School of Engineering and the Built Environment

MODELLING BEHAVIOURAL RESPONSES TO TOLLING BY MICROSIMULATION

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ABSTRACT

Over the past few decades there has been a renewed interest in road pricing. This has come about due to the increasing realisation of the negative effects of unrestrained car use, such as, the impact of congestion on the economy and pollution on the environment, to name a few. In this respect, road pricing offers a mechanism for controlling demand. To date, road pricing has been applied to city centres, sections of motorways, individual lanes, bridges, tunnels to name but a few examples. Charges can also be further refined and varied according to the time of day, day of the week, traffic volumes, vehicle types, vehicle occupancy, etc.

Moreover, the evaluation of transport schemes has become reliant on the careful consideration of all possible outcomes. An important technology which has been developed is traffic microsimulation modelling. This enables transport professionals to replicate by computer simulation the behaviour of individual vehicles within an exact representation of the actual road network. The robustness of microsimulation modelling, nevertheless, depends on the accuracy with which actual traffic behaviour is represented. In the case of road pricing the key element lies in predicting motorist's behavioural responses when confronted with tolls.

There are various scenarios in which tolls could be applied and some may offer alternative routes, alternative modes, etc. Yet, these all depend on an individual's willingness to pay to avoid a congested trip that comprises either increased journey times (measured as 'Value Of Time') or a more unpredictable journey time (measured as 'Value Of Reliability').

The purpose of this research is to advance the modelling of trip-makers behavioural responses to tolls in a PC-simulated environment. The objectives are therefore: (1) to determine the modelling procedure that proves most adequate to the requirements of the modelling of tolls, (2) to establish the necessity of including a VOT and VOR element in the route choice system of a model, (3) to review VOT and VOR values in the literature and to identify the variables that account for different valuations, (4) to assess whether values from literature are applicable to a UK context, and in case they are not (5) to develop a calibrated and validated microsimulation model that can be used in future research to derive UK values. From this modelling exercise, conclusions are derived about the challenges of modelling congested networks with highly variable travel times and its implications in the inclusion of VOT and VOR in simulation. Finally, recommendations for future research are presented based on the findings of this research.

TABLE OF CONTENTS

TABLES

FIGURES

EQUATIONS

GLOSSARY OF ABBREVIATIONS

4SM: 4-Stage Model

BPR: Bureau of Public Roads

DfT: Department for Transport

DA: Dynamic Assignment

DMRB: Design Manual for Roads and Bridges

DNS: Date not stated

DORA: Degree Of Risk Aversion

DTA: Dynamic Traffic Assignment

FAIR: Fast And Intertwined Regular (lanes)

GCE: Generalised Cost Equation

GDP: Gross Domestic Product

GPS: Global Positioning System

HA: Highways Agency

HATRIS: Highways Agency Traffic Information System

HOT: High Occupancy/Toll

HOV: High Occupancy Vehicle

IHT: Institution of Highways and Transportation

JiT: Just-in-Time

JTDB: Journey Time Database

MIDAS: Motorway Incident Detection and Automatic Signalling)

MEL: Midland Expressway Limited

MNL: Multinomial Logit Model

MSA: Method of Successive Averages

O-D: Origin-Destination

PAT: Preferred Arrival Time

RP: Revealed Preference

RUT: Random Utility Theory

SA: Stochastic Assignment

SD: Standard Deviation

SDA: Stochastic Dynamic Assignment

SP: Stated Preference

TRADS: Traffic Flow Database System

UE: User Equilibrium

VED: Vehicle Excise Duty

VOR: Value of Reliability

VOT: Value of Time

VOV: Value of Variability

WebTAG: Website-based Transport Analysis Guidance

CHAPTER 1. INTRODUCTION TO ROAD TOLLING

1.1 Road tolling in this research

The purpose of this research is to advance the modelling of trip-makers behavioural responses to tolls in a PC-simulated environment. Prior to the construction of a new road scheme, its suitability will be commonly assessed by using traffic models. These are frequently used to forecast the effects of schemes such as a new road layout or the provision of a new road link. In modelling terms the aspects used to create the forecast are based on drivers' willingness to accept given journey times, queues and road distances. Road tolling schemes are different in that they introduce a new variable: monetary costs. Toll roads typically offer drivers a shorter journey where travel times do not vary much from one day to the next. When presented with tolls, drivers need to decide whether and how much they are willing to pay to benefit from these advantages. This is a subjective choice, which is difficult to quantify but it is nevertheless crucial to modelling road tolling.

The objective of this research is to analyse values of time and reliability from the literature in order to find a trend such as tolling contexts, groups of drivers or time periods with similar values. After this, a model of a tolling context in the UK is formulated, calibrated and validated for use in future research to test values of time and reliability.

In order to understand the context of road tolling, this research starts by presenting a brief introduction of the principles of road tolling and the different ways in which it has been introduced across different countries. This chapter will investigate under which conditions tolling is implemented and which schemes are most suitable to the modelling purposes of this study.

1.2 Charging for road use

As part of the transport network, roads are an economic resource that plays a crucial role in sustaining economic success. The relationship between mobility and economic activity is set out in the Eddington Report (2006), which identified seven main roles of transport in the economy:

1. Transport increases business efficiency, through time savings and improved reliability for business travellers, freight and logistics operations.

2. Transport increases business investment and innovation by supporting economies of scale or new ways of working.

3. Transport supports clusters and agglomerations of economic activity. Transport improvements can expand labour market catchments, improve job matching, and facilitate business to business interactions.

4. Transport improves the efficient functioning of labour markets, increasing labour market flexibility and the accessibility of jobs. Transport can facilitate geographic and employment mobility in response to shifting economic activity.

5. Transport increases competition by opening up access to new markets. Transport improvements can allow businesses to trade over a wider area, increasing competitive pressure and providing consumers with more choice.

6. Transport increases domestic and international trade by reducing the costs of trading. Domestic trade links are particularly important to the economic success of some urban areas.

7. Transport attracts globally mobile activity to the UK by providing an attractive business environment and good quality of life. Such effects are of increasing importance but extremely difficult to quantify.

The above benefits can only be realised if the transport network is efficient. In the case of a road network, excessive demand leads to delays in journey times, these delays cost the economy money.

For instance, there are direct costs associated with the building and maintenance of the road network. These are traditionally funded by the State or by means of public-private partnerships. These costs are recouped from the users of the road network through Vehicle Excise Duty (VED) taxation and taxation on fuel.

There are other costs associated with the inefficient functioning of the network. These are usually referred to as indirect and relate to congestion caused by high levels of demand at specific points over the road network at specific times. This is inextricably linked to the productivity and competitiveness in an economy. The Eddington report predicted that existing congestion on the road network imposes a cost to the British economy in the region of £7-8 billion of GDP per annum. Conversely, the report calculated that 5 per cent reduction in travel time for all business and freight travel on the roads could generate around £2.5 billion in cost savings (some 0.2 per cent of Gross Domestic Product). It is therefore of key economic importance that the road network is as efficient and free flowing as possible.

The existing VED and fuel taxation systems do not address a more optimal management of the road network. Neither does it address the external impacts imposed on third parties, the environment and society as a whole. Growing levels of traffic causes environmental damage due to the negative effects (CO^2, particulated gases, etc) of combustions fuelled vehicles. Busy and congested roads are prone to high levels of accidents and a reduction in general wellbeing (loss of leisure time, mental stresses, less time to sleep) brought about by spending more time in queuing traffic. In the UK, environmental damage on the economy was analysed by the Stern Review (2007), which estimated that the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more.

The mechanism for abating these negative effects on the road network is to introduce better management of the road network. Road pricing works on the basis that the full costs (direct, indirect and external) associated with road travel are placed on the user so that each individual is faced with a series of decisions in relation to each journey they make. As well as recouping the direct costs of road building and maintenance, road pricing can effectively manage demand, and subsequently promote government policy, by encouraging people to make more efficient use of the existing road network. So, for instance, under a full national road pricing scheme a driver would pay more to drive at peak time on a major road, while it would be cheaper to drive off-peak on a quiet road.

1.3 Types of charging schemes

Based on the aspects discussed in the previous section, a wide variety of road pricing schemes have evolved. The following is a brief overview of some schemes that have been tested or are in operation at present both in the UK and abroad.

1.3.1 Point Tolls: Roads, bridges and tunnels

These tolls are typically used to fund new roads, bridges, tunnels or improvements to existing infrastructure. The user is charged for using such facility and the toll revenue is dedicated to recover the cost associated with the construction, maintenance and operation of the asset. The roads may be managed by the public or most typically involve some kind of concession arrangement with the private sector.

In some cases the arrangements allow for toll variations. As an example, the M5 in Hungary features a series of discounts with a 40 percent reduction for regular users, a 20 percent reduction for fleet owners, a 20 percent reduction for local residents, a voucher system for users of the Southern Food Market in Budapest paid for by the Food Market at 30 to 40 percent discounts, a 20 percent reduction for agricultural producers in the four counties around the road, and a 20 percent discount on monthly tickets for car-pools (4-passenger) (World Bank website).

1.3.2 Cordon Tolls

The user pays a fee to enter a particular area, usually a city centre. Tolls are charged each time the user enters or exits the area. The fee may vary by time of day, severity of congestion, vehicle occupancy, or type of facility and the objective is to discourage the use of the road at peak times and therefore ease congestion. Singapore, Stockholm and Oslo have introduced cordon tolls with the objective of reducing traffic on their roads.

1.3.3 Area Tolls

Similarly to cordon tolls, area tolls impose a fee to enter a particular (usually urban) area. Users can enter and exit the tolled area as many times as desired, for one daily charge. Fees may include discounts or exemptions for certain categories of drivers or vehicles. As an example, the London congestion charge features discounts available to residents, alternative fuel vehicles, electrically propelled vehicles, vehicles with nine or more seats, motor tricycles, roadside recovery vehicles and blue badge holders, and exemptions to two wheeled motorbikes, taxis, emergency service vehicles and public transport (TfL website).

1.3.4 High Occupancy Toll (HOT) Lanes (or Managed Lanes)

These are a tolled variation of the High Occupancy Vehicle (HOV) Lanes in which certain lanes are reserved to vehicles carrying at least two people. HOT lanes combine the vehicle occupancy restrictions of HOV lanes with pricing, typically offering free or reduced-cost service to HOV travellers, while also allowing single occupancy vehicles the possibility to pay a toll to use the lanes.
HOT lanes introduce pricing strategies to the use of HOV lanes so that the traffic volume on the lanes is controlled, ensuring that the lanes do not become congested while serving as many vehicles as possible (Burris and Xu, 2006).

The US has pioneered this variation, with projects on the State Route 91 (SR 91) Express Lanes in Orange County, California, the I-15 "FasTrak" Express Lanes in San Diego, California, the I-10W Katy Freeway QuickRide Program, in Harris County, Texas, the Northwest Freeway (U.S. 290) QuickRide in Harris County, Texas and the I-394 MnPASS Lanes in Minneapolis (U.S. Department of Transportation, dns).

1.3.5 Fast And Intertwined Regular (FAIR) lanes

This is another variation of HOT lanes in which freeway lanes are separated into two sections: fast and regular lanes. Fast lanes are dynamically-priced to ensure near free flow movement of cars. On the contrary, Regular lanes are not tolled and may still experience congestion, but users are eligible to receive credits if they possess an electronic tag. Credits equate to a portion of the Fast lane toll and are intended to compensate the Regular lane users for giving up the right to use the Fast lanes. These credits can be accumulated and then redeemed to use Fast lanes or public transport (Urban Analytics Inc. and URS Corporation, 2004).

1.3.6 Distance-based tolls or “pay as you drive”

In these schemes, the user pays by kilometres driven. Tolls are calibrated to reflect the costs imposed by each vehicle on other users. Austria, Switzerland, and Germany have launched automated weight-distance truck tolls (Zmud, 2005).

1.3.7 Credit-based Congestion Pricing

This is a revenue neutral, credit-based variation of road pricing to reduce road use at peak times. It is meant to overcome the negative equity impacts of congestion pricing by allocating monthly budgets to eligible travellers in a priced region to spend on congestion tolls. Under this scheme, eligible trip-makers receive an allocation of travel credits that can then be used to travel on priced roads during a given period of time (e.g. a month). Drivers that spend their monthly travel budgets must buy new credits to keep driving. On the contrary, those who do not use their credit can receive cashback on the remaining amount or keep the credits for the following period (Gulipalli *et al*. 2008). A demonstration project took place in Cambridge (Ison, 1998) but at present there are no known credit-based congestion pricing projects.

1.3.8 The vignette system

In the vignette system the user purchases a vignette (sticker) that grants access to all roads within a particular geographic area during a specified period. The duration of the pass can vary from one week to one year in duration and depends on the category of the road vehicle.

In Europe, the Eurovignette is a road toll for heavy goods vehicles above 12 tonnes common to Belgium, Denmark, Luxembourg, The Netherlands and Sweden. This system charges hauliers a specified amount for the right to use motorways of the participating Member States for a given period, i.e. a day, a week, a month or a year (European Commission website).

1.3.9 National Road Pricing

National Road pricing is a mileage-based system that applies to all roads in a certain country, although variation in fees may vary according to exact location, time period, or type of vehicle. In Switzerland and Germany this system is limited to lorries (McKinnon, 2006).

1.4 Conclusions

It is widely accepted that an efficient road network sustains economic development. However, there are costs associated with building and maintaining transport links. In some cases these costs are recouped by charging drivers a fee to use a facility, as in the case of many point tolls in bridges or tunnels. In other cases tolls are applied as a tool to manage excessive demand.

This chapter has shown how a congested road network damages the local and national economies of a country. Demand management has emerged as a key necessity in many countries and a number of road tolling schemes have evolved to suit each particular context. For example, some larger cities have chosen to impose cordon and area tolls on car users entering the urban area with the aim of encouraging the use of more sustainable modes of transport, which are often funded with toll revenues.

There are instances however, where drivers are offered a choice between using a free but congested facility or paying a toll to use a free-flowing alternative. This is the case or inter-urban roads with examples such as the HOT and FAIR lanes in the USA, where drivers can pay to use exclusive lanes. This is also the case of a large number of tolled motorways in Europe, where congested sections of the road are mirrored by parallel tolled roads. A driver confronted with this scenario decides whether and how much he is willing to pay for quicker and more reliable journey. This scenario is the focus of this research.

1.5 Purpose and structure of this research

When forecasting demand for a road facility, existing traffic models base route choice on a combination of travel time, distance of each route and monetary costs (the plain toll cost), which are tangible variables. By contrast, where there is a congested free alternative to the tolled facility, a driver is confronted with a choice between paying to save time or save money and endure congestion. The driver's willingness to pay is a subjective decision but it can be quantified into behavioural values of time (defined as the amount of money driver's are willing to pay to save travel time) and values of reliability (defined as the amount of money driver's are willing to pay to be able to predict how long the journey is likely to take). This is a key variable in successfully modelling route choice in the context of road tolling in simulation.

The objective of this research is divided into two succinct parts. Firstly, it reviews values of travel time and reliability from the available literature with the aim to identify a possible segmentation of VOT and VOR values by driver's and trip characteristics. Chapter 2 presents the results of this review and identifies the caveats of using these values.

Secondly, this research builds a model of a tolling scenario. Chapter 3 sets out to determine the features necessary to modelling tolls and determines the most suited modelling package for this study. Chapter 4 details the methodology and formulation of a model that replicates the M6 and M6 Toll Motorways in England. This model is calibrated and validated to a match travel times on a morning peak hour commute. Subsequently, chapter 5 discusses the challenges of calibrating a model to replicate day to day travel time variations in a very congested network, and its implications for modelling VOR effectively in microsimulation.

