through 1.1D to 1.2D, the dramatic change occurs at 1.2D where the free moving only constitute 57% of the total vehicle hours, while the flow delay and queuing delay constitute 12% and 30% respectively. Factoring the O-D matrix beyond 1.2D shows no further appreciable increase in network vehicle hours or its components. This was considered to be due to the fact that vehicles were queuing outside the network due to the saturated condition at 1.2D. It was considered that 1.2D approximated to the maximum load that could be handled by the Southampton network in its current state. This result was consistent with intuitive judgement that the Southampton network was unlikely to accommodate traffic increases in excess of 20% of the base case loading. CONTRAM output in excess of 1.2D would be unreliable and unrepresentative. The overall network speed (total network VKT divided by the total network vehicle hours) appears reasonable at 43 kilometres per hour and are consistent with Rogers (1991) who noted that a 'final mean speed of 41-44 kph seemed reasonable' in an urban network that included a significant proportion of high speed roads such as dual carriageways and motorway links.

1.2D was thus considered to represent a significantly higher state of network congestion compared to 1D and 1.1D where the network was predominantly operating below saturation. At the 1.2D congestion level, the queuing delay almost doubles from the 1.1D case and has increased by a factor of 2.3 from the 1D base case congestion level. Junction capacity becomes the limiting factor at this high congestion level as vehicles spend a considerable proportion of their journey time queuing. Some researchers have claimed that the typical driver may consider up to 20-30% of travel time spent stationary acceptable on busy urban roads at peak times (ROCOL,2000). The 30% queue delay at 1.2D appears to be consistent with this assertion.

While the flow delay increases by a factor of about 1.2 from 1D to 1.1D, it increases by a factor of over 1.4 between 1.1D and 1.2D. Despite the proportion of flow delay remaining almost constant from one congestion level to another, there is clear evidence of increased vehicle interaction or stream friction as congestion increases in the network. This flow delay is to be expected on high speed roads of the network such as dual carriageways and motor ways where speed–flow relationships are significant. Tables 6.9, 6.10 and 6.11 show how peak spreading affects these components of journey time.

Demand Matrix Level	1D	1.1D	1.2D	1.25D	1.3D
Freemoving	12566 (69%)	13530.4 (67%)	15695 (57%)	16049.7 (56%)	16228.9 (55%)
Flow Delay	1989.3 (11%)	2356.8 (12%)	3371.6 (12%)	3562.7 (12%/12.4%)	3738.3 (13%)
Queue Delay	3566.7 (20%)	4368.2 (22%)	8231.2 (30%)	9013.1 (31%)	9610.9 (32%)
Total Veh - Hrs	18122.1 (100%)	20255.4 (100%)	27297.7 (100%)	28625.5 (100%)	29688.2 (100%)
VKT	940683	1016108	1173159	1200998.2	1224438.8
Overall Speed	51.9	50.2	43	42	41.2
Mean links/route	19.86	19.86	20.32	20.33	20.32

Table 6.8 Effect of increased network congestion on network behaviour based on selected aggregate Performance Indicators

Congestion Level	1D				
Peak Spreading Level (%)	**0**	**5**	**10**	**15**	**20**
Free-moving Vehicle Hours	12,566.8 (69.4%)	12,596.4 (69.6%)	12,579.4 (70.3%)	12,467.5 (70.8%)	12,528.9 (70.9%)
Flow Delay Vehicle Hours	1,988.6 (11%)	1,980.6 (10.9%)	1,935.8 (10.8%)	1,895.8 (10.8%)	1,913.8 (10.8%)
Queue Delay Vehicle Hours	3,563.9 (19.6%)	3,527.2 (19.5%)	3,372.1 (18.9%)	3,254 (18.4%)	3,217.6 (18.3%)
Total Network Vehicle Hours in Modelled Period	18,119.2 (100%)	18,104.2 (100%)	17,887.3 (100%)	17,617.4 (100%)	17,660.3 (100%)
Total Network Vehicle Kilometres (VKT)	940732	943259	942493.7	934179	938184.4
Overall Network Speed	51.9	52.1	52.7	53	53.1
Mean Links/Route (No.)	19.86	19.85	19.81	19.81	19.80

Table 6.9 Summary of Overall Network Performance with Peak Spreading Level for 1D Congestion Level

Congestion Level 1.1D					
Peak Spreading Level (%)	**0**	**5**	**10**	**15**	**20**
Free-moving Vehicle Hours	13,529.6 (66.9%)	13,506.9 (67.2%)	13,636.4 (66.9%)	13,584.6 (67.5%)	13,544.4 (67.5%)
Flow Delay Vehicle Hours	2,354.1 (11.6%)	2,322.4 (11.6%)	2,362.2 (11.6%)	2,324.7 (11.5%)	2,317.3 (11.6%)
Queue Delay Vehicle Hours	4,360 (21.5%)	4,255.3 (21.2%)	4,387.8 (21.5%)	4,224.1 (21.0%)	4,199.7 (20.9%)
Total Network Vehicle Hours in Modelled Period	20,243.7 (100%)	20,084.6 (100%)	20,386.3 (100%)	20,133.4 (100%)	20,061.4
Total Network Vehicle Kilometres (VKT)	1015985	1014433	1021453	1018355	1014576
Overall Network Speed	50.2	50.5	50.1	50.6	50.6
Mean Links/Route (No.)	19.86	19.84	19.91	19,88	19.89

Table 6.10 Summary of Overall Network Performance with Peak Spreading Level for 1.1D Congestion Level

Congestion Level 1.2D					
Peak Spreading Level (%)	**0**	**5**	**10**	**15**	**20**
Free-moving Vehicle Hours	15,684.2 (57.5%)	15,505.5 (59.2%)	15,573.6 (62.3)%)	15,368.4 (63.3%)	15,276.7 (63.6%)
Flow Delay Vehicle Hours	3,355.1 (12.3%)	3,237.1 (12.4%)	3,095.5 (12.4%)	2,993.7 (12.3%)	2,955.4 (12.3)
Queue Delay Vehicle Hours	8,258.7 (30.2%)	7,435.3 (28.4%)	6,338.9 (25.3%)	5,919.8 (24.4)	5,804.9 (24.1%)
Total Network Vehicle Hours in Modelled Period	27,298 (100%)	26,177.9 (100%)	25,008.1 (100%)	24,281.3 (100%)	24,036.9 (100%)
Total Network Vehicle Kilometres (VKT)	1171997	1159846	1161918	1146266	1138332
Overall Network Speed	42.9	44.3	46.5	47.2	47.4
Mean Links/Route (No.)	20.34	20.23	20.17	20.13	20.15

Table 6.11 Summary of Overall Network Performance with Peak Spreading Level for 1.2D Congestion Level

At the lower congestion levels of 1D and 1.1D there is little change in the free moving vehicle hours as a proportion of the total vehicle hours with increasing peak spreading. However, at the 1.2D level where congestion is significant, the proportion of the free moving vehicle hours increases from 57.5% of the total vehicle hours with no peak spreading to about 64% of the total vehicle hours at 20% peak spreading. There is a marginal decrease in flow delay at the 1D and 1.1D congestion levels (-1.5 to –3.5%) as peak spreading increases from 0% to 20%. This is because at these low congestion levels vehicle interaction or stream friction is relatively smaller on the high speed roads. On the other hand, at the high congestion level of 1.2D, the flow delay decreases from 3,355.1 vehicle hours without peak spreading to 2,955.4 vehicle hours at the 20% peak spreading level. This represents almost a 12% decrease in flow delay and should be evident as improved flow conditions on the dual carriage way and motorway network.

The results are even more pronounced when one considers the queuing delay. At 1.2D, there is about a 30% decrease in the queuing delay without peak spreading from 8, 258.7 vehicle hours to 5, 804.9 vehicle hours at the 20% peak spreading level. It can be seen that by just distributing the travel market in time but without reducing the travel market, there is potential as suggested by the model results, to reduce the overall network flow delay and queuing delays at the high congestion level of 1.2D to a level comparable to that of the

1.1Dcongestion level. The total delay (flow and queue) is seen to be reduced by almost 25% at the 20% suppression level.

However, the results also show that even at 1.2D the benefits of peak spreading are more evident up to a certain level of suppression (15%) and hence demand elasticity. This can be seen for instance by the smaller changes in the total network vehicle hours and its components as the peak spreading level increases. For instance, the decrease between the 15% and 20% peak spreading levels is much smaller than that between the 0% level and the 5% level or between the 5% level and 10% level or between the 10% level and the 15% level. This seems to suggest that there maybe no significant benefits to be gained by peak spreading beyond the 15 to 20% peak spreading levels. This may be explained by the fact that the network will be more sensitive to changes in network load when it is operating nearer capacity when even small increases in load may significantly increase network costs. As the network load falls below saturated conditions, the decreases in network costs are less significant and no further amount of suppression may be economically beneficial, at least from a congestion point of view.

6.5.1.1 Vehicle Kilometres Travelled

In all the three congestion levels, the magnitude of the total network vehicle kilometres travelled basically remains constant with peak spreading. This suggests that the benefits arising from the network are predominantly due to peak spreading rather than re – routing; i.e. virtually the same routes at a given congestion level are being used at the different peak spreading level for that congestion level (obviously as congestion increases one would expect longer uncongested routes to become more attractive. This seems to be confirmed by the increase in the value of the parameter 'mean number of links/route' as congestion increases from 1D to 1.2D).

The fact that VKT change negligibly with increasing peak spreading of course has some implications for peak spreading as an impact and therefore for TDM policies that may cause it. This is namely that while peak spreading has the potential to yield improved network conditions at higher congestion levels (as shown by decreases in the vehicle hours, improved network speed and reduced queues), its wider environmental effects may not be as significant (i.e. taking VKT as a proxy for traffic environmental pollution).This is consistent with similar findings by COMSIS (1993). The report noted that peak spreading does not remove vehicle trips from the network but simply moves them to another time period. Therefore, where there was no change in mode, the VMT were not removed from the inventory. The report continued to say that although relief in congestion might be achieved by spreading out the demand, the overall implications for air quality improvements were likely to be insignificant. However, the better traffic flow conditions that may arise from peak spreading may significantly reduce emissions associated with slow moving and idling traffic.

6.6 Concluding Remarks about Peak Spreading

For the Southampton network at normal congestion, suppression levels of 5 – 20% of the peak hour demand (0800 –0900) and redistribution of this suppressed demand (of car trips) to the pre-and post-peak shoulders (0730-0800 and 0900-0930 respectively) to simulate a 'flatter' peak profile as might arise from peak spreading, yielded the following results. There was a small decrease of about –0.1% in total network vehicle hours at the 5% suppression level and a decrease of about –2.5 % at the 20% level.

The decrease in vehicle hours was relatively sharp between the 5% and 15 % suppression levels (-0.1% to –2.2%) but seemed to level out between the 15% and 20% suppression levels (-2.2% to –2.5%) suggesting that no further appreciable benefits could arise by applying suppression levels beyond the 20% level.

In terms of actual vehicle hours the 5% suppression level reduced the total network vehicle hours by only 15 vehicle hours from the original total network figure of about 18, 100 vehicle hours. The decrease at the 20% suppression level was 460 vehicle hours equivalent to £3 099 in the modelled AM peak from 0730 to 0930 per weekday or to £0.775 million over a 250 day working year.