Finally, Chapter 6 brings together the lessons learned from this study and gives recommendations for future research.

CHAPTER 2. MODELLING ROAD CHARGING: BEHAVIOURAL ISSUES

2.1 Introduction

The overview of road tolling covered in Chapter 1 elicited that road pricing can be a key tool for managing demand on congested roads. When confronted with tolls, different tolling scenarios offer drivers different choices. For example:

- In the case of point tolls at bridges and tunnels there may be no alternative, or the option may be to take a long detour.
- In the case of area or cordon tolls in urban areas, the alternative is usually opting for some means of public transport
- In the case of HOT/FAIR lanes and some tolled motorway the alternative is usually a parallel section of free but congested road.

This chapter aims to provide a synopsis of current research and understanding of drivers' behaviour when faced with the trade-offs between tolls and time savings, i.e. between paying to use an uncongested road or to use a free but congested alternative. Reproducing the willingness to pay for one option over another is of key importance to accurately predicting and modelling road tolling.

This chapter begins by presenting the Random Utility Theory (RUT) which explains how individuals make a decision when confronted with a set of alternatives. Then the focus moves to the mechanisms to value an individual's willingness to pay to save travelling time (defined a Value of Time or VOT) and the willingness to pay to reduce the uncertainty in travel time and therefore arrival time at destination (defined as Value of Reliability or VOR). A review of values from current literature follows with the aim of defining possible segmentation of values according to driver's or trip characteristics.

2.2 The Random Utility Theory (RUT)

The Random Utility Theory (RUT) attempts to explain how consumers choose between pairs of offerings. In the case of tolled roads, this is a decision on whether to pay to reduce their time spent on the road, as well as to reduce the uncertainty about how long the journey will take.

The Random Utility Theory is based upon the following assumptions:

1. Individuals are assumed to behave in a rational way and to have perfect information. Therefore, they choose the alternative that realises the maximum utility.

2. Individuals are faced with a series of alternatives (*A*). Each individual (*q*) is constrained by a series of restrictions that determine the alternatives available. Thus, $A_q \subseteq A$.

3. Each individual (*q*) associates a certain utility (U_i) to each of the alternatives available. Thus, $U_i \in A_q$.

A number of random utility functions have been derived over the years by a wide range of individuals, however, the most common and the one that is the starting point for many variations is that proposed by Kenneth Train. This acknowledges that the analyst is not able to identify all the attributes that govern an individual's behaviour and therefore there is a need to assume that measurement errors occur. Thus, utility is regarded as a stochastic variable made up of two components accounting for both the observable and unobservable behaviour. This is expressed as:

$$U_{iq} = V_{iq} + \varepsilon_{iq} \qquad (1)$$

Where: V is the deterministic variable

ε is the stochastic, unobservable part

The deterministic elements are readily observable and consist of individual socioeconomic characteristics such as income, age, gender, employment status, education, etc. and allow for the identification of systematic variation in tastes. The only problem stems from obtaining the correct measurements. Thus, *V* is a function of the characteristics of both the alternative and the individual (*x*), and of a series of parameters to be estimated (β).

$$V_{iq}(x_{iq}, \beta) \quad (2)$$

The stochastic elements, nevertheless, pose a greater obstacle, since they are not observable. Manski (1977, cited in Ortuzar and Roman, 2003) identified four distinct sources of randomness:

1. unobserved attributes;
2. unobserved taste variations;
3. measurement errors and imperfect information; and
4. instrumental (or proxy) variables.

Unobservable variables must be estimated from quantitative research techniques. The most popular of these are revealed and stated preference surveys:

- Revealed Preference (RP) or Revealed Choice (RC) surveys. These reflect actual decisions taken by motorists when faced with the choice to pay or avoid a toll. In principle, results from RP surveys are expected to more accurately reflect motorist VOT. It does however have the drawback of giving information only on the alternative chosen and those ones rejected. Furthermore, the lack of actual road pricing instances worldwide reflects on the scarcity of this kind of data.

- Stated Preference (SP) or Stated Choice (SC) surveys. Given the problems outlined above, Stated Preference is at present the main source of VOT data. SP methods include rating, rank-order and choice, the last one being the most common. In choice exercises, the interviewee is presented with a series of hypothetical scenarios, each one characterised by a different combination of attributes, and asked to choose which one they would prefer. This method presents the advantage of being able to assess schemes that have not yet been implemented, as well as giving an insight on the alternatives rejected by the interviewee.

Results from RP and SP are then processed by means of various forms of logit choice models (e.g. Multinomial, Nested, and Mixed/Random Effect) in order to identify the marginal rates of substitution between travel time and price of a trip and therefore the motorist's VOT.

It has been indicated in the literature that the collection method (SP or RP) has an impact on the values obtained, with SP surveys tending to underestimate the values of time. Thus, for example, Wardman (1998) compiled the results from five British studies that had derived values both from RP and SP data and found that values derived from SP were slightly lower. Ghosh (2001) concluded that commuters respond differently to controlled experiments and actual choice situations. Small, Winston and Yan (2002) found values derived from SP surveys to be less than half of those from RP sources.

Three possible reasons have been speculated for discrepancy. The first, considers that hypothetical or intended behaviour is not consistent with actual behaviour. For example, a person may intend to choose the cheaper option but end up leaving the house later than planned thus being forced to choose a faster but tolled road in order to arrive to their destination in time (Brownstone and Small, 2005). Secondly, values derived from the SP method might depend on the design of the actual survey. Hensher (2006) studied the impact of surveys as an instrument to reveal preferences and found that lower (relative) mean estimates of VTTS appear to be associated with designs that have a wider range on each attribute and a greater number of levels per attribute. Finally, respondents may just seek variety in their answers (Khan, 1995 cited in Hensher 2006).

Another point to take into account is the inability of individuals to accurately estimate time differences. Studies in which motorists have been asked to report on the perceived travel time savings derived from using the tolled facilities have shown that respondents tend to overestimate the savings by as much as twice the time. For example, Golob and Golob (2001) found that the median travel time savings estimated by users of the tolled lane was 15 minutes when the actual savings were only 8.5 minutes. Considering travel time estimates among toll lane users of the SR91 between 1996 and 1999, Sullivan *et al.* (2000) found that travellers overestimate their time savings by between 5 and 30 minutes. Accordingly, both the likelihood and frequency of using the HOT lanes were found to be related to the perceived travel time savings. In Houston, Burris and Appiah (2004) reported that respondents perceives an average travel time savings of 29.8 minutes, compared to the actual values of 17.33, 15.04, and 10.51 minutes recorded for the Katy AM, Katy PM, and US 290 QuickRide, respectively.

Travellers, however, seem to be able to learn to estimate savings with use. This was documented by Tretvik (1993) in a study of a tolled road in Trondheim. He asked respondents to estimate the amount of time that they perceived they had saved or would have saved using a toll route. In 1989 the average estimated saving was 6.7 minutes versus the actual 4.4 minutes. In 1994 the estimated value was 7.6 min compared to the actual 6.8 min. The overestimation therefore improved from +57% to +23%.

However imperfect these estimates might be, they are the only available methods to derive the value of time and reliability as perceived by the users. Results from available studies are reviewed in the following sections.

2.3 The Value of Travel Time (VOT)

As a starting point, it is important to draw a distinction between subjective VOT and the VOT used in economic valuations. These represent two different concepts of values of travel time and are therefore used for two different purposes in transport.

The social value of time reflects the losses to society as a whole derived from longer than expected travel times and reversely the gaining to society of projects saving travel time. The social value of time is therefore used to help decide the value of a proposed scheme over costs. The traditional approach to deriving social values has been to divide time into two broad categories: working time (i.e. trips made during working hours) and non-working time (i.e. trips to and from work, shopping trips, leisure, etc.). The value of working time is based on the cost-savings approach, where the opportunity forgone is working, and therefore the value is a percentage of the gross wage rate for each job category considered. The value of non-work time is calculated as a fraction of the working value.

By contrast, the subjective value of time reflects the value of travel time as perceived by motorists. This therefore depends on a wide range of factors such as the individual's socioeconomic characteristics and the particular characteristics or each individual trip. This is important because individual or subjective values give us an insight into how motorists make their travel decisions, and therefore they are particularly suited to be applied in traffic modelling to replicate the behaviour of drivers.

The value of time or willingness to pay to reduce travel time depends on a number of factors such as the motorist's socioeconomic characteristics (income, gender, etc.) the characteristics of the trip itself (purpose, time of day, length, etc) or even personal preferences (tendency to avoid highways, preference for straightforward routes, perception of safety, etc.). Therefore, accounting for heterogeneity in users is important in forecasting usage in the context of tolls. This Subjective Value of Travel Time Savings (SVTTS) is the object of this study and from now on it will be referred to as Value of Time (VOT) for simplicity.

2.3.1 Why value time?

The valuation of time finds its origins in the notion that time is an economic resource available to all individuals in the same quantity. Furthermore, time can not be stored, but only transferred between activities. Each individual then allocates time to different activities in such way that it maximises their utility. It is also important that the time allocated to activities does not have the same value for individuals, and this value can be measured in monetary terms.

The modern approach to determine the VOT is owed to DeSerpa (1971). DeSerpa's work acknowledged that there are activities that can not be shortened by individuals even though they would like to. This is the case of intermediate activities, such as travelling, that are carried out not for the sake of themselves, but as a necessary means to the desire activity. DeSerpa defined three types of value of time within the context of a utility function:

- The value of time as a resource, which is the ratio of the marginal utility of total time and the marginal utility of income.
- The value of time as a commodity. This is the rate of substitution between the activity and money in the utility function.
- The value of saving time in an activity.

Reducing travel time has an impact in the utility function because (1) time saved can be reallocated to more pleasurable activities and (2) there is a positive perception of the reduction of travel time itself. To these, Jara-Diaz and Calderon (2000, in Mackie *et al*, undated) added another two: (1) substituting travel for other activities may allow for other consumption patterns (e.g. books instead of petrol) and (2) saving travel time offers the possibility of retiming other activities to a more preferred schedule.

At present it is widely accepted that this subjective time can be valued in monetary terms and its value is an important input to traffic assessment, with two main applications (Hensher and Goodwin, 2004):

(a) consideration of construction of a new tolled road; and

(b) application of charges to an existing road network for reasons of demand management, congestion relief, or reduction of environmental damage.

Drivers choose between routes depending on the costs associated to each alternative. These are both monetary costs and time costs. For car trips usually these costs are a combination of operating costs, in vehicle travel time, parking costs (including time spent looking for a space and walking to the destination), and road tolls or congestion charges. The calculation given by the DfT (TAG Unit 3.10.2) is as follows:

$$G_{car} = v_{wk} * A + T + D * VOC / (occ * VOT) + PC / (occ * VOT) \qquad (3)$$

Where: *A* is the total walk time to and from the car
VOC is the vehicle operating costs per kilometre
D is distance in kilometres
Occ is the number of car occupants
VOT is the value of time
PC is the parking cost
Wwk is the weight applied to walking time

Thus, VOT affects the costs perceived by an individual for a specific route, and therefore has an effect on the choice of destination, route taken, and mode used. Therefore VOT is important in modelling because it is a crucial parameter in trip assignment analysis due to its importance in a traveller's choice among competing modes or routes, particularly when one is tolled.

2.3.2 Derivation of the Value of Time

Brownstone and Small (2005) define VOT as the marginal rate of substitution of travel time for money in a traveller's indirect utility function. It is calculated from discrete choice models. The subjective value of time is calculated as the ratio between the travel time coefficient and the cost coefficient. This represents the rate of substitution between cost and time for a given level of utility.

$$VOT = \frac{\beta_n^{T}(t)}{\beta_n^{C}(t)} \tag{4}$$

Where β_n^T is the vector of coefficients reflecting individual *n*'s particular tastes towards time and β_n^C is the vector of coefficients reflecting individual *n*'s particular tastes towards cost. This estimate is typically derived from disaggregate models of discrete choice based on the random utility theory.

2.3.3 VOT in literature: segmentation

In order to model the response of drivers to tolls it is necessary to include a mechanism to simulate their choices. As we have seen, an individuals' decision to pay a toll or not is considerably dependent on the value that they attach to the travel time and to be precise on how much value do they place on travel time savings.

By their very nature, those values of time are subjective and therefore vary from individual to individual. Furthermore, a particular individual will attach different values to time depending on the circumstances surrounding each particular trip. As a consequence, we conclude that use of a single value for all the trip-makers and all trips would obscure the variety of preferences and responses in their day-to-day travelling choices. On the other hand, segmenting the traffic demand in simulation into groups with similar VOTs would enrich the results of the model.

This section analyses the criteria found in literature to segment VOT. These variations are derived by means of estimating different choice models for different segments of the population, or by correlating travel time with exogenous factors, such as personal income, etc. (Hensher and Goodwin, 2004). The segments most commonly explored in literature can be classified in two groups: (1) demographic factors and (2) trip factors:

1. Demographic factors:
    - Income
    - Gender
    - Employment conditions (full-time vs. part-time workers)

2. Trip factors:
    - Trip purpose
    - Level of congestion on the network
    - Weekdays vs. weekends
    - Time period
    - Length of the journey

The objective of this section is therefore to identify whether results from each segment are consistent across studies, which would justify their inclusion in modelling, and in that case, whether it would be feasible to incorporate them into a model both in terms of calibration and software practicalities. Results are discussed next while values can be seen in appendices 1 to 16.

Income

Income is a variable widely explored in the literature, although the actual income segments vary from study to study. All cases reviewed discovered a clear relationship between income and VOT, with higher earners more likely to pay the toll. For instance, Calfee and Winston (1998) found that the value of commuting time increase by 129% for the highest earners as compared to those on the lowest incomes. Steimetz and Brownstone (2005) found that trip-makers earning more than $80,000 valued time savings for commuting trips 202% over those earning less that amount, and 50% over for non-work trips. Actual values can be seen in appendix 1.

Correlating income to trip purpose, Calfee and Winston (1998) investigated the differences in the relationship between VOT and income for work and leisure trips. Results showed that VOT increases with income at a different rate for both purposes. Those on incomes below the $30,000-$50,000 segment are willing to pay more to save time during working trips, while those on higher incomes are more willing to pay to reduce time in leisure tips. There is also an inflexion point around the $30,000-$50,000 mark, where VOTs for both leisure and work start decreasing.