At the individual driver level, drivers able to afford paying and therefore left to drive in the peak hour could experience reductions in travel time of between just 11 seconds to up to two minutes. This is in monetary terms equivalent to a journey time saving of between 2 pence and 23 pence respectively.

Compared to the £2.00 direct charge that can be expected if a pricing scheme were implemented in a city the size of Southampton, the average driver left in the peak hour would thus recoup only a small fraction (0.01% to 11.5%) of the direct charges that they paid. This seems to support literature evidence that the equivalent journey time savings of paying drivers will be lower than the actual out of pocket costs paid by these drivers (e.g. ROCOL, 2000; TRB, 1994).

Interestingly, drivers forced to shift to the peak shoulders from the peak hour were found by this research to experience reduced travel times of between 2.2 minutes at the 5% suppression level to 1.6 minutes at the 20% suppression level. These travel time savings are gained at the expense of shifting their trip timing by about 15 to 30 minutes. The travel time gains enjoyed by drivers forced out of their 'desired' period of travel appear to be larger than those gained by drivers remaining in the peak hour. This would not be too unexpected if the demand shifts were far outside of the given AM period - i.e. shifts of say greater than 1–2 hours; but coming from shifts of only 15 to 30 minutes shows just how beneficial peak spreading might be especially to the drivers forced out of the peak hour to the peak shoulders.

This research has also found out that drivers originally travelling in the peak shoulders would experience journey time increases of between up to a minute (66.4 seconds) in the pre-peak shoulder and up to two minutes (130.8 seconds) in the post-peak hour shoulder. Overall, however, these journey time increases do not make the journey times of drivers travelling in the peak shoulders greater than those of drivers in the peak hour except at the 20% suppression level when reduced travel times in the peak hour begin to be gained at the expense of drivers in the peak shoulders.

In general, the overall network decrease of up to –2.5% in vehicle hours as a result of peak spreading for the Southampton network at normal congestion was lower than the expected 5% gains suggested by the literature. This might be because, although there is clearly more capacity in the peak shoulders than in the peak hour, for the Southampton case, there seems to be some evidence of the peak period profile flattening off even before the peak spreading scenarios were applied to the base case trip O-D matrix profile. This could be due to car drivers already exhibiting some trip retiming to the peak shoulders and away from the peak hour in order to avoid the more congested peak hour conditions.

6.7 Trip Suppression Results

6.7.1 Introduction

In the sections that follow the network results estimated if trip suppression were to be the behavioural response adopted by travellers to a TDM measure such as road user charging are given. In this study, trip suppression is taken as the complete removal of some car trips from the trip matrix. This differentiates 'trip suppression' from other suppression mechanisms in which there is modification to car use rather than the absolute removal of such car trips from the demand matrix (e.g. peak spreading, destination changes).

Perhaps the ideal case of car trip suppression would be one in which both the car and person trips are not made, i.e. the trip is foregone. While from a travel demand management perspective, this may be the ideal behavioural response, the circumstances in which this may occur need to be plausible. Firstly, it must be inferred that, the fact that the journey was undertaken before the TDM was applied, there must be a utility associated with the trip for the individual(s) concerned. For this trip to be foregone, a substitute must have been found. Therefore the activity is probably being carried out at home as might occur with working from home (e.g. teleworking or through some other form of remotely accomplishing the trip purpose - usually electronic).

Most forms of trip suppression, however, involve the execution of the person trip through some alternative mode or by the same mode but with increased car occupancies or with reduced trip frequency or through trip chaining. The effect on the network is a possible reduction in SOV on the network.

6.7.2 Assumptions about The Road User Charging Scheme

In many respects the assumptions made about the differential pricing scheme in section 6.3.2 remain valid. Only the differential aspect of the pricing scheme is removed and a uniform charging structure over the whole modelled period is assumed in its place. Such a scheme at least can be expected not to provide any incentives for trip retiming. However, suppression mechanisms such as foregoing the trip, changing mode and even destination changes for discretionary trips can be expected. The plausibility of this assumption – at least empirically, can be illustrated by experiences from the Norwegian toll rings. For example in Oslo where the toll ring pricing was in force for 24 hours a day, traffic counts indicated a decrease of 8% ± 2% in the total number of inbound trips. Panel travel surveys of up to 25,500 respondents showed a 10.6% decrease in the number of trips affecting all modes, travel purposes and combinations of O–Ds (Larsen, 1995). It seemed that the reduction was due to a combination of destination changes by discretionary trips and to an extent a reduction in the total number of trips even though ticket sales and travel surveys revealed no significant shift in mode to public transport. The 24 hour nature of the scheme was not conducive to peak spreading.

In Bergen, the reduction in car trips was of the order of 6%-7%. This appeared to be mainly due to destination changes by discretionary trips. The wide pricing band of 0600 to 2200 was not conducive to peak spreading, although there was no significant shift to public transport. The differential pricing in Trondheim applied between 0600 and 1700 resulted in a 10% decrease in car drivers crossing the cordon. The main response mechanism was a shift in the timing of trips away from the tolled period. There was also some evidence of modal changes to cycling and to public transport (+8%).

Demonstration trials (CONCERT/EUROTOLL) reported by Hayes et al, (1999) indicated similar responses patterns according to the pricing structure. For example in the Trondheim TRON2 trials peak spreading constituted the main response while in the Bristol trials mode changes were predominant.

6.7.3 Trip Suppression Representation in CONTRAM for the Southampton Network

In order to enable comparison between peak spreading and trip suppression, similar peak hour suppression levels were assumed. In reality a uniform pricing structure across the two hour period can be expected to cause trip suppression right across the whole two hour period.

To represent trip suppression in CONTRAM reduction factors were applied in the peak hour to the O–D matrix for the car vehicle class only. Suppression levels of up to 20% in increments of 5% were assumed.. Bus and lorry vehicle classes constitute a very small percentage of the overall trip matrix of Southampton and therefore the suppression of car vehicles only was considered appropriate. Further, evidence seems to suggest that commercial vehicle operators would continue to operate their vehicles during the priced periods and incur the road pricing costs (e.g. Fearson et al, 1994).

As with peak spreading earlier, the application of reduction factors to all O–D pairs is an idealistic situation that seeks to quantify the potential upper bound network effects of widespread trip suppression by assuming that virtually all the O–D movements are affected by the pricing scheme and can potentially respond through trip suppression. In reality the benefits are likely to be less for reasons such as:

- Not all O–D pairs maybe affected by a particular TDM scheme.
- The travel market is heterogeneous and so some O–D pairs may exhibit may exhibit little or no suppression while some may exhibit higher elasticities. Modelling by Soberman and Miller (1998) for example showed that the 'auto – mode' share was more likely to be reduced by changes in car travel costs in markets in which transit provided a competitive alternative to the car. In markets in which the SOV was dominant or in which PT was dominant, there was little changes in behaviour as a result of increases in car travel costs. The dominance of a mode was defined by the probability of taking a trip by car. The authors defined $P_a = 0.1$ as the case in which the auto mode share is low and transit dominates; $P_a = 0.9$ is the case in which the

car dominates and transit is low while for $P_a = 0.5$, there was an equal chance of using either. Ghali et al, (1998) noted that responses may be influenced by the relative proportion of poor, medium and rich drivers in the origin zones.

- The possibility of induced traffic taking advantage of the improved travel conditions.
- The potential to reallocate some of the freed capacity exclusively to PT or and cyclists or pedestrians.

All these factors although not modelled in this research certainly have a bearing on the potential network effects of car trip suppression. A case study of the suppression of E-I (External-Internal) trips into the CBD in the presence of a mid cordon toll is considered later in this Chapter. This scenario approximates better to what could happen in reality as compared to the idealist situation considered so far.

6.8 Overall Network Results of Trip Suppression at normal congestion

Figure 6.11 and Figure 6.12 show the absolute and percentage decrease in total network vehicle hours as the peak hour trip suppression magnitude is varied. For comparison, the graph of the equivalent benefits when these peak hour suppressed trips are redistributed to the peak shoulders (peak spreading) is also shown. It can be seen from the graphs that suppression has the potential to produce significant reduction to the total network vehicle hours even at current levels of congestion. At low suppression levels of up to 5% the benefits are modest (1% decrease) but significantly larger than for peak spreading at similar peak hour suppression levels. A sharp increase in benefits occurs between the 5% and 10% suppression levels when a significant proportion of car trips are removed and capacity is rapidly released. However, the curve rises less steeply thereafter. This could be attributed to the fact that as the suppression level increases, the network operates in less saturated conditions in which vehicle interactions as depicted by flow delay and release of junction capacity through the reduction of queue delay become less significant. Significantly at higher suppression levels the network may become under utilised especially on the links where relatively smaller percentage reductions are evident in the free-flow component of the total vehicle hours. This is consistent with remarks made in the Southampton Provisional Local Transport Plan 2001/1 to 2004/5. It is reported there that the Southampton network generally operates within capacity during the off peak although there are some capacity shortfalls at peak periods and that these capacity shortfalls generally occur at junctions rather than on the links given the urban nature of the network. This seems to suggest that reduction of demand through TDM measures may have to balance the need to reduce delays particularly at junctions with the need to ensure that investment already committed to link capacity is justified by maintaining a reasonable degree of link capacity utilisation. Certainly, there does not appear to be significant network gains in terms of travel time reduction once junction and to an extent flow delays has been reduced.

Figure 6.10 Absolute Network benefits Trip Suppression and Peak Spreading

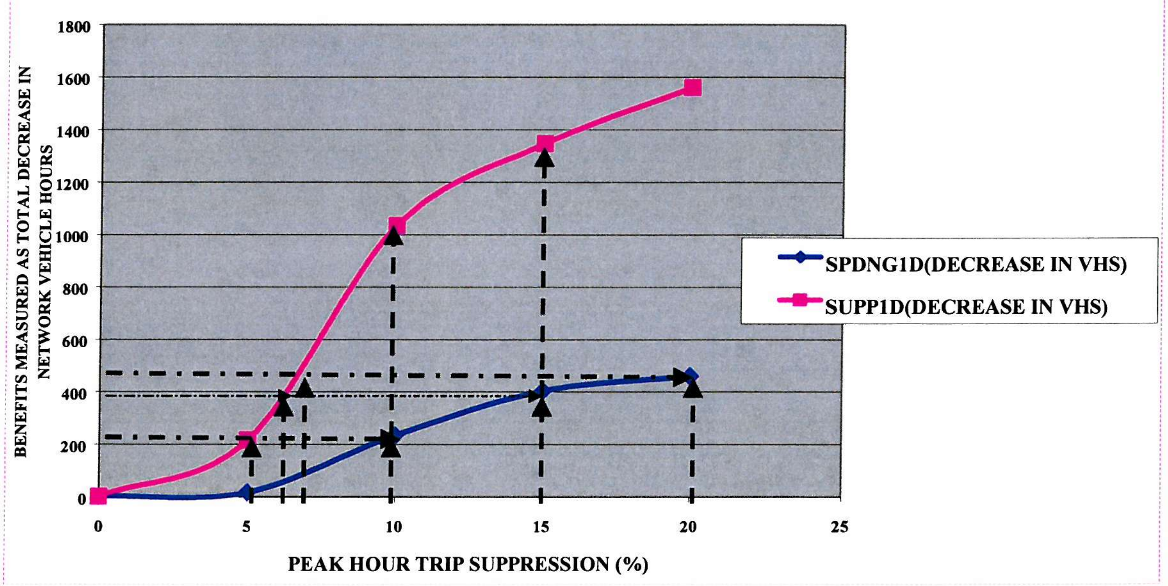
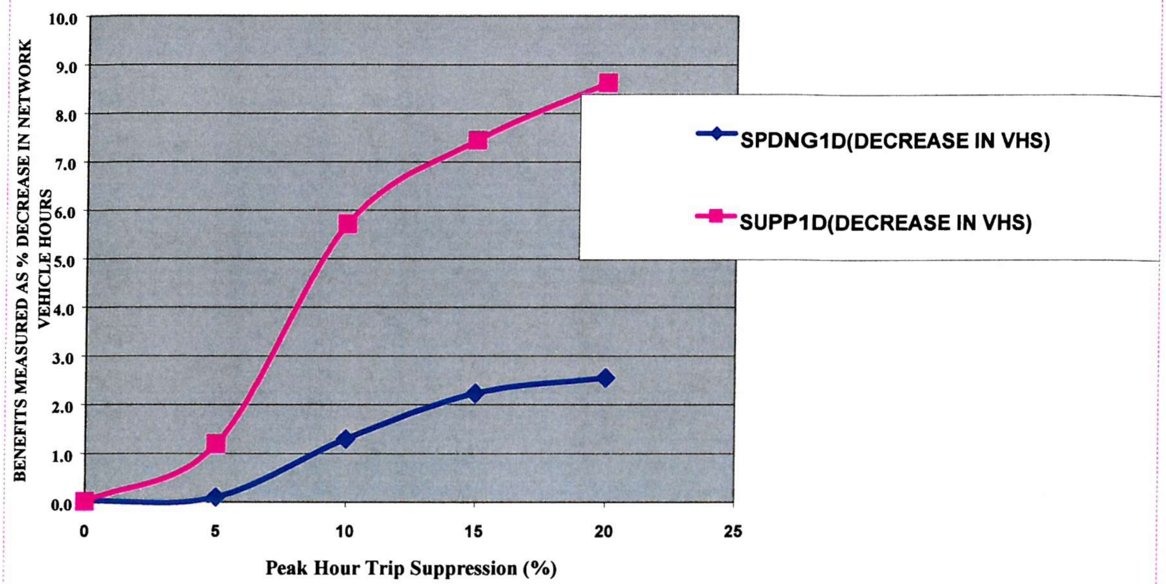


Figure 6.11 Percentage Network benefits Trip Suppression and Peak Spreading



suppression level (%)	VHS(freeflow)	VHS(flowdelay)	VHS(Qdelay)	Tot VHS	VKT	SPEED(KPH)
0.0	12566.8	1988.6	3563.9	18119.2	940732.3	51.9
5.0	12470.1	1946.7	3487.6	17904.5	932566.9	52.1
10.0	12138.1	1803.2	3144.9	17086.2	907653.5	53.1
15.0	11997.9	1749.4	3026.6	16773.9	896481.8	53.4
20.0	11893.1	1714.9	2952.0	16560.0	887540.1	53.6

Table 6.12 Variation of Actual Network Performance with Suppression Level

suppression level (%)	VHS(freeflow)	VHS(flowdelay)	VHS(quedelay)	Tot VHS	VKT	SPEED(KPH)
0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.0	-96.7	-41.9	-76.3	-214.7	-8165.4	0.2
10.0	-428.7	-185.4	-419.0	-1033.0	-33078.8	1.2
15.0	-568.9	-239.2	-537.3	-1345.3	-44250.5	1.5
20.0	-673.7	-273.7	-611.9	-1559.2	-53192.2	1.7

Table 6.13 Absolute Changes in Network Performance with Suppression level

suppression level (%)	VHS(freeflow)	VHS(flowdelay)	VHS(quedelay)	Tot VHS(1D)	VKT	SPEED(KPH)
0	0.0	0.0	0.0	0.0	0.0	0.0
5	-0.8	-2.1	-2.1	-1.2	-0.9	0.4
10	-3.4	-9.3	-11.8	-5.7	-3.5	2.3
15	-4.5	-12.0	-15.1	-7.4	-4.7	2.9
20	-5.4	-13.8	-17.2	-8.6	-5.7	3.3

Table 6.14 Percentage Changes in Network Performance with Suppression Level

6.8.1 Variations in the Components of Total Network Vehicle Hours

Tables 6.12 to 6.14 depict the changes in the various components of the total network vehicle hours with suppression level. It can be seen that all components of the vehicle hours decrease very little between the 0% and 5% suppression levels; very sharply between the 5% and 10% levels and again less rapidly after the 10% level. Significantly, it is the flow and queue delay vehicle hours that are most sensitive to changes in suppression levels as can be seen from Table 6.14. This sensitivity is highest between the 5% and 10% suppression levels, followed by the 10% to 15% suppression levels but is very modest between the 0% and 5% suppression band and again between the 15% and 20% suppression levels. This trend seems to confirm that even at this 1D base congestion level, it is mainly junction capacity rather than link capacity which is sensitive to congestion. This generally reflects urban network problems in which junction capacity rather than link capacity tends to limit network capacity.

Significantly, the results seem to suggest that at current congestion levels little benefits can be achieved at low suppression levels (up to 5%) since too little a 'load' is released from the network. On the other hand relatively high suppression levels (say greater than 15%) do not yield significantly larger benefits since the network would be operating in unsaturated conditions. Apparently there is a band of rapid and significant benefits (in the case of the Southampton network), i.e. above 5% to 15% within which suppression is most beneficial.

The little benefits to be gained up to the 5% suppression levels may appear curios at first. This is because quite often, the conventional link based speed–flow curve or cost flow curves are used to explain that even small reductions in demand can be beneficial. This is because these curves are much steeper at higher demand levels and small reductions in link flows can rapidly release capacity. The 'apparent' anomaly noted above, however, emphasises the need to understand the interactive behaviour of links and junctions in influencing network behaviour rather to treat links in isolation (e.g. Hills et al, 2000; May and Shepherd 1995; May, Shepherd and Bates, 2000). Thus the use of link based cost – flow curves would appear to overestimate the extent of the benefits to be attained at relatively low suppression levels for the network as a whole.

Generally the results seem to suggest that at current congestion levels, trip suppression may potentially have a significant effect on network performance, yielding percentage reductions of up to almost 9% in total network vehicle hours at peak hour suppression levels of 20%. How to achieve such suppression levels is, however, an entirely different issue. Nevertheless the results show that in the hypothetical case in which these suppression levels are assumed to be achieved the benefits to be attained are worth pursuing trip suppression as a behavioural response. Therefore policies that encourage such a response especially within the suppression range of 5% to 15%% for the Southampton network can be expected to be beneficial to overall network performance.

6.8.2 Equal Benefit Scenarios between different Behavioural Responses

The inclusion of the 'peak spreading' graph in Figures 6.10 and 6.11 was deliberate apart from providing comparison of the overall network benefits to be attained from trip suppression and peak spreading respectively. The dotted vertical lines in Figure 6.10 show lines of equal peak hour trip suppression for peak spreading and for the car trip suppression case. The horizontal lines represent equal benefit behavioural scenarios. For example, Figure 6.10 suggests that a reduction of 200 vehicle hours from the network could be achieved by 10% peak spreading (i.e. suppressing 10% of the car trips in the peak hour and then shifting these trips to the peak shoulders). It can also be achieved by suppressing 5% of the peak hour car trips altogether. Therefore these two behavioural responses although different, can yield equal or similar benefits.

As has been noted earlier, the literature is quite unanimous that after re routing, retiming and hence peak spreading is the most likely response to TDM measures. Indeed, Dawson (1986) in drawing lessons for western cities from the Hong Kong ERP noted that alternatives to travel by car would not include 'the relative readiness' of some motorists to transfer to public transport as gauged in Hong Kong and for that matter Singapore. This view is also consistent with recent findings by May et al, (1998) based on series of behavioural experiments encompassing stated preference surveys, field trials and laboratory simulators. The alternatives in western countries would be likely to include a greater emphasis on adjustments to the 'organisation of trip making' and in particular time of travel.

Literature evidence, however, suggests that modest absolute trip suppression in terms of changes to public transport or foregoing trips is achievable even in Western countries (e.g. 1.9%-5.9% CONCERT - see Hayes et al, 1999; Garling et al, 2000). To this extent Figure 6.11 can be used to define combinations of peak spreading and absolute trip suppression likely to yield benefits significantly higher than peak spreading alone but lower than can be achieved by higher but more unlikely levels of trip suppression alone. It can thus be expected that combining lower but possibly more achievable levels of absolute trip suppression with higher but moderate levels of peak spreading (also more likely to be achieved) could yield appreciable benefits. These issues are explored a bit further later in the next sections.

6.9 Combined Trip Suppression and Peak Spreading

It can be seen from Figures 6.10 and 6.11 that suppression of trips even at normal congestion has potential to reduce total network vehicle hours by up to 9% for the Southampton network. On the other hand peak spreading reductions are very modest and at about only 2.5%, are nearly 4 times less than the potential for suppression. One interesting thing about Figures 6.10 and 6.11 is that the benefits correspond to the same level of peak hour suppression. Whereas with the suppression scenario, the equivalent car trips suppressed from the peak hour are removed from the network (through a number of possible suppression mechanisms), the car trips in the later are not. It is to be expected as the literature suggests, that behavioural changes that completely result in the use of alternative modes or completely fore going the person trips are more difficult to achieve than those that simply modify the use of the car (e.g. May et al,1998, Hug et al, 1997). Thus re- timing of trips resulting in peak spreading is a behavioural response more likely to be achieved than complete suppression of the car trip. However, the results here suggest that peak spreading changes have very modest effects on the overall performance of the network at normal congestion. If some retiming and hence peak spreading could be achieved in conjunction with modest suppression levels one may expect the overall network improvement to be enhanced. The extent of these benefits is the main interest in this section.

6.9.1 Level of Suppression

There are indications from the literature that complete suppression of car trips is achievable to modest levels. For example in the CONCERT project, Hayes et al, (1999) reported of a 10% to 17% car suppression level in higher charged periods for tests carried in Trondheim in which differential pricing was applied to encourage peak spreading. In addition to this primary effect of drivers changing their time of travel, the total number of trips was reduced by between 1.2% and 5.9% depending on the charge level. This was indicative of some trip suppression as a secondary impact. These modest suppression levels were believed to have been obtained through modal shift.

Similar results were reported by O' Mahony et al, (2000) in the Dublin EUROPRICE pilot action project. Using a panel of 23 drivers, differential pricing tests suppressed up to 22% of the peak hour trips. The level of peak spreading achieved was lower than expected with an overall trip suppression of 6% being the result. This overall suppression was inferred to have been achieved through the use of public transport.

The LERTS project suggested shifts of up to 20% to public transport while the MobilPASS project reported up to 5% modal shifts. In order to quantify what the potential network effects would be if such behavioural changes were achieved area wide, various combinations of peak spreading and suppression were run in CONTRAM. The LERTS shift of 20% shift to public transport was considered quite exceptional. Instead the interest here was the intermediate potential bounded purely by the peak spreading curve and the suppression curves. It is quite evident from the examples quoted that a 6%-7% suppression level is probably achievable and a realistic one to test. For the scenarios run it was considered reasonably to extend this to 10% (e.g. Garling et al, 2000). It can also be inferred from Figures 6.10 and 6.11 that suppression levels of 1% would yield very modest changes in the network. A lower level of 2.5% was therefore assumed. The combined behaviour scenarios modelled are tabulated in Tables 6.15 to 6.18.