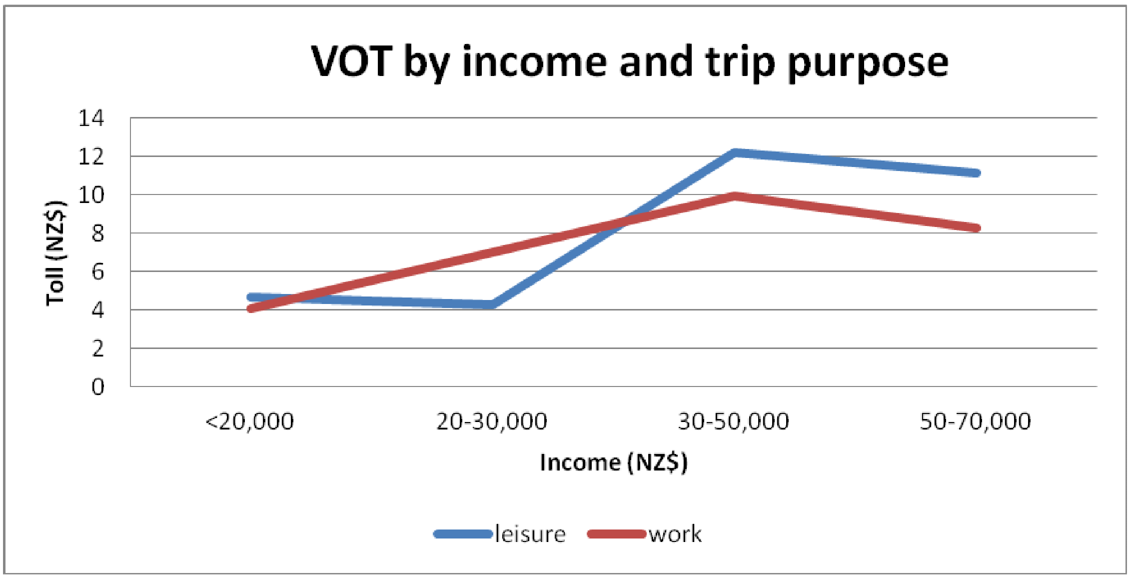

Figure 1. VOT by income and trip purpose (Radovich and Foster, 2000)

Tretvik (1993), on the contrary, found a better correlation between values. For the lowest and medium part of the income distribution, business is valued the most, followed by other purposes and finally commuting. The order becomes variable at the highest end of the income. In addition, the VOT for business trips keeps rising steadily with the income, while other trips stabilise or even start decreasing:

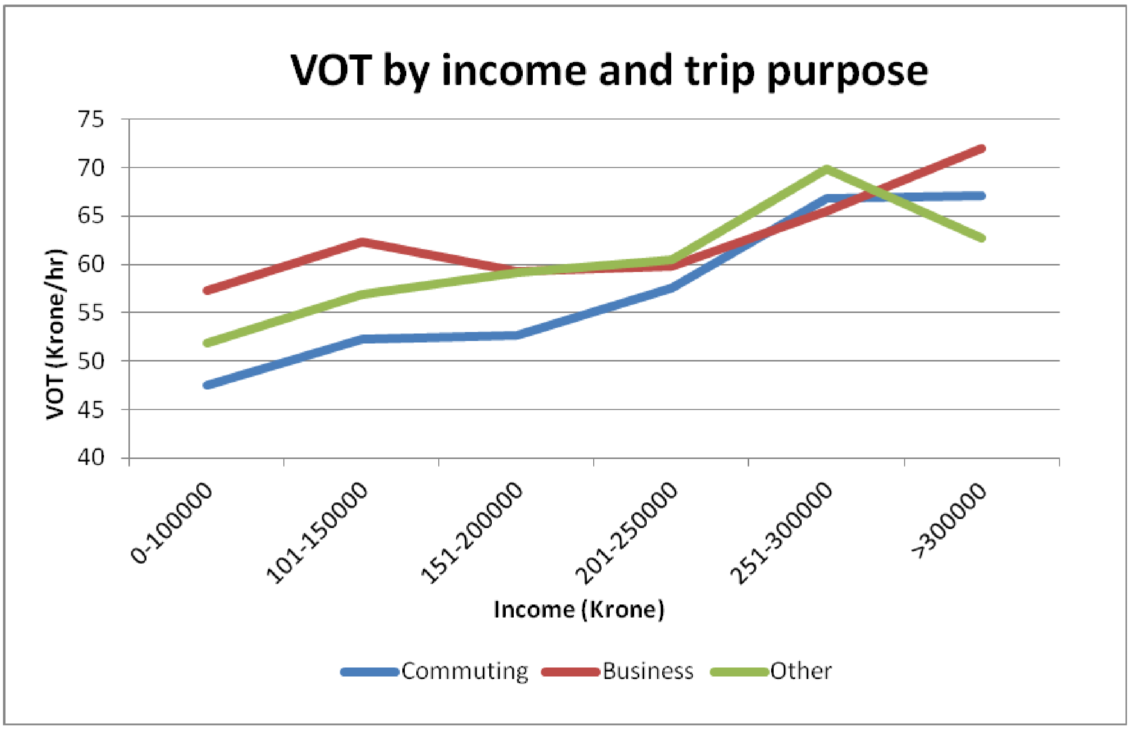

Figure 2. VOT by income and trip purpose (Tretvik, 1993)

From these results, it is apparent that the segmentation of VOR by income would be desirable. However, it is important to acknowledge that the cost implications of collecting these data and calibrating the model to it may be too high in realistic terms.

<u>Gender</u>

Gender and VOT appear to be correlated, with women showing a higher VOT than men for most scenarios. Analysing the I-15 HOT lane in San Diego, Ghosh (2000) found that women value time savings 30% above men for the morning commute and 17% more for the afternoon commute. His results are shown in appendix 2.

A similar conclusion is reached by Small *et al.* (2005) - although no indication of actual values is provided- and by Whelan and Bates (2001). This latter study estimated a base model for each journey purpose (commuting, business and other) by drawing on findings from a previous study on UK values of time by Hague Consulting Group (1996) and by other results from Bates and Whelan (2001). Results from these models indicate that women have a higher value of time for business travel, while there are no significant differences between males and females for the other two trip purposes.

Sullivan *et al.* (2000) reviewed actual usage of the SR91 HOT lane. Their results indicated that there is nearly twice as many women using the HOT lanes as solo drivers (i.e. paying the full toll) than men. It is also worth noting that the proportion of female commuters using the corridor is 35% versus 65% males.

It can therefore be concluded that it would be interesting to model gender and use different values of time for male and female drivers.

Working pattern

Although this attribute has not been researched in great detail, Steimetz and Brownstone (2005) found that full time workers have much higher VOT than part-timers both for work and non-work trips ($44.12 for full-timers versus $15.65 for part-timers in the case of work trips and $10.83 for full-timers versus $7.25 for part-timers for non-work trips). This means that full-time workers value time savings for work trips 182% more than part-timers and non-work trips some 50% more.

On the other hand, the self-employed tend to present higher levels of VOT (Whelan and Bates, 2001).

Although literature has shown the impact of these variables, it is acknowledged that it may not be practicable to reflect this variable in a model due to difficulties and costs of obtaining this kind of data.

Distance of the journey

Considering the length of the journey, results suggest that the likelihood of paying the toll increases with trip distance/duration and with the frequency of making the trip. This effect was observed for example by Algers et al. (1995). These results indicate that trips over 50km are valued at 138% higher than commuting trips under 50km and 200% higher than other trip purposes under 50km.

Supporting Alger's VOT estimates, Ghosh (2000) concluded that trip-makers are more likely to pay the toll to use the I-15 HOT lane in San Diego for longer trips. Along the same lines, Douma *et al.* (2006) in a review of the MnPass HOT lane in Minnesota reported that the likelihood to pay the tolls increased both with the trip distance and the frequency of travel.

Trip purpose

Regarding trip purpose, the distinction most commonly drawn in literature is between (1) commuting trips, (2) business trips and (3) leisure/shopping/other trips. Overall, results tend to indicate that those on business trips have a higher VOT and consequently are more likely to pay the tolls than those travelling for other purposes.

Appendix 3 compares business to commuting trips. The last column shows the percentage by which the VOT of business trips exceed commuting. As can be observed there are wide variations in this difference. Considering those studies that calculated solely one aggregated VOT, business travel values range from being 45% higher than commuting to 150% higher. A closer look into those studies that segmented VOT by income as well, reveals that business travel is still higher than commuting, but while for the first two studies the difference increases with income, for the last two that difference reduces with income.

Appendix 4 compares commuting to leisure/shopping and other purpose trips. The last column shows the percentage by which the VOT of commuting trips exceeds that of leisure/shopping/other trips. Interestingly, some studies conclude that commuting trips have a higher VOT, while others show a higher VOT for leisure/shopping/other trips. Such wide discrepancies mean that no clear trend can be discerned from these results.

Time segment

The study of the values of time for different segments of the day has focused on commuting trips, and has been shown to be generally higher for the morning commute than for the afternoon commute. This might be due to the pressures of arriving at work on time, while commuters seem to be more willing to put up with delays later. Appendix 5 comprises results by Ghosh (2000), Cirillo and Axhausen (2006) and Liu et al.'s (2007).

Looking in more detail at the morning peak, a study by Liu *et al.*'s (2007) showed how VOT increase gradually until they reach a peak in the 07.30 to 08.00 segment to gradually decrease again after that (see figure 3). This is the only study found that challenges the assumption that VOT is independent from departure time and its results demonstrated that those departing at different times confer indeed different values to their time savings.

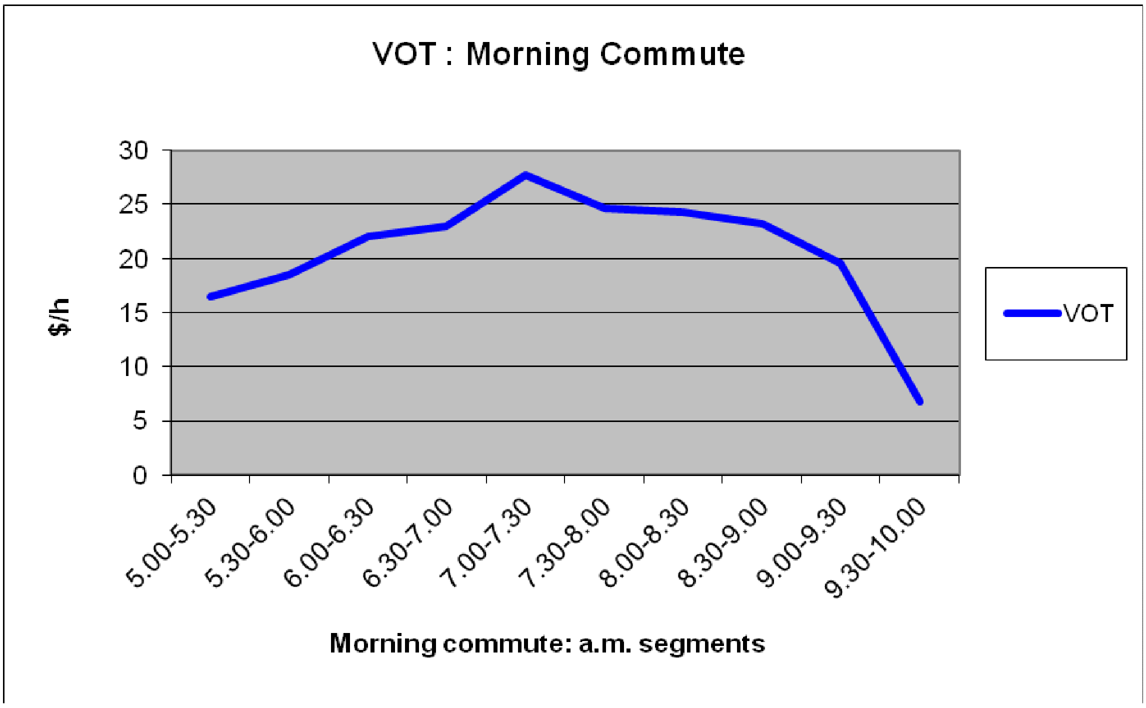

Figure 3. VOT in 30-minute segments for the morning commute

The differentiation in VOT by time segment in microsimulation may be relevant once more studies become available

Day of the week

The distinction between trips on weekdays and weekends is probably linked to trip purpose. In a study of a toll national highway into Madrid, Cantos and Alvarez (2009) found that VOT is 21% higher during weekdays as compared to weekends (results are shown in appendix 6). At present it would be feasible to use lower VOTs when modelling weekend traffic.

The VOT in congestion

For the purposes of this study, these are the most meaningful values of time since users confronted with tolls are also likely to be confronted with the choice to pay to avoid congestion.

Five studies were concerned with the values of time under congested circumstances and unsurprisingly, all results indicated that time spent in congestion is valued considerably higher than time spent in free flow conditions.

Hensher (2001) showed how the VOT increases gradually from free-flow conditions to slowed down conditions and is finally at its highest for start/stops.

Zhang, Xie and Levinson's (2004) study showed that drivers perceive stopped delay at ramps as more onerous than driving delay and free-flow time. Consequently, they argue that a "quality of service" or "quality of time" factor may also need to be included in the utility function.

Koenig, Abay and Axhausen (2003) also found the VOT under congested circumstances to be higher than under free-flow.

Cantos and Alvarez (2009) studied the value of travel time and time spent in congestion to access Madrid. They compared a tolled and a non-tolled highway in Madrid. Results show that time spent in congestion is valued more by motorists, with differences being wider in the case of shorter trips (15 min), where congested time was valued 40% higher than uncongested. Furthermore, the value of congested time was found to be higher for leisure and shopping trips than for work trips, and also higher for weekdays than for weekends.

Jovicic and Hansen (2003) showed how congested time has a higher value than free-flow time for all trip purposes analysed (commuting, leisure, education and business) with the values being particularly high for leisure and business, the latter increasing by 200%. Hensher (2007) found a VTTS under free flow conditions of $8.82 versus $33.67 under congestion. Significantly, the VTTS of congested time is shown to considerably reduce if passengers are present in the car, although in no case is it comparable to the uncongested time values. In contrast to congested time, the VOT of uncongested situations is unaffected by the number of passengers. Whelan and Bates (2001) found that congestion increases the VOT for business travel and commuting. No significant effect was found for other types of trips.

Appendix 7 summarises results from the above studies and compares the VOT in congested circumstances to that of free-flow traffic. The last column shows the percentage by which driving in congestion exceeds driving under free flow conditions. These results demonstrate that while the trend for higher values in congestion is clear, there are vast discrepancies when it comes to the actual differences, with the VOT in congestion exceeding that of free flow by percentages ranging from 107% to 476%.

<u>The VOT of freight</u>

The value of time for freight seems to be very diverse. Looking both at the results compiled by Zamparini and Reggiani (2007) in appendix 8 and the results from Smalkoski and Levinson (2004) and Richardson (2004) in appendix 9, it can be seen that values range from as low as $1.72/hr to as high as $47.21/hr. Furthermore, the two studies from the UK, they are equally quite apart ($11.19/hr and £45.36/hr).

Two studies by Fowkes, Nash and Tweddle (1989) and Fowkes (2001) may help shed light on the reasons for such differences in values. Fowkes, Nash and Tweddle (1989, in Fowkes 2001) indicated commercial vehicles have different values of time depending on the cargo. It is worth nothing, however, that none of the products specified in this study are perishable (e.g. groceries), which would be anticipated to have higher values. Appendix 10 details the values for all categories.

Fowkes (2001) considered the differences in values for HGVs and LGVs depending on whether the vehicle is owned or hired (see appendix 11). He specified three models: the first one considered the difference between two non-toll roads; the second one considered difference between a quicker toll route and a slower free route and values decreased considerably. However, this model included a constant specifying that all things equal the non-toll road would be preferred. It is worth noting, however, that 25% of the respondents to the SP questionnaire refused to pay any tolls. Model 3 excluded them from the model, which caused the values of HGV owners to rise by 78%.

At present, most microsimulation models include the possibility to model HGVs independently from cars. It is therefore feasible to use a specific VOT in the cost equation applied to this group.

2.4 The Value of Reliability (VOR)

Congestion not only has the effect of increasing travel times, but also makes travel times more unpredictable. As an example of the extent of this phenomenon, figure 4 illustrates average travel times into Copenhagen over a whole weekday.