% Peak Hour Suppression	How Suppressed Pk Hr Trips Redistributed
5	1st 2.5% totally suppressed; other 2.5% peak spread to peak shoulders
10	1st 2.5% totally suppressed; remaining 7.5% peak spread to peak shoulders
15	1st 2.5% totally suppressed; remaining 13.5% peak spread to peak shoulders
20	1st 2.5% totally suppressed; remaining 17.5% peak spread to peak shoulders

Table 6.15 2.5% Trip Suppression Scenario

% Peak Hour Suppression	How Suppressed Pk Hr Trips Redistributed
5	1st 2.5% totally suppressed; other 2.5% peak spread to peak shoulders as Table 5.x1 above
10	1st 5% totally suppressed; remaining 5% peak spread to peak shoulders
15	1st 5% totally suppressed; remaining 10% peak spread to peak shoulders
20	1st 5% totally suppressed; remaining 15% peak spread to peak shoulders

Table 6.16 5% Trip Suppression Scenario

% Peak Hour Suppression	How Suppressed Pk Hr Trips Redistributed
5	1st 2.5% totally suppressed; other 2.5% peak spread to peak shoulders as before
10	1st 7% totally suppressed; remaining 3% peak spread to peak shoulders
15	1st 7% totally suppressed; remaining 8% peak spread to peak shoulders
20	1st 7% totally suppressed; remaining 12.5% peak spread to peak shoulders

Table 6.17 7% Trip Suppression Scenario

% Peak Hour Suppression	How Suppressed Pk Hr Trips Redistributed
5	1st 2.5% totally suppressed; other 2.5% peak spread to peak shoulders as before
10	1st 7% totally suppressed; remaining 3% peak spread to peak shoulders
15	1st 10% totally suppressed; remaining 5% peak spread to peak shoulders
20	1st 10% totally suppressed; remaining 10% peak spread to peak shoulders

Table 6.18 10% Trip Suppression Scenario

6.10 Results of Combined Peak Spreading and Trip Suppression

Figures 6.12 and 6.13 show the absolute decrease and percentage decrease in total network vehicle hours for these modelled scenarios. It can be seen that peak spreading combined with modest levels of suppression does significantly improve the benefits achieved. For example, the Figures show that it is possible to double the benefits achieved from peak spreading from 1% to 2% (200 vehicle hour decrease to 400hour decrease) by suppressing 10% of the peak hour trips and redistributing the first 5% while shifting the other five percent to say public transport or even teleworking; similarly triple the benefits at the same peak hour suppression by overall suppressing the first 7% and spreading the remaining 3%. Also quite significant is the fact that at the relatively higher peak hour suppression levels of 15%-20% it appears possible to double the peak spreading benefits from the modest maximum 2.5% decrease in total network vehicle hours to almost a 5% decrease by completely suppressing the first 7% of car trips and peak spreading the remaining 8% to 13% respectively.

Figure 6.12 Variation of Benefits with Impact or Combined Impacts

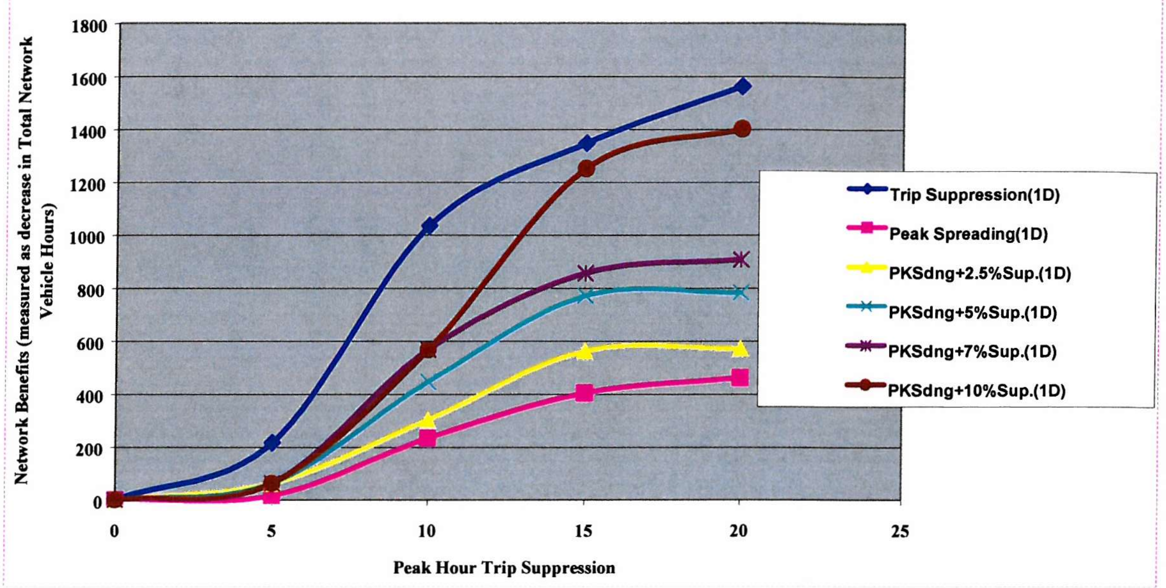
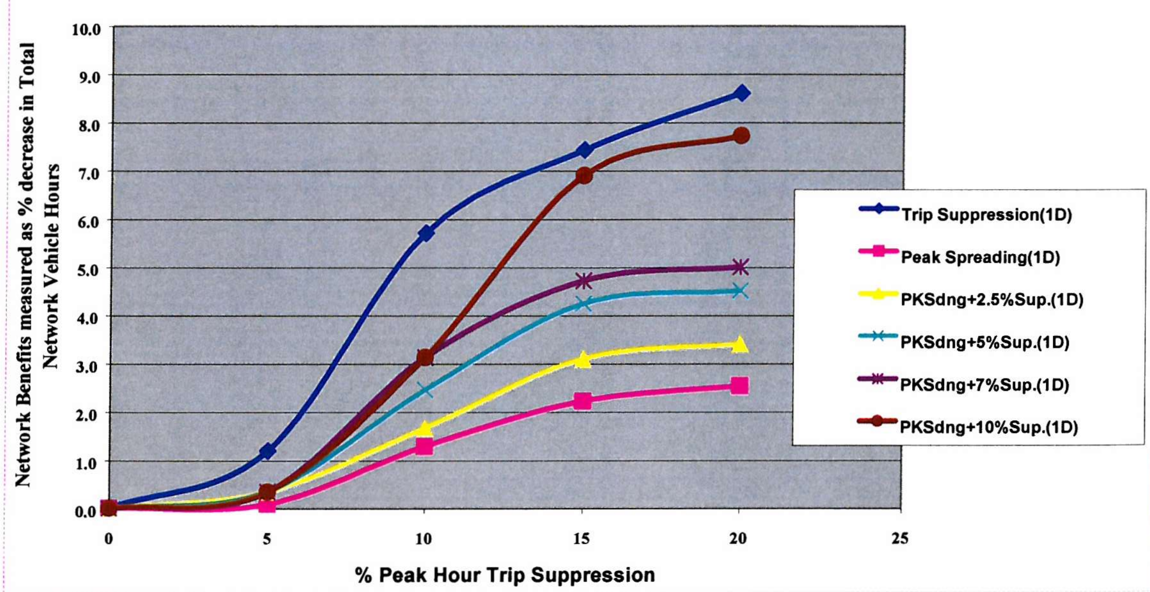


Figure 6.13 % Variation of Benefits for Impact or Combined Impacts



Although these benefits are as expected lower than those achieved if suppression were to occur in its entirety, they are appreciably higher than the benefits obtained through peak spreading alone. This is a significant result since evidence from the literature suggests that these levels of peak spreading and modest levels of suppression levels are both attainable. Importantly, this may mean that by achieving significant increases in benefits through modest suppression levels combined with peak spreading, it may be possible – at least in the short term to concentrate on improving existing public transport services through for example, increased reliability and comfort or such other public transport priority schemes without necessary having to invest extensively in bus fleets. Thus although the concern that alternatives must be available before TDM measures such as direct user pricing are implemented, it seems possible to absorb the demand created by suppression of modest levels of car trips into existing public transport capacity without the need for large increases in bus fleets. Indeed evidence suggests that journey time reliability is a major factor in encouraging a shift to public transport (e.g. Hodgson et al, 1997 in the MIST Project). While this is obviously a simplistic analysis since detailed study of specific bus routes is necessary, the analysis nevertheless depicts a plausible aggregate scenario.

Another useful use of Figures 6.12 and 6.13 is that a network operator can use it to establish behavioural responses that can yield equal or similar benefits. This can be useful in deciding from local knowledge or surveys which behavioural responses can be realistically be aimed for in order to yield specific targeted benefits or indeed if specific decreases in network vehicle hours and hence congestion are possible. This is because horizontal lines intersect the different curves at points of equal benefits for different peak hour suppression levels i.e. along a given horizontal line, the benefits remain constant with varying peak hour suppression level. Thus a 4% decrease in total vehicle hours can be achieved in a number of ways each of which might have its pros and cons or might apply to circumstances relevant the city in question:

a. By suppressing about 8% of the peak hour trips in their entirety (Trip Suppression 1D line). This situation relies on a significantly elastic market with respect to say car travel costs; or a market in which the cross elasticity between car travel costs and PT fares or other measures such as journey time reliability or comfort is significant. Such a measure would also require that the alternative modes are available.

b. On the (PKSdng + 10%Sup1D line)(Peak spreading & 10% suppression (1D)), one would have to suppress about 11% of the peak hour trips; of these only the first one percent would peak spread while the other 10% would have to be entirely suppressed. Most of the benefits would be derived from trip suppression rather than from peak spreading. Such a scenario maybe ideal but more difficult to attain.

c. On the (PKSdng + 7%Sup1D line), 12 % of the peak hour traffic would have to be suppressed; of these the first 5% would redistribute to the peak shoulders while the other 7% was suppressed entirely. In this instance almost equal proportions of trips are suppressed as are peak spread. This is probably a more realisable scenario than (b).

d. On the (PKSdng + 5%Sup1D line), 14% of the peak hour car trips would be suppressed; of these the first 5% would be suppressed entirely while the other 9% peak spread to the peak shoulders. Such a scenario is consistent with literature evidence (e.g. CONCERT project). This would thus appear to be a scenario that can be achieved in reality.

Alternatively the Figures could be used to compare the potential network effects of responses that accrue from the same peak hour suppression level. For example if a survey established that a 10% suppression of car trips in the peak hour were possible then:

a. The entire suppression scenario yields a 5.9% decrease in total network vehicle hours but maybe more difficult to achieve;

b. The (PKSdng + 10%Sup1D line) line yields about 3.2 % decrease;

c. The (PKSdng + 5%Sup1D line) yields about 2.5% decrease, in which 5% of the trips redistribute to the peak shoulders and the other 5% is suppressed entirely.

d. The (PKSdng + 2.5%Sup1D line) yields a 1.5% decrease, in which 2.5% of the trips are entirely suppressed and the other 7.5% is peak spread.

e. The (peak spreading line) only yields a 1.2% decrease in which all the 10% peak hour suppressed trips redistribute to the peak shoulders.