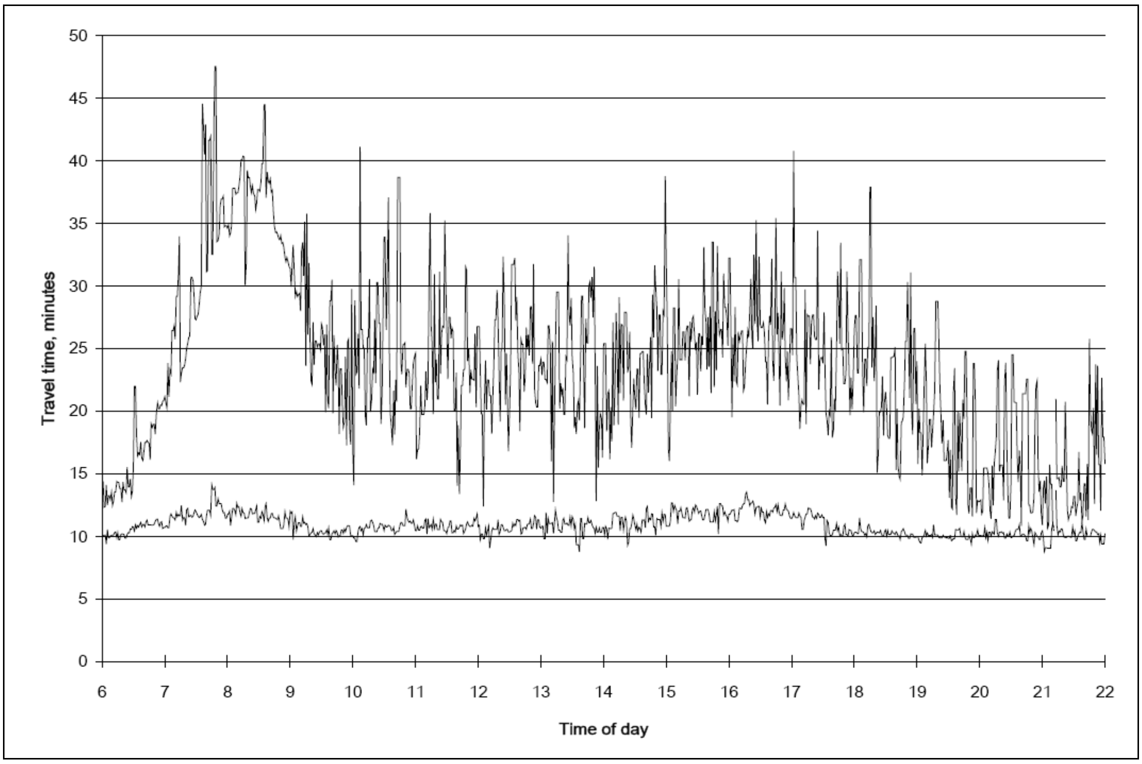

Figure 4. Travel times into Copenhagen (Fosgerau, 2008)

Unreliable travel times mean that travellers find it difficult to predict how long the journey will take. This is particularly burdensome in commuting trips, when the consequences may be arriving late to work. To avoid this, travellers may decide to reschedule their departure time, or choose a tolled facility that offers greater journey time reliability. Hence, reliability of travel time has a value to the motorists, and this Value of Reliability (VOR) or Value of Variability (VOV) is defined as the amount of money that the commuter is willing to pay for a reduction in uncertainty by a marginal amount (Ghosh, 2000).

As an illustration of how the VOR works, let's take for example a 40-mile journey. The total journey may take one hour in free flow conditions or around one 1 hour and 30 minutes during busy times. Under these circumstances, a traveller with a VOR of £10/hr would be willing to pay £5 to avoid that 30 minutes variation.

2.4.1 Deriving values of reliability

The interest of the literature in the Value of Reliability is fairly recent, and discrepancies still exist as to the appropriate definition of travel time variability, as well as the most reliable method to measure it. De Jong et al. (2004) identify three different measuring methods which differ in their assumptions of how variability is perceived by the traveller:

The mean versus variance approach

Unreliability is measured as the standard deviation (or variance) of the travel time distribution. This method usually is based on data from a Stated Preference (SP) survey, in which each choice alternative contains a set of several possible journeys, the average travel time and sometimes also travel costs. A utility function is then specified as follows:

$$U = \delta\, C + \alpha TT + \beta SDTT \qquad (5)$$

Where: U is the Utility
TT is the Travel Time
$SDTT$ is the Standard Deviation of Travel Time

δ, α, β are parameters to be estimated. They represent the marginal utilities of cost, travel time, and variability respectively, which are expected to be negative.

From the estimated model, the reliability ratio can be calculated. This measures the ratio of the travel time parameter and standard deviation of travel time parameter: β/α and gives the disutility of a minute standard deviation of travel time in terms of minutes of mean travel time. A monetary value for unreliability can be derived by combining this with a value of travel time - or directly if travel cost is also in the utility function.

It is also possible to allow for observed heterogeneity among travellers by including covariates such as socioeconomic or trip characteristics.

Percentiles of the travel time distribution

This approach is similar to the previous one, but involves the median travel time instead of the mean and distribution quartiles instead of the standard deviation of the travel time. Unreliability is therefore measured and valued as the 90th percentile of the travel time distribution minus the median (or the 80th percentile minus the median). The shorter than average travel times are not used, as they are regarded as being of little value to the travellers. Neither are values above the 90th percentile, these are seen as outliers (De Jong et al. 2004). Therefore, this measurement assumes that motorists are concerned with the probability of delay and therefore are more likely to pay more attention to the upper tail of the travel time distribution (Liu et al. 2004).

Again, it is also possible to expand the model to allow for observed heterogeneity among travellers by including covariates such as socioeconomic or trip characteristics.

Scheduling models

This approach differs from the other two in its interpretation of the disutility of travel time variability. While the previous two methods assume that the disutility of variability is due to the uncertainty in itself, the scheduling method is based on the assumption that travellers have a preferred time for arriving for a particular activity, and the cost that travel time uncertainty imposes on the traveller stems from any deviation from that preferred arrival time (PAT). Also, in this approach it may be assumed that the marginal disutility of arriving one minute early differs from the marginal disutility incurred by arriving one minute late, in such a way that $\gamma < \beta < 0$.

These models are commonly based on Small's model of scheduling choice (1982, in Noland and Polak, 2002):

$$U = \alpha T + \beta(SDE) + \gamma(SDL) + \theta D_L \quad (6)$$

Where: *U is* the traveller's utility

T is the travel time

SDE means Schedule Delay-Early, defined as the amount of time one arrives at a destination earlier than desired

SDL represents Schedule Delay-Late, which is the amount one arrives later than desired

D_L is a fixed penalty for late arrival

β, α and γ are parameters to be estimated

Once again heterogeneity among travellers can be modelled by interacting the parameters with covariates reflecting socioeconomic or trip characteristics.

2.4.2 Degree Of Risk Aversion (DORA)

Another aspect said to influence route choice under uncertain circumstances is the traveller's aversion to risk. The theory of Risk Aversion applies to many aspects of life and basically states that when an individual is faced with choices of comparable returns, they will tend to choose the less risky alternative. Liu et al. (2004) applied this to transport and coined the term Degree Of Risk Aversion (DORA) to refer to the extent to which motorists abhor routes with unreliable travel time. The DORA is calculated as follows:

$$\mathrm{DORA}_n = \frac{\beta_n^{\mathrm{R}}}{\beta_n^{\mathrm{T}}} \quad (7)$$

Where: β_n^R is the vector of coefficients reflecting individual *n*'s particular tastes towards reliability

β_n^T is the vector of coefficients reflecting individual *n*'s particular tastes towards time.

The higher the DORA value the higher the traveller's perceived cost of uncertainty and therefore the more risk averse that individual is. Travellers with a DORA higher than 1.0 value more greatly a reduction in variability than a reduction in travel time.

Thus for example, Liu *et al*. (2004) discovered that the median DORA for commuters using the SR91 Value Pricing Project in California was 1.73. This indicates that travellers value a reduction in travel time variability more highly than a corresponding reduction in the travel time for that journey. Making use of the authors' example for a driver who has two alternative routes: Route A is a 20-minute commute and fairly reliable. Route B normally takes 10 minutes but has a variability of about 6 minutes. For an individual with a DORA of 1.73 there are no significant differences between both choices, since *(10+1.73*6) ≈ 20.* By contrast, a less risk-averse individual would choose Route A, e.g. *(10+1.0*6) < 20.*

This concept has not seen a big take up, though, and Liu *et al.* (2004 and 2007) are the only studies found that have used it.

2.4.3 VOR in literature: segmentation

As we have seen, the value that individuals attach to how consistent travel times are from one trip to the next plays an important role in deciding whether to pay a toll for consistent travel times or risking travel time variations on the free route.

As happened with VOT, VOR values are subjective and therefore vary from individual to individual and even depend on the circumstances surrounding each particular trip. As a consequence, segmenting the traffic demand in simulation into groups with similar VORs would enrich the results of the model.

This section analyses the criteria found in literature to segment values of reliability. In contrast to the literature of VOT, VOR studies have explored less variables, so the possibilities for segmentation in modelling according to VOR are more limited, but still interesting. These are:

- Gender
- Arrival time
- Departure time; and
- Segment of the day

Regarding the VOR of cars, it needs to be noted that all studies reviewed refer to commuting trips. This is most probably due to the fact that unreliable times are more burdensome as compared to those that are expected to be at their work at a fixed time. The VOR of freight is reviewed separately.

The objective of this section is therefore to identify whether results from each segment are consistent across studies, which would justify their inclusion in modelling, and in that case, whether it would be feasible to incorporate them into a model both in terms of calibration and software practicalities. Results are discussed next.

Gender

Only the study by Lam and Small (2001) focused on the difference between males and females but they found gender to be a powerful explanatory variable. Actual differences varied depending on the model specified but ranged between 88% and 164% higher for females, which reflects a higher aversion to travel time uncertainty. This is in line with gender differences in VOT, where women were also shown to have higher VOT.

Appendix 12 compares the VOR of males to that of females. The last column shows the percentage by which female VOR exceeds male VOR values.

Since gender it a determinant factor, it would make sense to acknowledge it in a model by including a percentage of male and female drivers with different values of time.

Arrival time

These VOR values were derived from scheduling models, which assume that travellers do not dislike uncertainty per se, but for the possibility of arriving too early or even worse, too late at their destination. In a study of home-to-work commuting trips on the corridor formed by two parallel routes tolled and un-tolled routes into Barcelona, Asensio and Matas (2007) found that individuals value travel time variability because of the consequences of being early or late with respect the Preferred Arrival Time (PAT). Furthermore, late arrival has been found to be more burdensome to trip-makers than early arrival (Small 1982 in Noland and Polak, 2002). Asensio and Matas (2007) found that late arrival is valued at 34.4 €/hour, some 2.3 times over travel time while early arrival is valued at just 7 €/hour, which is equivalent to 48% of travel time.

The values derived by Asensio and Matas are shown in appendix 13:

Given that PAT is the critical criterion, restrictions in work starting times were observed by Asensio and Matas to impact significantly on the valuation:

a. Commuters with low delay allowances value delays almost three times as much as travel times.

b. Those with more flexibility value delay time just 50% above travel time.

c. Only those commuters with fixed work starting times give a positive value to savings in early arrival times.

The fact that work start time restrictions are a main consideration is reinforced by Ghosh's (2000) results from the I-15 HOT lane in the US (see appendix 14). His values suggest that commuters are more sensitive to travel time variability in the morning commute (i.e. when they are conditioned by the work start time). In the afternoon commute, although travel time variability existed, it did not encourage the use of the toll lane to the same degree, this was due to both a lower valuation of variability and of travel time and may be explained by the fact that there is no penalty for arriving late at home. In any case, it is also worth noting the large standard deviation of the results, which reflect the unobserved heterogeneity of tastes among commuters.

Departure time

The shape of the peak times is a consequence of individual scheduling decisions, where travellers trade off departures from their preferred schedule against travel time. Some trip-makers prefer to depart early and avoid congestion, while others will endure the worst traffic jams for not having to get up and/or depart earlier. The attitude towards both travel time increases and unreliable travel times are therefore intrinsically linked to the choice of departure time. This fact, overlooked by most studies was taken into account by Liu *et al.* (2007) and their results show that those leaving at different time segments have indeed different VORs (see appendix 15).

In saying this, it is also interesting to investigate the correlation between aversion to longer and uncertain travel times as measured by VOT and VOR for those leaving at each segment of time. This relationship, as discovered by Liu *et al.* has been graphed in figure 5.

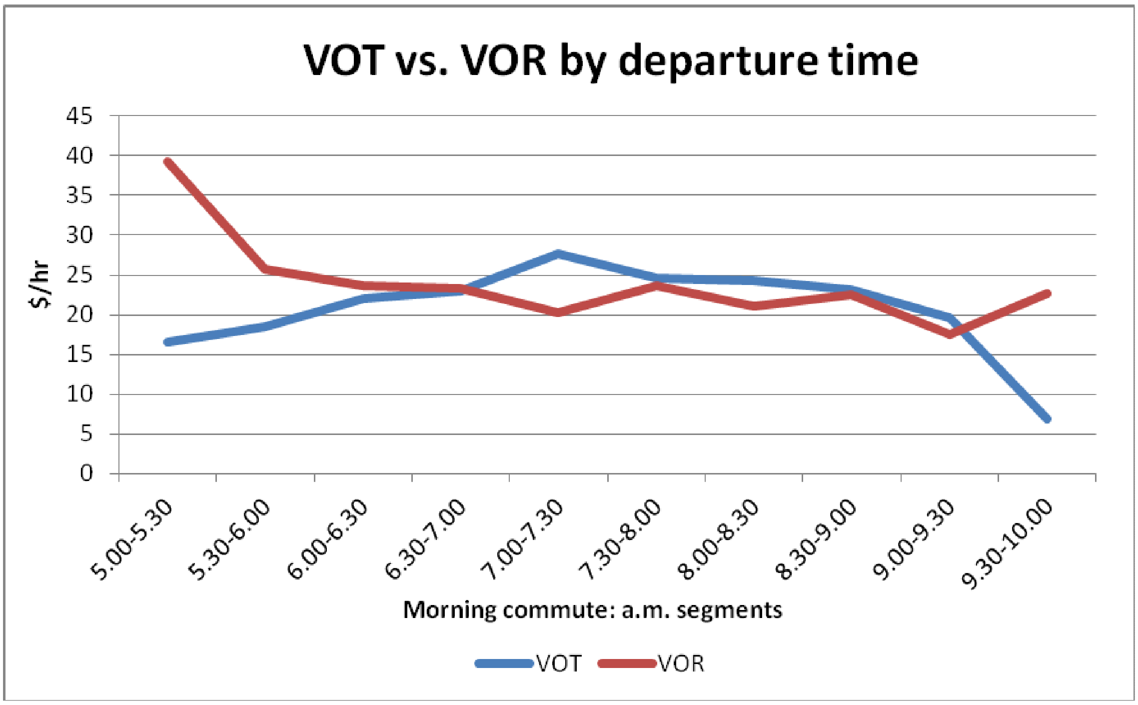

Figure 5. VOT vs. VOR by departure time

The graph shows how in the early time periods, VOR is significantly higher than VOT, which suggests that users of the tolled lane derive a greater benefit from predictable travel times than for any reduction in the total travel time. However, by the middle of the peak VOT outweighs VOR. At the end of the morning, VOR increase, meaning that only those with a higher risk aversion would choose to pay the tolls.

The findings of Liu *et al.* (2007) are partially disputed in a study by Small *et al.* (2005) on the same SR91 HOT lane. Their results suggest that reliability would account for roughly a third of the attraction of the toll lane, however, this percentage would be less at the beginning and middle parts of the rush hour and greater at the latter part. This contrasts starkly with the exceptionally high values of reliability derived by Liu *et al.* for the early part of the morning.

It is deemed desirable to include a variable in simulation that reflects these variations in VOR by departure segment. This may be done by linking VORs to each bin in the release profile of a model. However there is no mechanism to do this at present.

Freight

Unexpected delays in freight transport have different, and in a way more serious, implications than for cars. Missed connections, waiting periods, missed opportunities for applying JiT (Just-in-Time) to physical distribution and delays in production can cost hauliers and their client's money.

It is particularly difficult to compare how hauliers value reliability to how car users value it due to differences in the measurement units. While for car drivers the difference between mean and variance or quartile distributions is often used, for freight most studies use the scheduling approach with measures such as the "percentage not on time" or the "probability of delay". The latter is often measured as the probability of not arriving at the specified time or within the specified time interval. This approach also considers the burden of arriving early at the destination, which could also incur extra costs (De Jong *et al.,* 2004).

At present, the leading microsimulation models model HGVs as a separate category, and including VOR would only be a question of using a specific VOR in the generalised cost function applied to this group. Appendix 16 presents some results compiled by De Jong *et al.* (2004) but, as the authors note, results are difficult to compare, due to the differences in the measurement units used.

2.5 Using literature VOT and VOR in the UK

The previous sections brought together values of time and reliability from a variety of countries, currencies, years and tolling contexts. The next step was to use these values to derive a set of values (or value ranges) that could be applied to a UK tolling context. In order to do this, values found in literature were made comparable by converting them to a common currency in a common year and then a regression analysis was attempted to assess the true impact of variables.

Following the DfT practice in the UK, all values were then converted to 2002 British Pounds (£). Results from this conversion can be seen in appendix 17. Once this was done, a regression analysis was attempted to explain how values varied according to external factors. The variables identified to have a potential impact were:

a. type of facility (highway, bridge, HOT lane, etc.),
b. the characteristics of the toll (fixed flat tolls, variable tolls by real-time level of congestion, by peak times, by day of the week, etc.),
c. context (urban vs. interurban routes),
d. length of the tolled section,
e. availability of alternative routes.
f. collection method (RP, SP, loop data)

Unfortunately, most studies did not provide enough details about the tolling context from which values were derived, which meant that the regression analysis was not possible.

In addition to not being able to perform a regression analysis, some further caveats when trying to make sense of such a vast wealth of values.

Firstly, the conversion of values to 2002 British Pounds made values more comparable, but a question still remained about the relationship between the value and the purchasing power of each country (e.g. £2 may not be the same percentage of an American's income as a Norwegian's).

Furthermore, some papers reviews had derived values had using Stated Preference (SP) methods, while others used Revealed Preference (RP) techniques. This per se skewed any comparison, as it is widely acknowledged that SP yields lower values than RP (see for example Wardman (1998) Ghosh (2001) and Small, Winston and Yan (2005)).

Lastly, papers that identified the same trends and variables very often showed wide discrepancies in the actual values. As an example, although it is a general trend that time spent in congestion is valued more highly than time in free-flow conditions, the actual percentages by which the former exceeds the latter ranges from 100% to 475% higher depending on the study.

2.6 Elasticity of Demand

Elasticity is used to explain what happens to consumer demand for a good (in this case a tolled transport facility) when prices increase. It is generally defined as:

$$E_d = \frac{\%\text{ change in quantity demanded}}{\%\text{ change in price}} = \frac{\Delta Q_d / Q_d}{\Delta P_d / P_d} \quad (8)$$

The more elastic travel demand is, the greater the reduction in travel volumes resulting from higher prices or travel times. Conversely, the more inelastic demand is, the smaller is the reduction in traffic demand.

Elasticity of demand is dealt with in this study only for the purpose of completeness, since there is no mechanism in microsimulation to deal with it. As an indication of the factors influencing traffic volumes on tolled motorways, we will briefly presents the results from Matas and Raymond (2003) from a cross-section of several Spanish motorway sections:

1. Traffic on tolled motorways is strongly correlated to the level of economic activity of the country, with traffic increasing in periods of economic growth and decreasing during economic recession.

2. The sensitivity of demand to price depends both on the characteristics of the tolled motorway and on those of the free alternative. The more congested the alternative road, the more inelastic the demand for the tolled facility and vice versa. Similarly, the higher the percentage of heavy vehicles on the alternative route, the more inelastic the demand.

3. Demand is slightly more elastic on longer motorway sections, attributes to the fact that demand is more sensitive to price when the total toll to pay is higher.

4. Demand is more inelastic in tourist areas, which the authors attribute to the lack of information of these occasional users.

2.7 Conclusions

The purpose of this research is to advance the modelling of trip-makers behavioural responses to tolls in computer simulation. Transport schemes are commonly assessed using computer models to assess their effects and effectiveness. In these models demand is usually forecast based on drivers' willingness to accept given journey times, queues and road distances. In the context of road tolling, motorists are faced with a new variable: monetary costs.

Chapter 1 presented an overview of different scenarios in the implementation of road tolling. In inter-urban contexts, many toll roads present drivers with an alternative to a congested stretch of free road by offering shorter journey times where travel times do not vary much from one day to the next. When presented with tolls, drivers make their route choice based on how much they are willing to pay to enjoy a shorter and more reliable journey. This subjective choice is based on a trade-off between time and money which can be quantified as an individual's Value of Time and Value of Reliability, which are defined respectively as the money a driver would be willing to pay to reduce their total journey time by one hour, and to reduce travel time uncertainty by one hour.

This chapter started by discussing the Random Utility Theory underpinning route choice, which states that, when faced with any two alternatives, an individual chooses the one with the highest utility and that utility varies across individuals as a random variable. This was followed by an introduction to the methods used by different studies to elicit VOT and VOR values, namely Revealed and Stated Preference.

Although it is acknowledged that VOT and VOR values are personal and specific to each individual, the main objective of this chapter was to identify groups of society or trips with the same characteristics that share similar values. A review of the available literature was undertaken with the aim of identifying the variables that account for different segments in the valuation of time and reliability. The variables identified are summarised below.

<u>Variables accounting for differences in VOT:</u>

1. Income: There is a clear tendency of VOT to increases with income. However, VOT does not increase at the same rate as income and the rate varies with trip purpose.

2. Gender: Women show a higher VOT, and therefore are more likely to use a tolled road. The actual difference between males and females varies between studies and trip purposes.

3. Working pattern: Trends indicate that full-time and self-employed workers have higher VOT.

4. Length of journey: The likelihood of paying the toll increases with trip distance/duration and with the frequency of making the trip.

5. Trip purpose:Three trip purposes were considered, namely business, commuting and leisure/other. Trends clearly indicated the business trips have the highest VOT while the actual difference varies vastly across studies. A comparison between commuting and leisure/other travel revealed considerable discrepancies between studies.

6. Departure time: The morning commute seemed to have a higher VOT than the afternoon. Those departing at different segments of the morning commute show different VOTs.

7. Day of the week: VOT was found to be higher for weekdays.

8. Congestion: The VOT spent in congestion was found to be valued much higher than time spent in free flow conditions. The range of percentage difference is very wide, ranging from 100% to 475%.

9. Freight: Results show a wide variation, with values ranging from as low as $1.72/hr to as high as $47.21/hr.

Variables accounting for differences in VOR:

1. Gender: The only study that focused on gender indicated that women have a VOT between 88% and 164% higher than males.

2. Arrival time: This applies to commuting trips and trends indicate a high sensitivity of commuters to travel time variability in the morning commute, in particular when they inflexible fixed start times. The VOR in the afternoon commute, by contrast, is not valued as much.

3. Departure time: Similarly to VOT results, those departing at different segments of the morning commute show different VOR, showing that unreliable travel times are intrinsically linked to the choice of departure time.

4. Freight: Travel time reliability was found to be crucial to hauliers, since unexpected delays may result in missed connections and waiting periods that cost hauliers money. The wide differences in measuring units used in the studies reviewed (e.g. delay per mile, delay per time, % of not on time, etc.) made comparing results very challenging.

The aim of this review was to identify the segments of VOT and VOR with a view of using them in a simulation model as a variable that affects route choice. The review in this chapter identified a wide variety of possible segments based on both personal and trip's characteristics. Although desirable, the practicalities or commercial traffic assessment (e.g. costs of data collection, availability and reliability of data) and modelling limitations mean that not all of them are recommended for inclusion in a model. Considering the constraints just mentioned, the following segmentation is recommended: vehicle type (cars and HGVs); trip purpose (commuting trips, non- commuting trips); and day of the week (weekdays v. weekends).

The next chapter will review traffic assignment and models commonly used in traffic assessment nowadays in order to determine the most adequate one. The selected model will then be used to build a model which is intended for use in further research to test VOT and VOR.

CHAPTER 3. MODELLING ROAD CHARGING: REVIEW OF TRAFFIC MODELS

3.1 Introduction

Traffic models are frequently used to forecast the effects of new schemes. Tolled roads are a relatively new type of transport scheme in which route choice does not only depend on traditional aspects such as drivers' willingness to accept given journey times, queues and road distances, but they introduce a new variable: driver's willingness to pay to avoid longer and difficult to predict journey times.

Toll roads typically present drivers with a choice between a free but congested road and a tolled but free-flowing alternative where travel times are generally shorter and do not vary much from one day to the next. In order to accurately model this scenario, it is necessary for models to include a variable in their route choice mechanisms to account for an individual's choice between time and money. This trade-off between time and money can be quantified as an individual's Values of Time and Values of Reliability, which are defined respectively as the money a driver would be willing to pay to reduce their total journey time by one hour, and to reduce travel time uncertainty by one hour. Chapter 2 undertook a review of VOT and VOR values and identified societal groups and journey types that share similar values and have a potential to be used as variables in route choice in simulation.

This chapter provides a review of different types of commonly used transport models in order to determine their suitability to model the behavioural traits identified in chapter 2 which relate to road pricing. They are then compared to the desirable features to model road tolling in order to select the most appropriate method. This will provide the basis for the remainder of this research, where a model of a tolling context in the UK is formulated, calibrated and validated for use in future research to test UK-specific values of time and reliability.

3.2 Modelling tools

In essence, all modelling software considers the demand for a facility and assigns percentages to the available routes depending on an underlying assignment procedure. These assignment procedures can be classified into 'static user equilibrium assignment' and 'dynamic traffic assignment' (with meso or microsimulation). These are combined with demand models to produce a determinate modelling tool (Vovsha et al., 2005).

Table 1 summarises the options and these are described below in relation to their suitability to modelling tolls.

Table 1. Assignment procedures and demand models

	Description	Types
Assignment procedures	- used to allocate traffic demand to the available routes - route choice is modelled by means of predetermined trip tables	- Static user equilibrium assignment - Dynamic traffic assignment (meso or micro-simulation)
Demands models	- used to model trip generation, trip distribution, mode choice, and time-of-day choice	- 4-step trip-based models - Activity/tour-based models

3.2.1 Assignment procedures

In the field of transport modelling the term "traffic assignment" is used to refer to the process of allocating the forecasted demanded of trips to the links that form the simulated road network. The basic principle guiding this process is that each link has a cost to the driver, which is typically a combination of travel time, distance, and direct monetary cost such as tolls. The total cost of traversing the networks is therefore the sum of all the links used to get to the destination. The basic premise in traffic assignment is that all travellers behave in a rational manner thereby trying to minimise the cost of their journey (Fellendorf, 1998).

User equilibrium assignment (UE)

The objective in equilibrium traffic assignment is to allocate a predicted flow to a given origin-destination set on the network in order to attain an equilibrium state. The most accepted equilibrium state principle was developed by Wardrop (1952). Wardrop described his "User Equilibrium" by stating that:

1. "*Under equilibrium conditions traffic arranges itself in congested networks in such a way that no individual trip-maker can reduce his/her path costs by switching routes*"; and
2. "*Under equilibrium conditions traffic arranges itself in congested networks such that all routes between any origin-destination pair have equal and minimum costs, while all unused routes have greater or equal costs.*"

This is a deterministic, static method that assumes that all costs on all routes are constant over the assignment period and that trip-makers have perfect information about the trip costs in all routes. Furthermore, identical values of the cost components apply to all drivers and vehicles. The result of the application of these rules is a constant demand on any network link in an assignment period (Cragg, 2007).

The steps of equilibrium assignment models are, firstly to identify a set of routes available to trip-makers, secondly, to assign suitable proportions of total demand to each route, and finally, to check for convergence to the equilibrium solution by means of an iterative process. The most common ways to reach a solution is through the Method of Successive Averages (MSA) or the Frank-Wolfe algorithm.

The constraints associated with static, equilibrium methods of traffic assignment are as follows:

1. Static assignment is unable to represent the formation and dispersion of queues. This hinders its use for the analysis of highly congested road networks, which are the most likely scenario for road charging.

2. Static assignment assumes that all demand occurs over one time interval and therefore this method of assignment has no concept of arrival or departure times. Given that trip retiming is a likely outcome of road charging, this method is not suitable.

3. Equilibrium models only yield average travel times, making it impossible to evaluate travel time variability due to congestion.

All the above reasons make UE methods unsuitable for the purposes of this study.

Dynamic User Equilibrium

The principal feature of dynamic traffic assignment is that it considers the dimension of time. The Dynamic User Equilibrium therefore looks for a flow pattern that satisfies Wardrop's Equilibrium Principle in a dynamic way, such that: "The travel cost incurred by traffic on all routes entered at each instant are equal and no greater than those that would be on any unused route at that instant" (Han and Heydecker 2006).

This dynamic version of the user equilibrium still outputs average travel times, which makes it unsuitable to quantify travel time variability, which is desirable in the modelling of congested roads. In addition, DUE is difficult to solve analytically for real size networks, which restricts its use (Bellei et al., 2005).

Simulation-based methods

Simulation based methods overcome most of the constraints associated with static and user equilibrium models:

1. They take a dynamic approach. In dynamic, as opposed to static assignment, travel demand and network conditions are not assumed to be constant in time. Queues build up and disperse so consequently travel times change dynamically and vehicles are able to reroute as a response to the circumstances. This is an improvement on static assignment, where a vehicle will follow the route it was initially assigned to at the beginning of the trip independently of whether there are new shorter routes.

2. They account for stochastic effects by modelling different perceptions or knowledge of the condition in the network (e.g. travel times). Microsimulation models include routeing algorithms which enable individual vehicles to reroute according to the conditions on the road in real time (e.g. cars may decide to alter their route if congestion builds up ahead).

3. By modelling individual vehicles, this makes it possible not only to measure average travel times, but also variation in travel time.

4. Microsimulation models capture heterogeneity in terms of vehicle types, travellers' characteristics and trip purposes. This disaggregated approach also allows for the segmentation of users according, for instance, to their value of time and aversion to travel time unreliability. Vehicles can also easily be grouped into classes to which the modeller can apply common features such as the same parameters in the generalised cost equation.

Finally, the most remarkable aspect of microsimulation is its ability to replicate irregularity on the network. This is done by means of randomly generated numbers that govern for instance the release of vehicles onto the network and the type of driver behaviour (e.g. gap-acceptance, propensity to change lanes) that each vehicle will be allocated. This means that each time a model is run it will yield different outputs (travel times, queue lengths, etc.) and, consequently, the outputs from a single run are not necessarily representative of the typical traffic conditions of the network. On one run, for example, a slow moving vehicle on a road where overtaking is prohibited could result into the formation of a platoon while on the next run traffic could be moving freely. All these variables can account for as much as a 25% difference between runs (US Department of Transportation, 2004).