Surveys that determine the most likely response for a particular city or town can help to decide whether the expected network benefits were worth implementing the scheme for congestion relief purposes.

6.11 Concluding Remarks

Table 6.19 below summarises the percentage decreases in total network vehicle hours for the Southampton network at normal congestion if the specific behavioural responses occurred.

Behavioural Response	**Low suppression level (up to 5%)**	**Med Sup levels (5 - 15%)**	**High Suppression levels (15 – 20%)**
Trip Suppression	Less than 1% decrease in VHS	1- 7.5% decrease	7.5-9% decrease
Peak Spreading	Less than 0.1%	0.1 – 2.2%	2.2 – 2.5%
Combined suppression & spreading	Less than /up to 0.3%	0.3 – 5.6%	5.6 – 8%

Table 6.19 Comparative range of decrease in network vehicle hours by response for similar suppression levels in peak hour at normal congestion

1. It can be seen that for all responses, very little benefits occur at very low suppression levels of up to 5%.
2. For all responses the largest reductions in network vehicle hours occurred in the suppression region 5% to about 15% when a large enough load was released from the network to cause appreciable junction capacity to be freed. Although some of the improvement came from a reduction in flow delay, this was not as significant as the improvement arising from decrease at junction delays (i.e. queuing delay).
3. As further suppression occurs (15% to 20%) the network improvements tail off. At these higher suppression levels, the network is now operating so low below saturation that there are no further appreciable benefits derived. This is understandable since as the network becomes less congested little decrease in vehicle hours can be obtained from both flow delay and queue delay. In fact at

such relatively high suppression levels, the network may become under utilised as excess capacity becomes available. If indeed the disincentive of direct charges is such that no latent demand is generated to take advantage of the improved network conditions, higher suppression levels may be uneconomic because the load on the network may not justify the investment already sunk into the infrastructure.

4. On a comparative basis, Table 6.19 shows that trip suppression has potential to yield the highest network improvements. In the hypothetical case in which this response was possible, the network would gain from this response. In reality trip suppression may be more difficult to attain.
5. The benefits from peak spreading were comparatively low and at -2.5% were about four times less than those of trip suppression.
6. Combining peak spreading with modest levels of absolute trip suppression has potential to improve network gains beyond those of peak spreading alone and comparable to those of absolute trip suppression.

6.12 A Case Study of the Suppression of Radial CBD Trips in Southampton

So far, this chapter has assumed the ideal scenario in which virtually all the O-D movements are affected by some TDM measure such as road pricing. The aim was to try and estimate the likely upper bound network benefits of selected suppression responses in an ideal situation. The TDM measure causing such responses could for example be where a network wide system of multiple cordons and/or zonal pricing system were in place. Such a system would mean travellers crossing a cordon and travellers within a cordon would all have to pay for travelling in the network. However, in the more practical and likely situation a single cordon or a very limited number of cordons might be in place. Therefore some trips would not be affected by the pricing as can be seen from Table 5.23 in Chapter 5. In such a situation, it is the radial trips that would be mainly affected since re-routeing would not be feasible for such trips.

6.12.1 Scenarios Modelled

It was therefore decided to consider what the network effects would be if only E-I trips into the Southampton CBD were suppressed in response to a cordon pricing scheme such as a CBD or a mid cordon. Trips into Southampton were appropriate for suppression since they are dominant in the AM peak. Two scenarios were modelled. In the first case, suppression in the presence of a 200 pence CBD cordon toll was investigated. This implies that network effects would arise from both the diversion effect of the tolls on through trips and from the suppression of radial trips with no re-routeing alternative. It was assumed that trips into the CBD were more likely to be suppressed than trips to zones outside of the CBD cordon, if a CBD cordon was in place. Further, the radial nature of public transport is more likely to provide a possible alternative mode for trips with destinations in the CBD. The optimistic scenario of suppressing up to 20% of the trips into the CBD in the peak hour was assumed.

In the second scenario, it was assumed that the 20% trips suppressed in the first scenario, retimed to the peak shoulders in equal proportions, i.e. half the car trips suppressed from the peak hour shifted to the pre peak shoulder and the other half shifted to the post peak hour shoulder. The total number of car trips over the whole O-D matrix was retained. A CBD cordon toll of 200 pence was assumed to be in place. The network effects from this scenario would arise from the re-routeing effects of through trips and the spreading of CBD bound trips over a wider time profile of the AM peak. The results of these scenarios are tabulated in Table 6.20 alongside the results of other previously considered scenarios.

Scenario Modelled	Total Network Vehicle Hours and (% Change from Base Case Scenario)	Total Network VKT and (% Change Base Case Scenario)	Overall Network Speed (KPH) and (% Change)
Base Case (1D)	18,120.4 (0.0%)	940,623.2 (0.0%)	51.9 (0.0%)
CBD Cordon Tolling (200 pence)	21,197.9 (+17%)	987,901.5 (+5.0%)	46.6 (-10.2%)
Network wide Suppression, no re-routeing	16, 565.8 (-8.6%)	887,540.1 (-5.7%)	53.6 (+3.3%)
20% E-I (CBD) Suppression assuming no re-routeing	17,476.5 (-3.6%)	915,769.3 (-2.6%)	52.4 (+1.0%)
20% E-I (CBD) Trip Suppression with CBD Toll (200 pence) + re-routeing	19,303.4 (+6.5%)	932,486.6 (-0.9%)	48.3 (-6.9%)
Network Wide Peak Spreading, no re-routeing	17,660.3 (-2.5%)	938,184.4 (-0.3%)	53.1 (+2.3%)
20% CBD E-I Peak Spreading assuming no re-routeing	18,064.8 (-0.3%)	943,452.1 (+0.3%)	52.2 (+0.6%)
20% E-I (CBD) Peak Spreading with CBD Toll (200 pence) + re-routeing	21,056.8 (+16.2%)	985,392.6 (+4.8%)	46.8 (-9.8%)

Table 6.20 Comparison of Network Performance for Different Response Scenarios

The trends in Table 6.20 are basically as expected. Firstly, network wide suppression yields the highest reductions in total network vehicle hours. Network wide peak spreading, which at -2.5% reduction in total network vehicle hours, yielded only about a quarter of the reductions from network wide suppression as was reported earlier in the chapter. Suppression of radial trips into the CBD reduced total network vehicle hours by about 3.6%. This decrease was comparable to that caused by network wide peak spreading of trips (-2.5%). This appears to suggest that for the Southampton network at current congestion levels, suppressing 20% of the radial trips into the CBD may produce similar reductions in total network vehicle hours as the reduction caused by peak spreading 20% of the trips in the entire O-D matrix. However, the results suggest that, peak spreading would not reduce the VKT to the same extent as the reduction caused by suppressing 20% of the radial trips into the CBD. In fact, the VKT of network wide peak spreading, are marginally lower if not similar to the base case scenario VKT. This is to be expected since under peak spreading, the same routes may be used by drivers but at different times. The benefits of reduced vehicle hours, therefore arise because drivers travel at different times instead of overloading the network by travelling at the same time. The marginal decrease in VKT under peak spreading may arise because shorter routes may become available for some drivers as a result of travelling at less congested times, although the VKT results suggest that drivers appear to use their original routes after peak spreading. On the other hand, network vehicle hour reductions from trip suppression arise mainly because of reduced car vehicle trips and hence reduced loading on the network. The reduction in VKT follows from the reduced number of car trips on the network. Obviously, unless the person trips are also reduced through for example working from home, trip suppression requires that alternative modes are provided to enable the purpose of the trip to be accomplished.

Generally, the results suggest that suppression mechanisms appear to yield higher network benefits than peak spreading and re-routing respectively. Re-routing on its own is seen to cause net network deterioration for the total network vehicle hours, VKT and overall network speed. Network wide suppression and network wide peak spreading are seen to yield higher network benefits than the suppression or peak spreading of radial trips into the CBD alone. This appears to be because less trips are affected when only a certain portion of the O-D matrix is affected. Ideally, it is those O-D movements that contribute the most to congestion (e.g. contribute the most delays and hence the most vehicle hours) that should be targeted since significant improvement in network performance may arise if such trips responded favourably to TDM measures. The former scenarios of network wide suppression or peak spreading, can be considered to represent the upper bound benefits while the later scenarios of partial suppression or peak spreading can be considered to represent the more realistic range of benefits that may be expected from implementing a CBD cordon rather than an network wide road user pricing scheme. The re-routing effects on the other hand represent the lower bound benefits that can be expected if the travel market was inelastic.

The results also suggest that, by causing re-routing, tolls may undermine the benefits accrued from elastic effects. For example, in the presence of tolling in which re-routeing is allowed to take place, suppression of up to 20% of the radial trips into the CBD, results in an overall network increase in total network vehicle hours. However, when only suppression of 20% of the radial trips into the CBD is allowed to occur without re-routeing, a 3.6% decrease in total network vehicle hours occurs. This seems to suggest that the re-routeing effect offsets the benefits that accrue as a result of the elastic response. Similar effects were noted when re-routeing and peak spreading were allowed to occur. However, the scenarios in which elastic responses occurred in conjunction with re-routeing, were seen to be better than the re-routeing scenario alone. The elastic responses offset some of the adverse effects that may rise from the boundary effects caused by the re-routeing.

The VKT changes are also as expected. With CBD tolling alone, the VKT increase by just over 5% at a toll of 200 pence. When network wide suppression of trips is assumed, the VKT decrease by about 5.7%. It is assumed in this scenario that no re-routeing occurs. When only trips into the CBD are suppressed assuming that no re-routeing occurs, the VKT decrease by about –2.6% compared to the base case scenario. When 20% of the trips into the CBD are suppressed and re-routing also permitted as a result of imposing a CBD toll of 200 pence, the VKT are seen to be only –0.9% lower than the base case scenario because through trips re-route to longer boundary routes. The same trends are observed for peak spreading. Clearly the extent to which network effects will vary according to which geographical areas or which O-D pairs are affected by a road user pricing scheme, is one that requires more detailed study than has been possible in this work. Nevertheless, the finding that re-routeing may undermine the network benefits of elastic responses is consistent with literature evidence. May and Milne (2000), expressed the concern that the ability to re-route appeared to reduce the benefits of road pricing even when suppression levels of up to 15% were achieved. They stated that since re-routeing was a very likely response in practice, concerns had to be raised regarding the overall benefits of direct user charges.

6.13 Summary of Chapter

This chapter has studied what the potential network effects of selected elastic responses might be using the Southampton network as a case study. In order to estimate the potential upper bound changes in total network vehicle hours, it was assumed that virtually all the O-D movements would be affected by the pricing measure implemented and that re-routeing would therefore not be a feasible option. Such a TDM pricing scheme could be a network wide system of cordon tolls and/or a network wide zonal system. The results suggested that suppression of up to 20% of the peak hour car trips would yield up to about 8.5% reduction in total network vehicle hours at normal congestion. These would result in significant reductions in congestion. However, the results also suggested that if the 20% car trips suppressed in the peak hour were transferred to the peak hour shoulders to simulate peak spreading, only a 2.5% reduction in total network vehicle hours would be achieved. At about only a quarter of the reductions for absolute trip suppression, the peak spreading reductions were lower than expected. The explanation could be that, the peak profile is already flattening out probably as a result of drivers travelling earlier or later to avoid the most congested conditions in the peak hour. It was also shown in this chapter that when relatively low levels of car trips were suppressed in combination with peak spreading, significantly higher benefits were possible compared to those of peak spreading alone. However, these benefits were as expected, still lower than those obtained from higher levels of car trip suppression without spreading the suppressed trips to the peak shoulders.