Unlike the deterministic models previously mentioned, microsimulation models require the combination of data from a number of runs in order to ensure statistically robust results. Hence, there is not a set number of runs that can be prescribed to every model; the total number of runs required is dictated by every instance according to the confidence interval desired on the output and the necessity to avoid the overlapping of values within which the true mean could lie (Seaman, 2006).

Models

Conventional 4-step models (Ensor, 2006):

These models follow five sequential steps: (1) the trip generation stage determines the number of trips to feed into the model from land use data such as number of jobs in the area, residential units, etc.; (2) the trip distribution stage assigns trips to destinations; (3) the resulting trip matrix is then split by modes in the modal split stage; (5) the trip assignment stage loads trips on the possible paths.

In a 4-stage model, pricing is considered either at the mode choice step or at the trip assignment stage. At the mode choice step, the choice between modes is typically represented as a "nested logit" model, where paying the toll is a sub-mode of the mode “car”. At the trip assignment stage, toll roads can be represented by using generalized cost to identify the shortest paths instead of travel time

A series of limitations reduce the 4SM's value as a modelling tool for road pricing. Firstly, the 4SM can only represent aggregated populations, which means that it cannot distinguish between different types of drivers, vehicles, trip purposes, etc.

It is also a steady-state model, which assumes that all interactions happen in one time segment. As discussed when talking about the UE, the static analysis period makes impossible to account for any effects of unreliability or the VOR. It is also not possible to evaluate dynamic pricing.

The limitations of this model do not allow for the representation of likely reactions of drivers to tolls. First, the 4SM assume that every trip is independent of all other trips. In reality, road pricing may encourage people to link trips to avoid paying a toll twice. Second, the 4SM cannot account for any travellers deciding to shift their time of travel because of a pricing policy. It also does not account for trips suppressed due to the effect of tolls, since the trip generation stage of the 4SM is independent of trip distribution. The total number of trips is therefore not influenced by pricing. To overcome this caveat a factor should be included that reflects the decrease in the number of trips due to the tolls - particularly when alternative routes are not attractive to travellers.

Activity-based/tour-based models

Tour-based models differ from traditional 4-stage models in that their unit of analysis is not each single trip, but a sequence of linked journeys starting and finishing at the traveller's home (Rohr, 2005). This is a more realistic approach, if we consider, for example, an individual that leaves home in the morning to go to work, at the end of the day collects the children from school and on the way home stops at a supermarket to do the daily shopping. This kind of trip chaining is a likely response to pricing schemes such as cordon tolls, as individuals may try to do several things in the charging zone and only pay once.

One such model is used by the authorities in Portland. This model is made up of several levels. At the highest level, it stands the full day activity pattern model, predicting a person's daily activity patterns and the trip chains associated with that. Primary and secondary tours made up of a chain of trips are the unit of travel in such models. A time of day model determines the timing of activities. A person's activity pattern is thus predicted in terms of frequency, timing, purpose, and complexity of the tours. A joint destination and mode choice model is applied at the primary home-based tour and secondary work-based tour levels (Urban Analytics Inc. and URS Corporation, 2004).

Activity-based models also allow for the modelling of a wider variety of road pricing schemes, such as those based on a pass or transponder. Furthermore, these models can incorporate variables such as individuals who are late for work and therefore more willing to pay a toll for a faster journey (Vovsha *et al.* 2005). Activity or tour-based models are particularly suited to the requirements of road pricing modelling, in particular when combined with dynamic assignment in microsimulation.

The major drawback with activity-based models is their increased complexity. In an assessment of activity based microsimulation models against traditional aggregated ones, Lemp *et al.* (2007) highlighted the effort involved in coding travel surveys as tours instead of as trips and the subsequent difficulties in calibrating the model. All in all, they concluded that "*if the experience of this research team is any indication, the added effort (and skill requirements) of activity-based models may not be feasible for most metropolitan planning organizations, particularly in the near term (p.86).*"

3.3 Assessment of models for use with road tolling

Road tolling differs from other transport schemes in that drivers' decision to pay a toll or not is influenced by their willingness to pay to reduce their total journey time and to be able to predict how long that time will be.

In order to be able to model this variable accurately, the model needs to offer a series of features. In general terms, an accurate and detailed representation of travel time and the build-up of queues is an essential feature of any candidate model, given that the decision to pay a toll or not is highly dependent on the conditions on each alternative route. Furthermore, this is a subjective decision, and therefore a model needs to be able to represent demand in a disaggregate manner so that groups of vehicles can be assigned individual characteristics. A detailed account of desirable features is presented next.

Capacity to give precise outputs in travel times and travel time variability

In the context of road tolling drivers have a choice to pay a toll or not. This decision is highly dependent on the conditions on each alternative route. Therefore the accurate and detailed representation of travel time and the build-up of congestion is an essential feature of any candidate model. A model must therefore be able to produce detailed travel times in real time and not just estimated averages. In a dynamic model real-time travel times can be fed back to vehicles on the network to inform their route choices. A model's capacity to model advanced pricing strategies such as dynamic tolls (i.e. those where the exact charges depend on the conditions of the road) is also dependent on its ability to model the build-up and dispersion of congestion.

Capacity to model individual vehicles

The more disaggregate the representation of traffic demand, the easier to capture heterogeneity in terms of vehicle types, trip purposes, value of time, etc. Such a disaggregate approach enables the segmentation of users in groups of similar characteristics and allows manipulation of their attributes to better reflect reality (i.e. assign higher values of times to commuting trips, model taxis as exempt from tolls, etc.). By contrast, models based on aggregate demands consider users as being homogenous, which is clearly unrealistic.

Capacity to accurately modelling space and time

This enables vehicles to interact on the road in real time. In this scenario, the road network is populated with a mixture of individual vehicles, each one with a different set of characteristics such as different maximum speeds, different overtaking preferences, breaking down, causing queues and affecting overall travel times on the network just as in real life.

Representation of queuing

Given that tolls are most often imposed in contexts of congestion, an accurate mechanism for the representation of queuing is essential. This includes the capacity to recognise when queues block intersections downstream.

Capacity to react in real time

In real life drivers are capable of reconsidering their route and reroute at any time depending on the conditions ahead (e.g. if they learn about a hold-up on the radio traffic news). Only dynamic models allow drivers to reroute by reacting to updated information on congestion.

Capacity to model time of day

A likely response to tolls is for users to adjust their departure time to avoid or minimise tolls if possible. Only models that account for time of day can incorporate this functionality. Static models, on the contrary, assume that all trips depart and arrive within one single period of time, which makes it impossible to model trip rescheduling.

From this review, dynamic traffic assignment with microsimulation emerges as the most suitable technique for the modelling of road choice in the context of road tolling.

3.4 Conclusion

This chapter has briefly introduced the modelling tools available to practitioners. They were classified into ‘assignment procedures’ and ‘models’. We discussed each one in an attempt to uncover their benefits and constraints relating to the desirable features that would enable the modelling of road pricing.

In the context of road tolling, drivers have a choice to pay a toll or not. This is a subjective decision dependent on the conditions on each alternative route. Therefore the accurate and detailed representation in real time of travel time, the build-up of congestion and the network where traffic queues and blocks the road were seen as an essential feature of any candidate model.

Furthermore, the decision to pay a toll or not is a subjective one. Chapter 2 provided an insight into groups of people and journey characteristics that share similar VOT and VOR values. In order to include these in a model, a model need to be able to represent demand in a disaggregate manner, where vehicles can be assigned individual characteristics. The modelling of different classes of vehicles allows for the application of values per type or exemptions of some classes from paying tolls altogether.

As a results of this review, dynamic traffic assignment with microsimulation emerged as the most suitable technique for the modelling of road choice in the context of road tolling. Next chapter presents the formulation of a microsimulation model which is intended for future research into the derivation of UK-specific VOT and VOR values.

CHAPTER 4. METHODOLOGY

4.1 Introduction

The purpose of this research is to advance the modelling of trip-makers behavioural responses to tolls in a PC-simulated environment. When forecasting demand for a road facility, existing traffic models base route choice on a weighed combination of travel time, distance of each route and monetary costs (the plain toll cost). This is a linear equation known as the Generalised Cost Equation (GCE) and the result is that those routes with the lowest values are preferred. Road tolling schemes are different in that they introduce a new subjective variable: the willingness to pay a toll for shorter and more reliable travel times.

This subjective choice is based on a trade-off between time and money which can be quantified as an individual's Value of Time and Value of Reliability. These are defined respectively as the money a driver would be willing to pay to reduce their total journey time by one hour, and to reduce travel time uncertainty by one hour. Both VOT and VOR lie at the heart of the choice to pay a toll or not, and therefore this study argues that these two values should be included in the generalised cost equation of a model.

Chapter 2 presented a review of VOT and VOR values from the literature with the aim of defining possible segmentation of values according to driver's or trip characteristics. As a result, the following segmentation was recommended: vehicle type (cars and HGVs); trip purpose (commuting trips, non- commuting trips); and day of the week (weekdays v. weekends). This review was however unable to identify any values that could be used in the UK. Values in literature came from a variety of countries, currencies, years and tolling contexts and were also derived using methods known to yield discrepant results. The analysis concluded that these values could not be used to derive a single value or distribution of values that could be generalised to the UK context and it was therefore considered necessary to derive values from a specific UK case context.

Chapter 3 introduced the modelling tools commonly used by practitioners and compared them to the desirable features that would enable the modelling of road pricing. In essence, the accurate and detailed representation in real time of travel time, the build-up of congestion and the network where traffic queues and blocks the road were seen as an essential feature of any candidate model. This review concluded that dynamic traffic assignment with microsimulation is the most suitable technique for the modelling of road choice in the context of road tolling.

This chapter brings together the findings of this research up to this point and details the formulation of a microsimulation model of the M6 Toll and M6 Motorway in England. This model is intended for use in future research to derive VOT and VOR values in the UK.

4.2 Tolling in the UK: The M6 Toll case study

While tolling has been advocated in policy in the UK for some time (e.g. the Eddington Report 2006), it remains a highly contentious issue among policy makers. Examples are limited to a congestion charge in London, and one toll road (M6T) in England. It was the latter that was used in this study.

The M6 Toll was created as an alternative to the congested section of the M6 through the West Midland in England. The free M6 motorway is one of the main arteries in the UK road network, linking London to key industrial areas of the West Midlands, the North West and Scotland. It is the longest motorway in the UK with a total of 230 miles (370km) as well as one of the most congested, in particular along the West Midlands stretch, near Birmingham, where it carries up to 160,000 vehicles per day, in contrast with its design flow of just 72,000. Between junctions 4 and 11 during the rush hour average speeds can be as low as 17mph (Daily Telegraph website: http://www.telegraph.co.uk / news /uknews/ 1429355/2-to-use-first-toll-motorway. html).

These unsustainable congestion levels on the M6 finally prompted the construction of a toll road to bypass the West Midlands conurbation surrounding Birmingham. Thus, the M6 Toll became the first and, so far, only toll motorway in the UK. It was opened to traffic in December 2003 and since then has been a topic of controversy, with successive rises in toll fees and boycotts by the haulage sector in protest at the high tolls (Association of British Drivers Website: http://www.abd.org.uk/local/m6_toll.htm).

The M6 Toll consists of a 43-kilometer (27 mile) long dual three-lane motorway. On the North, the M6 Toll connects with the M6 at junction 11a. On the South, the M6 Toll connects with junction 3a of the M6 and with the M42 immediately prior to junction 9. In addition to the principal entrance and exit links to the M6, at Great Wyrley northbound carriageway and Weeford Park southbound, the M6 Toll can be accessed and exited at a total of 8 intermediate junctions with reduced tolls (M6 Toll website).

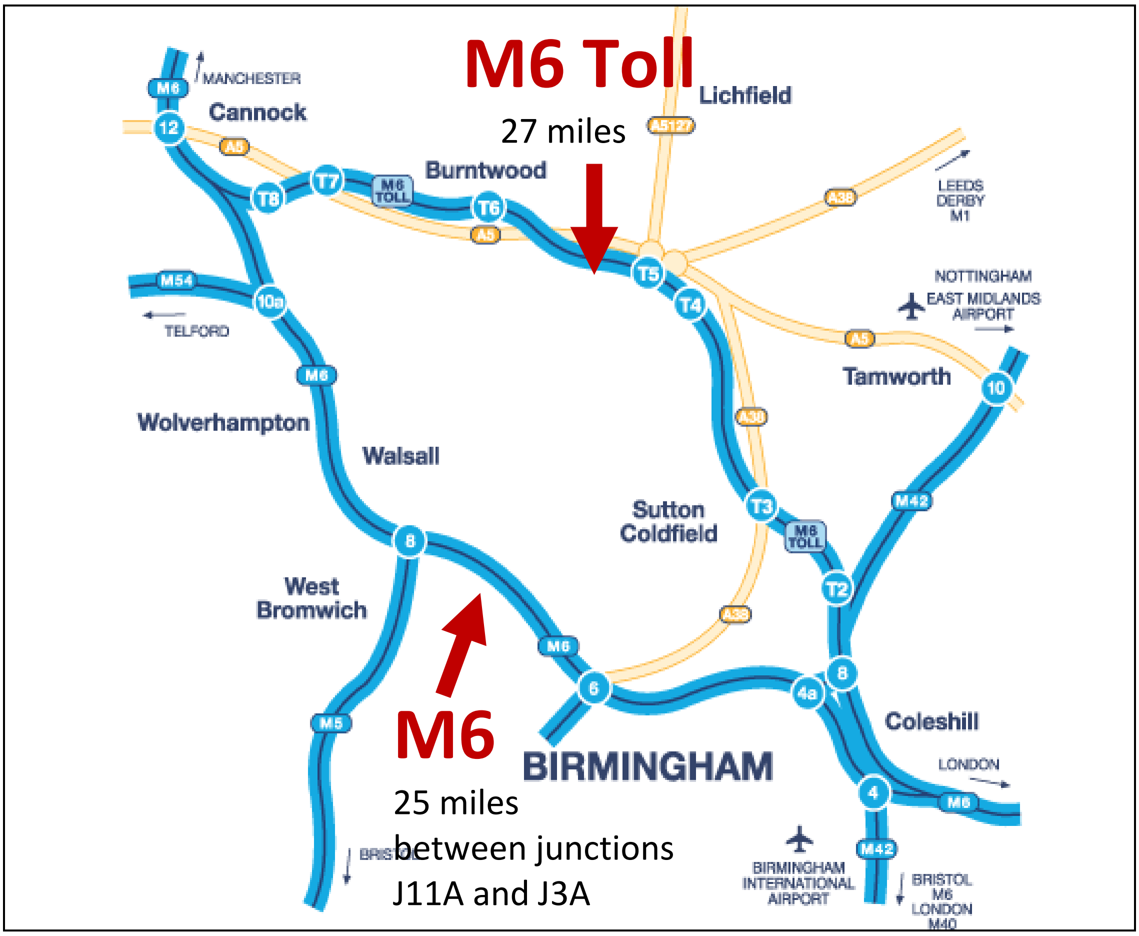

Figure 6. The M6 and the M6 Toll (Source: M6 Toll Website)

Toll prices vary by vehicle type and toll point of entry or exit. Discounted prices apply to night time, weekends and for tag users. Over its operative life, tolls have suffered periodic adjustments and increases as detailed below (Source: M6 Toll website).