However, it was argued that the literature suggests that high levels of car trip suppression maybe more difficult to achieve than smaller levels of absolute car trip suppression in combination with higher but potentially achievable levels of peak spreading. Absolute car trip suppression assumes that the car trip will be given up altogether while the person trip was made by some alternative mode or the utility of the original trip achieved through for example teleworking. In peak spreading, the car trip is not foregone but is made at a different less congested time, i.e. this is a modification to the way the car trip is made and does not result in a reduction in the number of car trips made considered over the whole peak period profile.

It was also argued that a more realistic scenario such as a CBD cordon scheme rather than a network wide scheme, would indicate what the network benefits could be in a not 'so ideal' scenario. Were such a scheme to be implemented, radial E-I trips, particularly those into the CBD were more likely to respond elastically while through trips would potentially re-route. A fairly quick representation of tolling and trip suppression of trips crossing the CBD cordon, and one of tolling and peak spreading of the above indicated CBD bound trips, indicated that the overall network performance of the network would depend on the extent to which the benefits from elastic responses could outweigh the disbenefits that might arise from boundary effects as a result of re-routeing due to the tolls. This study seemed to suggest that for the Southampton network, the boundary effects would outweigh the gains from the elastic responses. However, these scenarios (of trip suppression/tolling, and peak spreading/tolling) showed a marked improvement over the scenario of re-routeing alone in which the O-D matrix was considered inelastic. It is apparent from the brief study of targeting specific O-D movements considered here, that more detailed studies of how benefits may vary by targeting specific O-D movements are required. Such studies might consider for example, if those O-D movements that yielded the most benefits by virtue of their spatial orientation and use of congested roads might in practice show greater elasticity to travel costs. This might not necessarily be so if such trips had higher values of time for example compared to other O-D movements, or if the additional travel costs due to tolls for example did not constitute a significant proportion to the travel costs. This is consistent with concerns that shorter trips would suffer most from pricing measures even though in principle, longer trips might contribute more to transport externalities in general than shorter trips. These issues are beyond the objectives of this research.

7 CONCLUSIONS AND FUTURE RESEARCH

7.1 Introduction

This research was concerned with estimating the potential network effects of TDM responses in alleviating network congestion. The responses that were explicitly considered in the network modelling are re-routeing, retiming, trip suppression and combined responses of peak spreading and trip suppression. Because the network data available was that for the AM peak period, the estimated effects pertained predominantly to this period of day and could be expected to arise mainly from changes in the behaviour of trip purposes associated with this time period. These include work trips (commuting), educational trips and to some degree employer trips. These trips are usually classified as non-discretionary or essential trips in the literature. The time period over which these behavioural responses were assumed to take place was in the short to medium term.

Re-routing was modelled in order to evaluate the baseline theoretical case of inelastic behaviour in which the travel market was assumed to only respond by changing their routes. The modelling in this case was essentially conventional since it is common practice in the literature to simulate increased costs of traversing a link or to represent the application of direct charges by increasing the impedance of the affected links through the generalised cost function (e.g. Wigan, 1971; Wigan and Bamford, 1973; Mekky, 1995, 1996, 1997; Milne, 1993; Smith et al, 1994; Milne, 1997). However, modelling usually differs according to the variables in the generalised cost used in the assignment modelling and care therefore has to be taken in ensuring consistency of units. For example some models are calibrated on generalised cost functions based on time and money, others on time and value of distance and so on. The Southampton model available for this study was based only on minimisation of journey time. It was possible to model the toll in CONTRAM by adding the toll in monetary units to a generalised cost function. The travel time costs were converted to monetary costs by multiplying the travel time by the value of time in the generalised cost function. To emphasise the behavioural effects in route choice as a result of the tolls, the term perceived cost instead of generalised cost was suggested in CONTRAM.

The methodology adopted to estimate the network impacts of the elastic effects was a hypothetical 'what if' approach based on literature guidance. The rationale for this approach was that there is still lack of understanding about travel behaviour and more specifically, the relationship between travel costs and travel behavioural outcomes. This cast some doubt on the validity of the output predicted by existing demand models. The methodology circumvented the need to develop, calibrate and validate a behavioural demand model to predict the behavioural responses. The methodology also circumvented the need for interaction between the network model and an external demand model such as a strategic model. In this way it was possible to devout considerable effort towards estimating the potential network benefits of the assumed behavioural responses. The methodology by its simplicity was also able to differentiate between different suppression mechanisms unlike other assignment based methods such as elastic assignment which although potentially able to be adopted to differentiate amongst different suppression mechanisms would inevitably increase the complexity of the modelling task (e.g. Milne, 1997; White et al, 1995). The methodology was also adopted because of the need to avoid costly data collection as well as because of the limited time within which the study was undertaken. The methodology can be adopted for any town or city.

The network benefits estimated were essentially an upper bound estimation of the network changes that could arise from the specified behavioural changes. The CONTRAM assignment model was employed to quantify these network effects for the Southampton network as a case study. The actual estimated network changes are specific to the Southampton network although the general trends or directional changes can be expected to be more generic.

It was assumed for the purpose of this study, that the behavioural responses arose from assumed road user charging scenarios although they could well have arisen from any other appropriately designed TDM measure;-at least in terms of the nature of the behavioural responses rather than in their magnitude. The conclusions drawn from this study and reported in this chapter pertain to both the literature especially in so far as the behavioural responses are concerned and to the actual network modelling using CONTRAM which depended so much for inputs on guidelines from the literature evidence.

7.2 Context of Behavioural Response

The remarks arising from the behavioural context of TDM measures are of a more general nature. They, however, serve to put into context the complexities associated with trying to predict the outcome of policy measures whose success depends on human behavioural changes. From a policy perspective, the main issues relevant to this research were the nature of the behavioural responses, the likely causal factors and the magnitude of the behavioural changes to be expected.

7.2.1 The Nature of the Impacts

The following qualitative issues were evident in the literature:

The factors that influence the behavioural outcomes of TDM measures appear to go beyond the need to simply gain savings in travel time or minimise travel costs (e.g. Johnston, 1991; Cullinane, 1992; Bartley, 1995 (in MIRO); Hodgson et al, 1997 (in MIST); De Palma et al, 1997). Factors such as habit, convenience, journey time reliability, circumstances and constraints associated with specific trip purposes and market segments, the desire to travel at certain times (trip timing) rather than to simply minimise travel duration (trade off between trip timing and trip duration), socio - economic and demographic differences, subsidies such as access to a company vehicle, car - ownership, attainment of a driver's licence, the passage of time (short, medium and long term responses) and even the type of TDM measure all appear to have potential bearing on the travel behavioural outcome (e.g. Prevedous et al, 1992; Bartley, 1995 (MIRO); Collis and Inwood, 1996 (Bristol); Meyer, 1999; Tertoolen et al, 2000). The MIST study reported by Hodgson et al, 1997 often found respondents ranking convenience and reliability ahead of journey duration by both car and bus users. The MIST project sought to study the contribution of public awareness campaigns to integrated transport strategies.

While the qualitative effects of these factors (e.g. the 'directional changes') appear to be understood, the quantitative effects/influence of these factors still remains an area of uncertainty (e.g. Harvey, 1994; Marshall and Bannister, 1997,2000). This is because quantitative measurements for a subject as subjective and complex as human behaviour is a formidable task, made even so by difficulties in isolating the causes of these behavioural changes (Marshall and Bannister, 2000). The adoption of a hypothetical approach rather than a predictive one is therefore understandable.

As to the nature of the impacts, although re-routeing is the most likely response (e.g. May et al, 1998; Bonsall et al, 1998 (working paper)), there is evidence to suggest that other behavioural responses are possible if so encouraged by circumstances, TDM scheme design and the adoption of appropriate incentives and disincentives (e.g. Sullivan and El Harake, 1998; Mastako et al, 1998). Various demonstration projects such as CONCERT and MobilPASS have also demonstrated that driver responses other than re-routeing are possible. Further, stated intentions from a number of studies do reveal some potential elastic responses beyond mere re-routeing (e.g. Collins and Inwood, 1996; Bartley, 1995). A primary response is usually evident although a series of minor or secondary responses may also be evident (e.g. Johnston and Rodier ,1994; Harvey, 1994). It was assumed in this work that the primary response influenced the extent of the network benefits.

There also appears to be evidence in the literature to suggest that the nature of the behavioural changes is greatly associated with the design of the TDM scheme rather than with a specific TDM measure (see Table 4.1 and also Gillen, 1994). For instance, peak spreading is likely to result from any of a number of time differentiated measures such as differential road user charging schemes, increased peak period congestion and flexi work arrangements. Destination changes are likely to arise from spatially differentiated policies such as increased parking costs at certain locations, restricted zone access or the application of direct road user charges at specific locations. However, there appears to be an understanding in the literature that the magnitude (as opposed to the nature of the response) and hence the elasticity of the response for a given market segment, is influenced more by the 'coercive aggression' of the TDM measure. There appears to be an implied view that direct user charging methods have the potential to extort relatively larger responses than non direct charging methods (e.g. Cullinane, 1992, Decourla-Souza, 1993; Rodier and Johnston, 1997; Tolofari, 1997; Taylor et al, 1997; Gärling et al, 2000; Marshall and Bannister, 2000). There, however, does not appear to be a unique 'quantitative' indication as to extent of these differences. For example Gärling et al, 2000 suggested from a study in Goteborg in Sweden that 10% constituted an upper limit on the amount of change that can be expected in the short to medium term through the use of 'non-coercive' strategies. Demonstration trials such as LERTS seemed to suggest that a 20% peak period suppression level is about the maximum that can be achieved with direct user charging. Decorla-Souza (1993) concluded from a modelling study that congestion pricing would reduce daily traffic by 2.5% in that particular area while by comparison, this reduction would only be 0.4% if stringent regulatory employer based strategies were applied - a ratio of 6:1 in this particular study. Quantitative comparisons amongst different studies are obviously difficult because of the different contexts in which they are carried out, the different charge levels applied and the different charging schemes modelled or assumed-i.e. there is rarely a significant degree of commonality to enable parallel comparison (e.g. Bartley, 1995); May and Milne, 2000).

Generally, in so far as the nature of the responses are concerned, modification to car use rather than absolute suppression of car usage appears to be a more realistic outcome of TDM measures in western countries with high car ownership and use (e.g. Dawson, 1986 and recently confirmed by May et al, 1998). Such modifications to car use might include retiming of trips resulting in peak spreading, reduced trip frequency and trip chaining and possibly destination changes for trips such as shopping trips. While the evidence in Singapore demonstrated significant modal shifts to public transport, experts point out such experiences may not be directly transferable to western countries for a number of reasons (e.g. Dawson, 1986). This included the fact that public transport in Singapore for example already enjoyed a significant share of the travel market and mass movement was already significantly centred around the use of public transport.

7.2.2 The Magnitude of the Impacts

The evidence on the magnitude of changes with respect to specific behavioural changes is less clear cut from the literature if not uncertain. This appears to be due to difficulties in isolating the actual magnitude of behavioural changes attributable to the TDM as differentiated from say background growth or other exogenous factors (e.g. Marshall and Bannister, 2000; O' Mahony, 2000). For example a pilot action study in Dublin (O' Mahony, 2000), found a 22% reduction in car use from the programme participants in the peak period. There was 99.5% confidence that this was due to the charging scheme. There was, however, not enough evidence to conclude that the 6% increase in traffic in the off peak period was due to re timing as a result of the differential nature of the pricing. More baffling was the 1% decrease in VKT in the off peak period despite the apparent increase in traffic in this period. What was evident though was the response by drivers to avoid travelling by car in the peak period. The alternatives by which the journeys were made varied from some evidence of retiming to modal changes to public transport and even cycling. The quantification of each of these behavioural responses was not a straight forward issue.

Another result of note is the finding by May et al, (1998) that the values of time from road user charging were somewhat higher than those suggested by public transport fare changes. This would suggest lower elasticity estimates from road user charging as compared to public transport fares. Yet evidence elsewhere in the literature seems to suggest that road user charging is potentially the most 'coercive' TDM compared to other less coercive measures including public transport fare changes. This example serves to illustrate the uncertainties still inherent in giving clear cut quantitative evidence on the behavioural changes to be expected from TDM measures. It would appear that detailed quantitative evidence on such behavioural changes may have to be carried out specifically for the locality under study taking into account the prevailing local conditions. The elasticity estimates of -0.1 to -0.5 suggested by the literature have to be used as guidelines rather than as typical values. This is further illustrated by the studies at Leeds and York Universities (e.g. Smith et al, 1994) where an elasticity of -0.5 was assumed in the SATEASY elastic assignment modelling. Studies at a later date (May et al, 1998) concluded that this -0.5

value was higher than what localised behavioural experiments suggested (May and Milne, 2000).

Another point of concern that is evident in the literature is that road user charging elasticities may be undermined if employers compensated drivers for the charges that they paid. For example, Kuppam et al, (1998), concluded from stated preference surveys that employer subsidies encouraged commuters to travel by car when a significant but not necessarily all of introduced direct charges were compensated for. This seems to imply that for some drivers, en-route charges and indeed destination end charges may have to be complemented by 'destination end' non fiscal policies such as a limit on parking spaces at the work place in order to influence travel behaviour.

There, however, appear to be a bolder if not consistent value in the literature about the potential upper bound general car trip suppression level in charged peak periods. The figure 20% suppression level appears to be consistent across a number of studies and interestingly even amongst studies in both Europe and the United States. There also appears to be some consistency in the fact that this 20% suppression level is unlikely to present as absolute trip suppression but translate into a myriad of responses such as retiming, trip chaining, destination changes, modal changes amongst others. There appears to be a related bold conclusion that absolute trip car suppression (i.e. car trips completely removed from the network rather than translated into modified car use behaviour) is unlikely to exceed 10% (e.g. Tertoolen et al, 2000) although the frequently quoted figure seems to be around 2.5% at the lower end (e.g. Decorla-Souza, 1993) to 5%-7% at the upper end (e.g. Hayes et al, 1999). Such an absolute suppression of car trips from the O-D matrix could potentially arise from teleworking/commuting (1-2%) and through modal changes such as carpooling, walking, cycling and the use of public transport within existing land use patterns. This suppression level may be expected to increase in newer towns designed on land use patterns based on high density-mixed land use patterns. From an elasticity estimate point of view transport demand elasticities appear to be within the band of -0.1 to -0.5 at an aggregate level.

7.3 Conclusions about the Network Effects of Behavioural Changes

Although re-routeing alone is unlikely to be the sole response of travellers in real life, the inelastic modelling served to reinforce some known policy issues. For example, it was found out that the network performance deteriorated with increasing cordon charge level as expected, when evaluated on total network vehicle hours and from VKT. Network performance was also found to deteriorate with increased coverage as represented by the number of cordons for the same performance indicators. This too was expected for inelastic assignment. The deterioration with increasing charge level can from a policy context be explained by the fact that more people re-route to longer and unsuitable routes as the charge level increases. The deterioration with increasing number of cordons stems from the fact such an increase in cordon number is an increase in scheme coverage. As a result more O-D pairs are affected leading to more people re-routeing to longer and unsuitable routes as they tried to avoid the charges. From this perspective, multiple cordons appear to perform worse than single cordons when evaluated on total network vehicle hours and VKT under inelastic modelling.

From a policy context, the apparent deterioration in network performance with increasing charge level and scheme coverage has at least two contrasting interpretations. The first interpretation indicates the potential for travellers to shift to facilities on the boundaries of the scheme as they try to avoid paying the charge. These boundary effects may not only present as increases in flows on ring roads, it may also present as increases in demand for parking on zones at the peripherals of the charging schemes. This may happen because of some travellers driving to the edges of the charging schemes and then completing their journeys by some alternative mode such as walking or using public transport. Based on this interpretation, multiple cordons would cause the most adverse boundary effects. These effects would increase with increasing charge level for both single and multiple cordons.

A second interpretation could be that the deterioration of the network under inelastic assignment is an indication of the potential for travellers to change their travel behaviour in real life as network costs increase. Under inelastic assignment this potential to respond in ways other than re-routing is not represented. However, literature evidence suggests that increases in travel costs are associated with changes in travel behaviour although the relationship is not fully understood, and hence the continued research interest in trying to develop models better able to represent and predict the outcome of this relationship. It was shown from the modelling that despite an increase in costs due to tolling, a substantial number of trips continued to cross the cordons. These trips were radial trips with destinations inside the cordons and origins outside it (E-I) and vice versa (I-E trips). Under inelastic modelling, it is assumed that all these trips continue to travel as before despite the increase in travel costs modelled as time penalty. This basically assumes that all trips unable to re-route, are willing to pay. In reality some of these drivers will be priced off because they had low values of time and could not afford the toll or did not value their time savings highly. Based on this interpretation, multiple cordons had the higher potential to cause elastic behaviour.

A study of some O-D movements for E-I trips into the CBD, indicated that although overall network performance may deteriorate under inelastic assignment, some of these specific trips could enjoy significant travel time savings. For some O-D pairs considered in this work, travel time savings of up to about three minutes were found. However, the equivalent monetary travel time savings were lower than the tolls paid, particularly at higher tolls.

The elastic modelling showed that peak hour suppression levels of up to 20% could result in an overall network decrease in vehicle hours of up to 9% at normal congestion. Most of this decrease occurred between the 5% and 15% suppression levels (7.5%) with the other 2.5% achieved between the 15% and 20% suppression levels.

When the same suppression levels were applied and the suppressed trips then redistributed to the pre and post peak shoulders to simulate flattening of the peak profile as might occur with peak spreading, the percentage decrease in the total network vehicle hours was only 2.5%. This was about four times less than the benefits accrued with trip suppression. These benefits were therefore very small.

Peak spreading is, however, the most likely behavioural response after re-routing and the benefits from peak spreading can be expected to be realised in practice than those requiring significant levels of car trip suppression instead of modification in car use. However, the literature notes that total suppression levels of 1% to 7% have been and can realistically be achieved in conjunction with peak spreading. Modelling using the Southampton network showed that combining moderate levels of trip suppression with peak spreading, had the potential to double the benefits achieved with peak spreading alone from 2.5% to about 5%. This result is quite significant since it implies that appreciable network benefits can be achieved without the need to completely suppress a large proportion of the peak period travel market.

In general, single behavioural changes on their own (other than complete trip suppression), yielded relatively low overall network benefits at normal or current congestion levels. However, it was demonstrated that significant benefits could be achieved through a combination of behavioural changes even with moderate levels of trip suppression at normal congestion. This seems to reinforce the view that a combination of TDM measures rather than one single measure is a better policy direction to pursue since it has the potential to provide a wider range of alternatives to those forced to modify their travel behaviour. This may also ease the need to achieve high levels of investment in public transport alternatives in otherwise overly short periods of time.

From a direct user charging perspective, the modelling has also basically shown that if direct pricing were the TDM yielding these benefits, then compared to the £2.00 direct charge that can be expected if a pricing scheme were implemented in a city the size of Southampton, the average driver left in the peak hour would thus recoup only a small fraction (0.01% to 11.5%) of the direct charges that they paid. This seems to support literature evidence that the equivalent journey time savings of paying drivers will be lower than the actual out of pocket costs paid by these drivers. Peak Spreading modelling also showed that the benefits can be expected to be substantially higher at higher congestion levels. This was consistent with expectation and literature evidence.

When suppression mechanisms were considered in the presence of tolls for some radial trips with destinations in the CBD and origins outside the CBD cordon, the results suggested that re-routing effects would undermine the benefits gained from the elastic responses. However, the overall network performance under these scenarios were found to be better than if re-routeing alone were to occur. The finding that the re-routing effects might undermine the gains from the elastic responses was also consistent with literature evidence (e.g. May and Milne, 2000).

Although the behavioural modelling adopted in this research is very simple since it does not offer direct predictive mechanisms or relationships between travel costs and/or attributes and behavioural responses, it has, however, shed light on the potential network effects of different behavioural responses as might arise from TDM measures such as direct user charging. It has shown that the overall network benefits to be realised from the most likely behavioural responses particularly peak spreading and destination changes might not be as high as is intuitively imagined. Rather a combination of responses even in moderation maybe more beneficial. It is to be expected that some individual trips will, however, enjoy significant travel time savings. The strength of the modelling approach employed here, is that it can be adopted to any city or town since it requires no coefficients specific to one locality. Instead assumptions maybe made according to the problem at hand and a significant range of outcomes or scenarios can be tested to help in identifying the scenario likely to yield the best results. Identifying this scenario in advance can then help to decide if a more detailed study is worth pursuing in view of the benefits that can be potentially achieved. With respect to the Southampton situation for example, the methodology has shown that a policy aimed at simply achieving peak spreading would not be beneficial at normal congestion unless such a policy also managed to achieve moderate levels of absolute trip suppression.

7.4 Future Research

Obviously the need to improve understanding of the behavioural outcomes of TDM policies remains an area of immense research interest. The need to develop models better able to predict the behavioural responses of these measures and their consequent network effects is on going in transportation research. Some specific issues that may require further study follow below.

The extent to which different market segments are sensitive to specific TDM incentives and or disincentives (Behavioural research). Since modification to car use rather than complete foregoing of car use appears to be a more likely behavioural response, research is required in determining 'cross elasticities' between competing time slices in the retiming of trips. Such cross elasticity estimates could potentially be determined between competing time period as short as fifteen minutes. After all evidence suggests that sharp variations in price between adjacent time slices significantly influences retiming (CONCERT, MobilPASS, LERTS)

While most studies (e.g. May and Milne, 2000; Gower and Mitchell, 1998; Mekky, 1995, 1996,1997; Tolofari , 1997, ROCOL, 2000 are consistent in that pricing schemes would result in improved travel conditions within the charged area or charged facilities, few studies consider the transfer effects of such schemes especially the effects on boundary routes. This is turn implies that the net effect of pricing on the network as a whole remains unclear. Fears at present now appear to stem not on what the benefits would be in the charged area and to those left to enjoy those benefits but rather on what the potential adverse transfer effects to neighbouring non-priced areas, zones and routes. The literature seems to shed little light if not mixed messages as to the potential extent of this problem. This research by modelling various cordon arrangements seems to suggest that this is a potential real problem especially where limited capacity exists on alternative routes. The problem, however, goes beyond the effect on these boundary roads but also what pressures might arise on parking at the zones on the peripheral of such schemes. This is an area that requires more detailed investigation.