Table 2. M6 Toll: toll prices from 2003-2014

Year	Mainline Plazas (Intermediate Plazas)		
	Cars	Vans	HGV
December 2003*	£2	£5	£10
July 2004	£2	£5	£6
August 2004 Ŧ	£3 (£2)	£6 (£6)	£6 (£6)
June 2005	£3.50 (£2.50)	£7 (£7)	£7 (£7)
January 2007	£4 (£3)	£8 (£8)	£8 (£8)
January 2008	£4.50 (£3.50)	£9 (£9)	£9 (£9)
January 2009^	£4.70 (£3.70)	£9.40 (£9.40)	£9.40 (£9.40)
January 2010	£5 (£3.70)	£10 (£9.40)	£10 (£9.40)
March 2011	£5.30 (£4)	£10.60 (£10)	£10.60 (£10)
March 2012	£5.50 (£4)	£11 (£10)	£11 (£10)
March 2013	£5.50 (£4)	£11 (£10)	£11 (£10)
March 2014	£5.50 (£4)	£11 (£10)	£11 (£10)

*discounted prices applied to the first 10 million vehicles Ŧ Standard tolls introduced after the 10 million vehicles figure was reached ^Weekend discounts also introduced

4.3 The microsimulation model: model formulation

Microsimulation models with dynamic traffic assignment are best placed to model tolls due to their capacity to model individual vehicles that travel on an accurate representation of the road network, interacting with each other and reacting in real time to the conditions of the traffic. These models also offer the possibility to assign different behaviour to each vehicle on the network, thus enabling the segmentation of drivers into groups of similar characteristics in terms of value of time, trip purpose and vehicle types. This accurate representation of space and time makes it possible to generate precise inputs and outputs regarding travel times and travel time variability.

The following sections describe the development of the base model that represents the network and conditions on the M6 and M6 Toll roads. The model for this study has been developed in microsimulation package S-Paramics, developed by SIAS Ltd.

4.3.1 Network coding

The microsimulation model covers the entirety of the M6 Toll from where it diverges from the M6 at junction 11a to where it rejoins it at junction 3A. The M8 was modelled from junction 11 to junction 3 (southbound). This model was set to run on a weekday during the morning commute, from 6am to 9am. This is in line with

Figure 7. The model network

4.3.2 Informing the model: Data Sources

In order to build this model, it was necessary to find a data source providing figures for traffic flows on both the M6 Toll and the equivalent section of the M6, as well as travel times from the beginning to the end of both routes. The Highways Agency's Journey Time Database (JTDB) was identified as the most complete source of data available. This is publicly available database accessible from the HA's HATRIS (Highways Agency Traffic Information System) webpage. Data in the JTDB is gathered from three sources, with the MIDAS (Motorway Incident Detection and Automatic Signalling) system of inductive loops at 500m intervals being the most extensively used source. If MIDAS was not available Trafficmaster journey time data and ITIS spot speed data from vehicles equipped with GPS devices would be used as alternatives.

Data extracted from the JTDB was compared to a limited number of datasets collected by the M6 Toll's managing company Midland Expressway Ltd. with the aim to establish its accuracy and validity. A regression analysis was carried out to test the correlation between both sets, which showed a quasi-perfect correlation with an x-coefficient of 1.000.

In order to assess the impact of tolls and derive the VOT and VOR, it was also necessary to obtain these dataset for at least a period of time before and after each toll increase. The JTDB contains M6 data since September 2002 and M6 Toll data since April 2004 (only speed and journey time), which covers all toll increases since the M6 Toll opened.

The JTDB provided a variety of data, out of which this study was interested in journey time, speed and flows. This data is presented in 15 minute intervals by "link" (typically sections between junctions as detailed in table 3). Traffic flows from the JTDB were used to produce the survey file to initially estimate demand in the model but they were crucial in determining the proportion of vehicles that choose with the M6 or the M6 Toll at each decision point (i.e. J3A northbound and J11A southbound).

Initially, it was thought that traffic flows for the whole length of a road could be estimated by simply adding flows on all links within a 15 minute period. However, there was a mismatch between the 15 minute time interval in which data is presented and the time it takes for a vehicle to travel the length of the road. On the M6 Toll southbound, for example, it takes 15 minutes for a vehicle to travel from junction 11A to a point between junctions T4 and T3, and around 24 minutes to travel the whole length. On the M6Toll, this shortcoming was overcome by:

1. Estimating the changeover point i.e. the length of the road where vehicles reach the 15 minutes travel time. As we have said, this was between T4 and T3. Then

2. Adding traffic flows on links from J11A to T4 in the current 15 minute interval; and

3. Adding traffic flows from the next 15 minute interval along on links from T3 to J3A.

4. For link T4 to T3 the appropriate share of vehicles was assigned to the present 15 minute period and the rest to the one along.

The sum of all these was taken as the total travel time on the M6 Toll from J11A to J3A. The same process was repeated to estimate flows on the M6. Flows derived with this method were then compared to flows estimated by simply adding all the link flows within one 15 minute interval and were found to be very similar. It was then established that adding all the link flows in an interval was accurate enough.

Table 3. Links in M6 and M6 Toll

	M6	M6 Toll
Links	J3A to J4	J3A to T1
	J4 to J4A	T1 to T2
	J4A to J5	T2 to T3
	J5 to J6	T3 to T4
	J6 to J7	T4 to T5
	J7 to J8	T5 to T6
	J8 to J9	T6 to T7
	J9 to J10	T7 to T8
	J10 to J10A	T8 to M6 J11A
	J10A to J11	
	J11 to J11A	

For each link, the JTDB provided a variety of data, out of which this study was interested in journey time, speed and flows.

Flows were used to produce the survey file to initially estimate demand in the model and they were crucial in determining the proportion of vehicles that choose with the M6 or the M6 Toll at each decision point (i.e. J3A northbound and J11A southbound). In addition to the M6 and M6Toll, data was sought for the roads joining the M6 an M6 Toll at intermediate junctions in order to calculate in and out flows. Out of these, the JTDB contained data only on the M5, M54 and A38 and A42 and these contained numerous gaps. Given that the JTDB contains link counts but no turn counts, at junctions where no data existed it was not possible to know how many vehicles entered and left the M6 and M6 Toll. This was overcome by assuming that:

- if the link after the junction carried more vehicles than before, the difference was calculated and assumed to have all entered the junction while no vehicles left.

- if the link after the junction carried less vehicles than before, the difference was calculated and assumed to have all exited the junction while no vehicles entered.

Speed was considered a proxy for the existence of queues on the road and was used in the model for profile development. (i.e. the higher the queue the steeper the profile).

Journey time was used in the validation of the model. Journey time is key to this model as drivers are assumed to choose one route or its alternative based on it. It was also necessary to obtain journey time data from a variety of days in order to establish how much drivers can expect TT to vary from one day to the next on each road.

Chapter 2 established that it is desirable to estimate VOT and VORA by vehicle type and therefore a further piece of data considered key was the breakdown of vehicle by type that use each road. These data were derived from two sources: the DfT's AADT matrix traffic flows and a survey carried out by the M6 Toll's managing company Expressways Ltd (MEL in 2008). These data showed that both roads carry different shares of vehicle types (e.g. typically less HGVs using the M6Toll than the M6).

Finally, the tolls payable at each plaza in January 2009 were sourced from MELs website and are shown in table 4. These were applied to the links meant to represent each plaza.

Table 4. M6 Toll: Daytime tolls in January 2009

	Cars	Vans	HGV
Mainline Plazas	£4.70	£9.40	£9.40
Intermediate Plazas	£3.70	£9.40	£9.40

4.3.3 Assignment and routeing

In essence all modelling tools consider the demand for a facility and assign percentages to the available routes depending on an underlying cost equation.

<u>The Generalised Cost Equation (GCE)</u>

S-Paramics determines the route for a vehicle thought the network by considering the perceived journey costs of every individual segment (called links) of the total O-D route. These are calculated by using a simple linear Generalised Cost Equation (GCE) based on distance, predicted travel time and tolls.

This equation takes the form of:

$$\sum_{Journey.links}(A * t_{link} + 60 * B * d_{link} + C * p_{link}) \qquad (9)$$

Where: *t* is the 'time' for each link
d is the 'length' of the link
p is the 'price' of the toll in monetary cost units
A, *B* and *C* are cost coefficients

The length of the link is taken from the model, while the time taken to traverse the link is estimated from previous runs (for the first run, the time is derived for each link as the distance divided by the speed). A, B and C are the cost coefficients, with default values of 1, 0 and 0 respectively, which means that by default, only time is taken into account. For the base model the GCE coefficients were calculated in accordance with TAG 3.5.6 and may be taken as initial values. These are meant to be adjusted in further research to reflect VOT and VOR values for the segments identified in chapter 2:

1. Vehicle type: cars v. HGVs

2. Trip purpose: commuting trips v. non- commuting trips; and

3. Day of the week: weekdays v. weekends.

The GEC coefficients used in this model are those of a commuting trip on a weekday for cars and HGVs. An extra parameter for Light Good Vehicles was added although research into this vehicle type was not specified in the literature reviewed. Table 5 presents the parameters by vehicle type.

Table 5. TAG parameters used in base model

	Value of the Parameter		
	Cars	**LGVs**	**HGVs**
Time	1	1	1
Distance	0.36	1.08	4.07
Cost	0.07	0.02	0.02

Thought was given to eliminating the distance parameter, as the M6 and the M6 Toll are similar in length (25.5 miles for the M6, and 27 miles for the M6 Toll). However minimal the impact of the distance term in route choice may be it is still not zero, and in consequence it was decided to maintain it.

Stochastic Dynamic Assignment

The route choice determined by the GCE was further refined in Paramics by applying Stochastic Dynamic Assignment (SDA), which is a combination of Stochastic Assignment (SA) and Dynamic Assignment (DA).

In order to account for drivers' imperfect knowledge, S-Paramics uses Stochastic Assignment, which is achieved by means of a perturbation factor. The perturbation parameters control variance in the true cost. Thus, at the point of route choice, vehicles calculate the cost of using each route first by consulting the results of the CGE and then by applying a perturbation parameter that creates a variance to the cost. This ensures that vehicles travelling between an O-D pair will select different routes. An initial perturbation of 5% was set for cars and LGVs and 2% for HGVs. These are in line with current modelling practice. Perturbation factors mean that vehicles are also able to choose routes which are that percentage more expensive than the cheapest option.

This is further refined by the use of a dynamic routeing subsystem which allows individual vehicles to modify their routes constantly. This is done by means of routeing tables (rather than "trees") that are updated at user-defined intervals to reflect the current level of congestion on the network. Thus, at every decision point of the network, each individual vehicle is able to consult those updated tables and reroute as convenient. In the base model, routeing tables were set to be updated at 2 minute intervals in line with best practice (SIAS, 2011). This dynamic feedback allows the model to continually update the estimated costs based on the actual delay experienced by vehicles already on the network.

Dynamic feedback, however, only affects familiar drivers, while unfamiliar drivers will not be aware of any changes in congestion. The degree to which familiar drivers react to route feedback also differs, with the more aggressive drivers taking rat run choices while the least aggressive will tend to stay on major routes and accept the delays. Familiarity is therefore another way of determining the percentage of vehicles that will reroute due to congestion. This was set by vehicle type at 50% for cars and LGVs, and 10% for HGVs. These percentages are within the recommended range (SIAS, 2011).

4.3.4 Demand Estimation

Demand matrices are calculated in S-Paramics by using an applied distribution (a prior matrix) and a physical network (routeing file) to calculate an input that will best satisfy a series of targets (the survey data).

<u>The prior matrix:</u> applies a distribution to the estimation process. Values in the prior matrix act by weighing movements between O-D pairs.

Normally, the prior matrix comes from observed data such as roadside interviews or registration plates) or even from other models such as macroscopic or larger strategic models). In this case, none of these sources was available so JTDB flow data had to be used.

Another caveat was that the JTDB provides data on link counts but not on turn counts, as explained in section 4.3.2. Thus, the flows on each link the M6 and M6 toll are known and so are the flows on the links immediately before both roads split (J11A) and after they rejoin (J3A). However, with the exception of the M5, A42, M54 and A38(M) the number of vehicles entering or exiting though each intermediate junction are not known. Link counts are sufficient to build the "Survey File" that the matrix estimation process aims to satisfy, but not to inform the "Prior Matrix File."

Under these circumstances, a seeded prior matrix was used. A seeded matrix classifies zones on the network and weights trips between zones according to that classification. The criteria for this classification were based on zones that are likely to carry more or less traffic. Thereby, zones connecting with motorways M5, M42, M54 and A 38(M) were given higher weights than less important roads. Table 6 shows the full classification.

Table 6. M6 Junctions

Junction	Destination	Ranking
J11	Wolverhampton A460	Minor
J10A	WALES/Wolverhampton/Telford **M54**	MAJOR
J10	Walsall/ Wolverhampton A545	Minor
J9	Wednesbury A461	Minor
J8	Birmingham W&S / West Bromwich **M5**	MAJOR
J7	Birmingham N/ Walsall A34	Medium
J6	Birmingham Centre &NE **A38/A38(M)**	MAJOR
J5	Birmingham East / Sutton Coldfield A452	Minor
J4A	**M42**	MAJOR
J4	Birmingham Airport Coventry A446	Medium
3A	**M6**	MAJOR

Table 7. M6 Toll Junctions

Junction	Destination	Ranking
T8	Wolverhampton/ Telford A460/A461	Minor
T7	Cannock/Great Wryley **A34/A5**	Medium
T6	B5011	Minor
T5	A5148	Minor
T4	**A5**	Medium
T3	**A38**	Medium
T2	A446	Minor
T1	**M42**	MAJOR
J3A	**M6**	MAJOR

The routeing file: is created by collecting a PIJA file, which stands for the 'Proportion of vehicles going from points I to J that are Assigned to each link.' The PIJA file is generated by taking the estimate of delay on each link and turning movement in the network at the end of each PIJA interval (set by the modeller) and using that information to generate a set of routes through the network. A user-defined number of virtual vehicles test the network for each OD pair using the same settings (perturbation, etc.) as real vehicles. These virtual vehicles do not interact or affect real vehicles in any way. The PIJA file produces an estimate of the number of vehicles using each route between each OD pair based on flows and delays within a given run.

The PIJA file was collected by using 100 vehicles, which provides a complete sample of the route choice in the model. Virtual trips were released at 2 minute intervals, coinciding with the dynamic feedback period (each time routeing tables are updated based on congestion) in order for the virtual trips to sample every possibility for rerouting. During the collection of the PIJA, demands came from the Prior matrix as agreed with modellers at SIAS.

The survey data: is the target that the matrix estimation process aims to satisfy. The survey file was collated from data from the JTDB, which provides flow data for each link on both the M6 and the M6 Toll.

4.4 Base model calibration: Travel Time and congestion

The model calibration process consists of further adjustments to the network and the matrices in order for the model to accurately represent traffic conditions. Two main refinements were undertaken at this stage:

Matrix adjustment

The initial matrix as developed by the Matrix Estimation module underestimated congestion on the M6 and achieving realistic delays is essential, as this is a key factor in route choice.

It was deemed that the key route choice in the model happens at junctions 11A (Southbound) and 3A (Northbound) where the M6Toll begins and ends (Figure 7). This choice is based to a large extent on the congestion past those junctions. Once a vehicle has made its choice at either of those junctions, there are very few realistic opportunities for swapping roads.