Continuing on the theme of boundary effects, very little evidence in the literature on the network effects of destination changes. This is an area that requires urgent attention especially since co-operation between different local authorities may be required to contain transferring any adverse effects to other business centres or to allay fears that customers may switch their shopping for example to neighbouring non priced centres.

While facility pricing or linear pricing may yield some nominal net overall network improvements due to reassignment, the corresponding effects for area wide pricing are less clear. Few studies made the comparison between opposing effects of the magnitude of the improvement in network performance of the charged area that in non charged facilities or areas outside the charged area. Such comparison would not only show if there was a net improvement in the overall performance of the network as a whole but would shed light on the extent to which diversionary effects of road user pricing scheme might be undesirable. This is an area requiring further research.

Lastly, pricing measures are likely to affect certain travel markets more than others. In particular, certain O-D movements or pairs are more likely to be affected than others simply because of the spatial design of the scheme. Therefore, it worth investigating how geographical coverage may affect network performance by considering the potential responses of specific O-D pairs affected. The extent to which the effects of geographic coverage may be affected by the elasticities of the affected O-D pairs or travel markets also provides a potential area of further research.

GLOSSARY OF TERMS

1.1D-Base case O-D matrix factored by 10% to represent demand increase of 10%
1.2D-Base case O-D matrix factored by 20% to represent demand increase of 20%
1D-Base case O-D matrix
ADEPT-Automatic Debiting and Electronic Payment for Transport
AGE (model)-Applied General Equilibrium
APRIL-Assessment of Road Pricing In London
ATT-Advanced Travel Telematics
AVI-Automatic Vehicle Identification
AWS-Alternative Working Schedules
CAAA (1990)-Clean Air Act Ammendments of 1990
CARDME-Concerted Action on Demand Management in Europe. A project which started in 1994 and which was completed in 2001. It was mainly concerned with interoperable road tolls.
CARLA-Combinatorial Algorithm For Rescheduling Lists Of Activities
CBD-Central Business District
CONCERT-a European demonstration project that ended in 1998 after 30 months was orchestrated around a framework that related behavioural impact hypotheses to key areas of application such as integrated payment with smart cards, road user restraint by pricing and by access control, and multi-modal traveler information. CONCERT addressed demand management issues such as the ability of public transport incentives to 'pull' and the ability of road/pricing/access control to 'push' behavioural changes by motorists. Also addressed was the ability of multi-modal travel information services to accentuate travel behavioural changes-(http://www.euconcert.com/concert/indice.htm) (accessed 17 August 1999).
CVs-Commercial Vehicles
DANTE (Project)-Designs to Avoid the Need to Travel in Europe
DCM-Discrete Choice Modelling
DETR-Department of the Environment, Transport and the Regions.
DOT-Department of Transport
DRACULA-Dynamic Route Assignment Combining User Learning and microsimulAtion.
DRIVE I, II (Projects)-Dedicated Road Infrastructure for **V**ehicle safety in **E**urope
DTLR-Department of Transport, Local Government and the Regions
DUE-Deterministic User Equilibrium
ECMT-European Conference of Ministers of Transport
E-E trips-External–External trips have both their origin and destination outside a specified cordon.
E-I and I-E trips-External to Internal and Internal to External trips. Trips moving with an origin outside a zone or cordon and a destination inside the cordon; and vice versa.
ELGAR-Environmental Led Guidance and Restraint. This TDM demonstration project ran from January 1996 to June 1998 under Bristol City Council with funding by the European Commission and the then DETR. Its aim was to test a variety of TDM measures with a view to improving air quality in Bristol.

EMME/2-Multimodal Equilibrium/Equilibrium Multimodal
ERP-Electronic Road Pricing
ETC-Electronic Toll Collection
ETPs-Employer Travel Plans
EUROPRICE-European Urban Road Pricing Network comprises a group of major cities across Europe whose aim is to advance road pricing initiatives in Europe. The cities are Bristol, Belfast, Copenhagen, Edinburgh, Genoa, Leicester, Rome and Trondheim and are supported by the European Commission, General-Directorate for Transport (DGVII)
EUROTOLL-European Project for Toll Effects and Pricing Strategies. This project was part of the General-Directorate for Transport (DGVII) Fourth Framework Programme for European Transport. The primary aim of EUROTOLL was to obtain understanding of road user reactions to transport demand management (TDM).
FIFO-First In First Out
GAUDI Project-Generalised and Advanced Urban Debiting Innovations
GLA-Greater London Authority
GMTU-Greater Manchester Transportation Unit
GTA-Greater Toronto Area
GTPs-Green Travel Plans
HB (trips)-Home Based trips either begin or end at a residence.
HBEB (trips)-Home Based Employer Business
HBW (trips)-Home Based Work trips
HOV-High Occupancy Vehicle
IHT-Institute of Highways and Transportation
I-I trips-Internal-Internal trips; Trips whose origin and destination are both inside a specified cordon.
ISTEA-Intermodal Surface Transportation Efficiency Act
IVHS-Intelligent Vehicle Highway System**;** A term used in American transport literature to describe intelligent transportation management measures that include automated highways, route guidance, in-vehicle motorist information systems, advanced traffic management and control concepts.
KPH-Kilometres Per Hour
LERTS-**L**eicester **E**nvironmental **R**oad **T**olling **S**cheme -conceived as an innovative demonstration of electronic road tolling in an urban area of the UK. It was sponsored by the then DETR together with Leicester City Council to the sum of £3.5M and examined the impacts of charging for private car travel in the city of Leicester. The demonstration operated between August 1997 and May 1998.
LGVs-Light Goods Vehicles
LOS-Level Of Service. This concept was described in the 1965 Highway Capacity Manual. It relates the operating speed in a stream of traffic, to the congestion of the traffic stream measured as flow or flow to capacity ratio. Six levels of service exist, designated A to F. LOS A represents free flow conditions while LOS F represents forced or breakdown flow where traffic approaching a point exceeds the amount that can traverse the point and queues form behind such locations.
LTS-London Transportation Study
LUM-Land Use Management

MARTA-Monitoring Attitudes towards Road Transport Automation
MCL-Melbourne City Link-a fully automated toll road built in Melbourne, Australia. It was a privately funded and operated toll road that encourages traffic to pass around the central administrative district (CAD) rather than through it.
ME2-Matrix Estimation
MIRO Project-Mobility Impacts, Reactions and Opinions. The MIRO Project was a collaborative study of public opinion about a range of traffic or travel demand management measures in Europe sponsored under the DRIVE II Programme.
MIST-Maidenstone Initiative for Sustainable Transport
MobilPASS-The Stuttgart MobilPASS cordon pricing experiment/demonstration project was conducted in Germany in 1994/1995. 400 participants were issued with a smart card called a MobilPASS which provided a completely automated system for paying transportation charges.
MPC-Marginal Private Costs-a driver entering a congested stream of traffic will only consider the cost that they incur. The MPC is therefore the additional cost borne and perceived by the driver on entering the congested stream of traffic.
MPO-MetroPolitan Organisations
MSC-Marginal Social Costs-A driver entering a congested traffic stream does not take into account the costs that they impose on other drivers. The additional cost to other drivers of adding one extra vehicle to the traffic stream is called the MSC.
MVMODL-MVMODL is one part of the TRIPS demand modeling module within TRIPS. MVMODL is actually the full name of the program but the MV comes from MVA the parent company that first developed TRIPS.
NHB (trips)-Non Home Based trips
O-D-Origin-Destination
OECD (1994)-Organisation For Economic Co-Operation And Development
OGVs-Other Goods Vehicles
PARAMICS-Parallel Microscopic Simulation of Road Traffic-This is a Suite Of Software Tools For Traffic Simulation.
PCU-Passenger Car Unit
PESAP-Program Evaluating the Set of Alternative Sample Paths; a simulation model that explores the implications of changes in the transport network or land use pattern on individual activity-based travel choices.
Post Pk Hr ShD-Post Peak Hour Shoulder
Pre Pk Hr ShD-Pre Peak Hour Shoulder
Que Del-Queueing Delays
ROCOL-Review of Charging Options for London. The ROCOL Working Group was formed in 1998 and their ROCOL report was published in 2000. The purpose of the group was to provide an assessment of the illustrative options for use of powers that would be available to the new mayor of London. The report amongst other issues, illustrated how the mayor's powers might be deployed, the impact they could have on London's traffic and transport, and the possible responses of the public and businesses.
RP (surveys)-Revealed Preference Surveys- respondents state how they actually respond to scenarios they encounter in real life.
RTRA-Road Traffic Reduction Act

SACHAS-SAturn CHoice ASsignment
SACHDI-SAturn CHoice Module D1
SACTRA-Standing Advisory Committee on Trunk Road Assessment
SATCHMO-SATURN Travel CHoice Model
SATASS-SATurn ASSignment
SATEASY-SATurn Elastic Assignment is a variation on SATASS, SATurn ASSignment
SATURN-Simulation and Assignment of Traffic in Urban Road Networks
SCHEDULER-SCHEDULER is the full name of this activity based program and its name captures the concept in the program and is not an acronym.
SCOOT-Split Cycle Offset Optimisation Technique
SHRP-Strategic Highway Research Program
Singapore ALS-Singapore Area Licensing Scheme
SLM-Single Link Model
SMASH-Simulation Model of Activity Scheduling Behaviour
SO-System Optimal
SOV-Single Occupant Vehicle
SP (surveys)-Stated Preference Surveys. Respondents state how they would respond to some given hypothetical scenarios.
STARCHILD-Simulation Of Travel/Activity Responses To Complex Household Interactive Logistic Decisions
STEN-Space Time Expanded Network
TCM Transportation Control Measures
TCS-Travel Characteristics Survey
TDM-Travel Demand Management
TEA-21-Transportation Equity Act for the 21st Century
TM&C-Traffic Management and Control
Tot Net VHS-Total Network Vehicle Hours
TPM-Transport Policy Model
TRAM- Traffic Restraint Analysis Model
TRANSPRICE-Trans-Modal Integrated Urban Transport Pricing for Optimum Modal Split
TRAVEL/2 (model)-An American four stage model with internal feedback so that cost changes in the demand modules can be fed back into the assignment model to ensure consistency between the assignment model costs and demand model costs.
TRB-Transportation Research Board
TRG-Transportation Research Group
TRIPS-Transport Improvement Planning System is a transportation planning package which enables strategic as well as detailed analyses of multi-modal transportation networks. It was originally developed by the MVA Consultancy.
TRL-Transport Research Laboratory
TRM-Traffic Restraint Measures
TRON 1&2 (Projects)-These were field trial projects in TRONdheim, Norway. TRON 1 (1996) demonstrated integrated payment for public transport, parking and crossing the toll ring in Trondheim. In TRON 2, (1997) the main objective was to demonstrate and evaluate road pricing as a demand management instrument.

TSM-Transportation System Management
UTMS-Urban Transportation Modelling System represents the original sequential four stage model of Trip Generation, Trip Distribution, Modal Choice and Assignment.
Veh Hrs-Vehicle Hours
VHS-Vehicle Hours
VKT-Vehicle Kilometres Travelled
VLADIMIR-Variable Legend Assessment Device for Interactive Monitoring of Individual Route Choice
VMT-Vehicle Miles Travelled
VOT-Value of Time
WATROD-A program used to analyse route file data in CONTRAM
WILTRAM-West Inner London Traffic Model
WPPL-Work Place Parking Levy

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