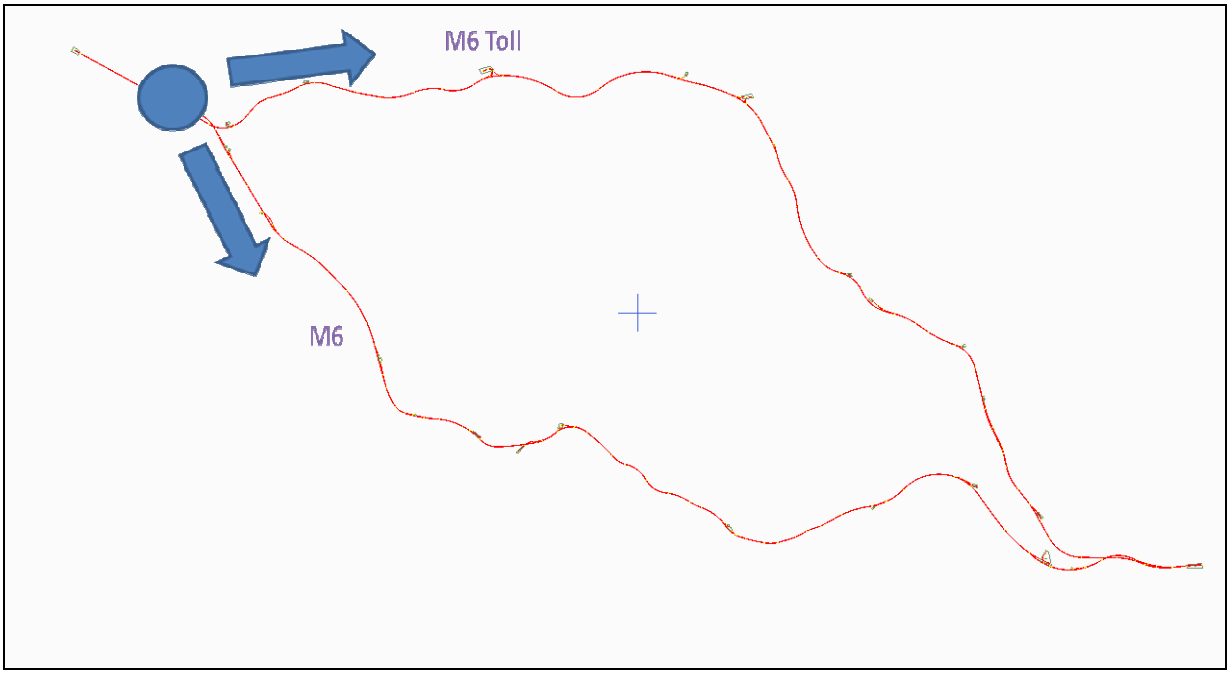

Figure 8. Decision point for vehicles travelling southbound

The focus was therefore to achieve total end-to-end delay as a compound of all links on the M6, rather than reproducing delays at each link accurately. Therefore, the estimated matrix was perturbed on a trial-and-error basis by increasing the number of vehicles travelling between internal junctions within the M6 in order to raise total end-to-end congestion and obtain realistic journey times.

<u>Profile adjustment</u>

A close observation of traffic flow data revealed that demand peaks at different times on the M6 and M6 Toll, with the M6 peaking earlier, probably to account for the fact that drivers need to start their journeys earlier to compensate for longer and unpredictable journey times.

S-Paramics allows for the use of different profiles within a single matrix to account for this. The release profile dictates the percentage of vehicles released onto the network in each 5 minutes interval. Profiles were calculated by using

JTDB traffic flow data on 14 January 2009. These are shown in figures 9 and 10 below.

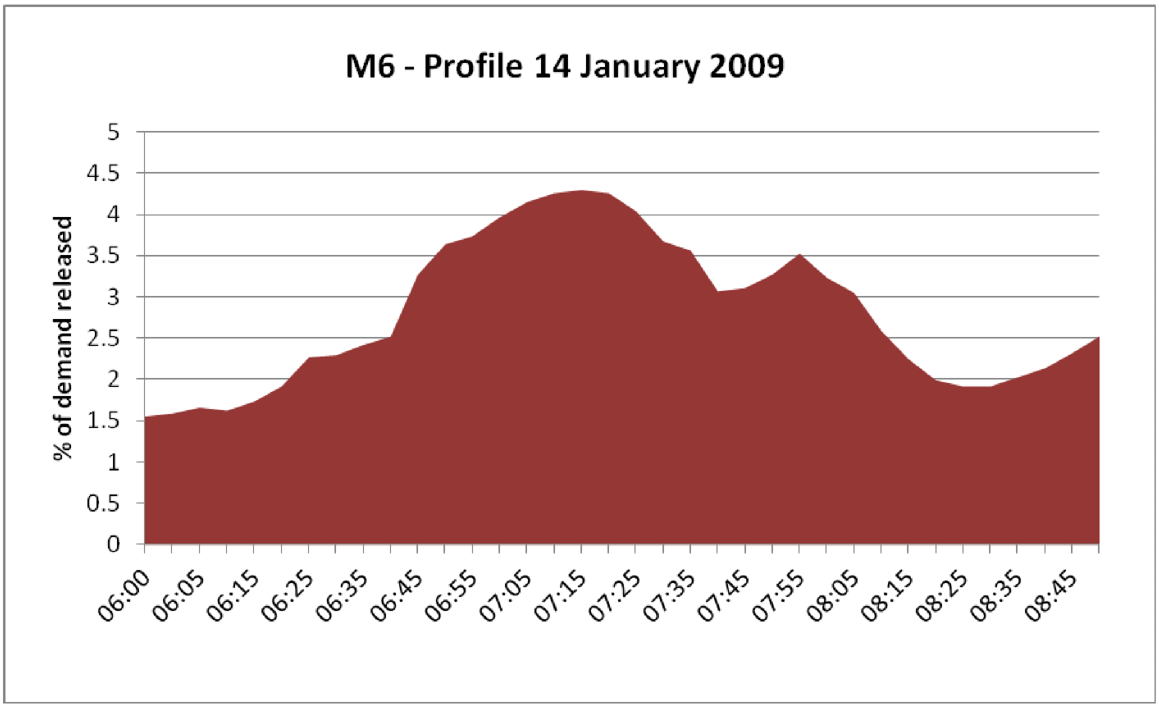

Figure 9. Release Profile of the M6

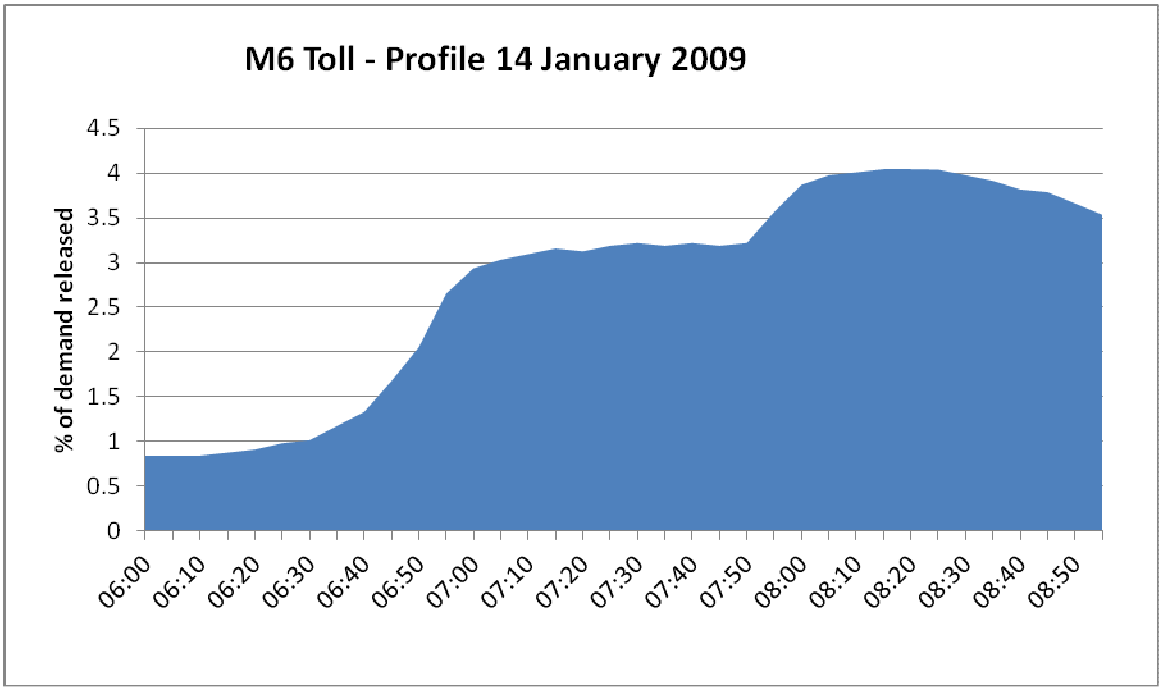

Figure 10. Release Profile of the M6Toll

4.5 Conclusions

Toll roads are frequently mirrored by an alternative free but congested route. In these cases, drivers are confronted with the possibility of paying a toll to save travel time and to safely assume that today's travel time will be very similar to yesterday's travel times. This introduces a new variable that is currently not accounted for in traffic modelling: the willingness of an individual to pay for shorter a more reliable travel time. This variable can be quantified as an individual's Value of Time and Value of Reliability. These are defined respectively as the money a driver would be willing to pay to reduce their total journey time by one hour, and to reduce travel time uncertainty by one hour. Chapter 2 concluded that the VOT and VOR values gathered from the literature review were not applicable to the UK and recommended the derivation of new UK-specific values.

This chapter has gone on to detail the formulation of a Paramics microsimulation model that is intended to be used in future research to derive VOT and VOR values in the UK. This is a model of the M6 Toll Motorway that bypasses Birmingham, which at present is the only toll road in the UK. This base model presented covered the entirety of the M6 Toll and the parallel section of the M6, which is one of the most congested roads in Europe. This model represented a weekday during the morning commute from 6am to 9am.

The Highways Agency's Journey Time Database was the primary data source, after establishing its validity against a database provided by the M6Toll managing company. Traffic flow data were used as the base to estimate demands, speed data were used in profile development and journey time will be used in the validation of the base model detailed in the next chapter.

The base model run on Stochastic Dynamic Assignment, whereby vehicles are capable of rerouting in real time by basing their decision on actual delays on their route. Vehicles calculated the cost of each alternative by means of a weighted combination of time, distance and monetary costs. As a starting point, the weighs applied to these costs were derived in accordance with TAG 3.5.6.

The next chapter discusses the validation of the model and some of the issues that modelling travel time and variability presents.

CHAPTER 5. BASE MODEL RESULTS AND VALIDATION

5.1 Introduction

The aim of this research is to contribute to the advancement of the modelling of behavioural responses to tolls in microsimulation models. Chapter 4 detailed the formulation of a microsimulation model in Paramics of the M6 Toll Motorway that bypasses Birmingham, which at present is the only toll road in the UK. This model covered the entirety of the M6 Toll and the parallel section of the M6, which is one of the most congested roads in Europe. This base model was calibrated to reproduce observed conditions on the road on a weekday during the morning commute from 6am to 9am with the main focus of replicating the share of vehicles that choose each alternative route.

The present chapter undertakes the validation of the base model against travel time and travel time variability. As seen in chapter 2 drivers choose between routes depending on the costs associated to each alternative. These costs can be valued as time costs (time spent travelling) as well as monetary costs (charge to use the road facility). Travelling is an intermediate activity, which is carried out not as an end in itself but as a necessary mean to the desire activity (DeSerpa, 1971) and therefore there is a value in shortening the time spent travelling which is quantified as the value of time (VOT).

Chapter 2 also introduced the concept of a Value of Reliability (VOR). The interest in VOR is fairly recent, but nevertheless equally important as congested roads do not only increase travel times, but also make travel times more unpredictable, which means that drivers have to adjust their departure time or risk arriving late at their destination.

It is therefore crucial for any model of a tolled road to replicate accurately the end-to-end travel times and day-to-day variations in travel times on both the tolled facility and the free alternative as these will impact on route choice. With this aim, this chapter focuses on the validation of the based model against the following:

- End-to-end travel time on each route, to ascertain that vehicles using dynamic assignment are basing their route choice on accurate delay data;

- Traffic flow immediately after the decision point, to ascertain that the number of vehicles choosing each alternative route is realistic;

- Proportion of cars and HGVs, to be able to test different time and cost coefficient in the derivation of those; and finally

- Day-to-day travel time fluctuation by assuming each model run represents a different day.

The first three criteria are commonly used measures in modelling practice and are discussed in the first part of this chapter. Validation against travel time variability is non-standard and more challenging as discussed in the second part of the chapter.

5.2 Traffic flows, vehicle proportions and travel time

Validation of the base model was based on the average of 5 runs, using three different measures: 1) traffic flows at the decision point, 2) vehicle proportions and 3) travel times. These are discussed in turn.

<u>1. Traffic flows at the decision point</u>

The “decision point” is defined as the point where vehicles get to choose between routes. At junction 11A, the M6 offers the possibility of continuing on the free motorway or diverting to the M6 Toll by paying a toll. Although there are other intermediate entries and exits that are tolled, vehicles using them in the model do not have the option to choose any other alternative route. Therefore, the only route choice and the only point where the GCE affects demand assignment occurs at J11A.

The GEH statistic was used in comparing the difference between observed and assigned flows at this decision point. The GEH statistic is defined as follows:

$$GEH = \sqrt{\frac{(M-C)^2}{0.5\times(M+C)}} \qquad (10)$$

Where: *M* is the modelled flow

C is the observed flow.

A generally accepted value for the GEH statistic is less than about 5.0 (DMRB volume 12, section 2, part 1). Table 4 shows acceptable GEH statistics on the two links immediately after J11A.

Table 8. Observed and modelled flows

M6 (J11A to J11)			M6 Toll (J11A to J8)		
Observed	**Modelled**	**GEH**	**Observed**	**Modelled**	**GEH**
7137	7029	2	4141	4332	3

After J11A, flows on the remainder of the M6 and M6 Toll are affected by vehicles using intermediate junctions. Observed flows for the in and out movements are not available and have been approximated in the matrix estimation process. However, these are only relevant in so far as they produce realistic travel times.

2. Vehicle proportions

It is necessary to model the correct spread of vehicle types between routes in order to calculate different toll parameters for cars, HGVs and LGVs. Table 5 shows a comparison between observed and modelled percentages of vehicle types per route.

Table 9. Observed and modelled vehicle type proportions

	M6		***M6 Toll***	
	Observed	**Modelled**	**Observed**	**Modelled**
Cars	67%	72%	96%	100%
LGVs	17%	12%	3.2%	0%
HGVs	14%	15%	0.8%	0%

3. Travel time:

End-to-end travel time was considered a key measure for the validation of the model as it is assumed that the higher travel times on one route determine the probabilities of choosing the other alternative. Modelled travel times were derived by averaging results from 10 runs. In Paramics, each run represents a different instance of the journey (i.e. a different day). In microsimulation, results between runs may vary as they are the result of the number of vehicles released onto the network per time segment, the combination and interaction between them and their sensitivity to rerouting based on network conditions . All of these factors vary from run to run and it is therefore good practice to average results from a set of runs.

Figure 11 compares travel times observed on 14th January 2009 to the average travel times of 10 Paramics model runs. As it can be seen, a good correlation was achieved.

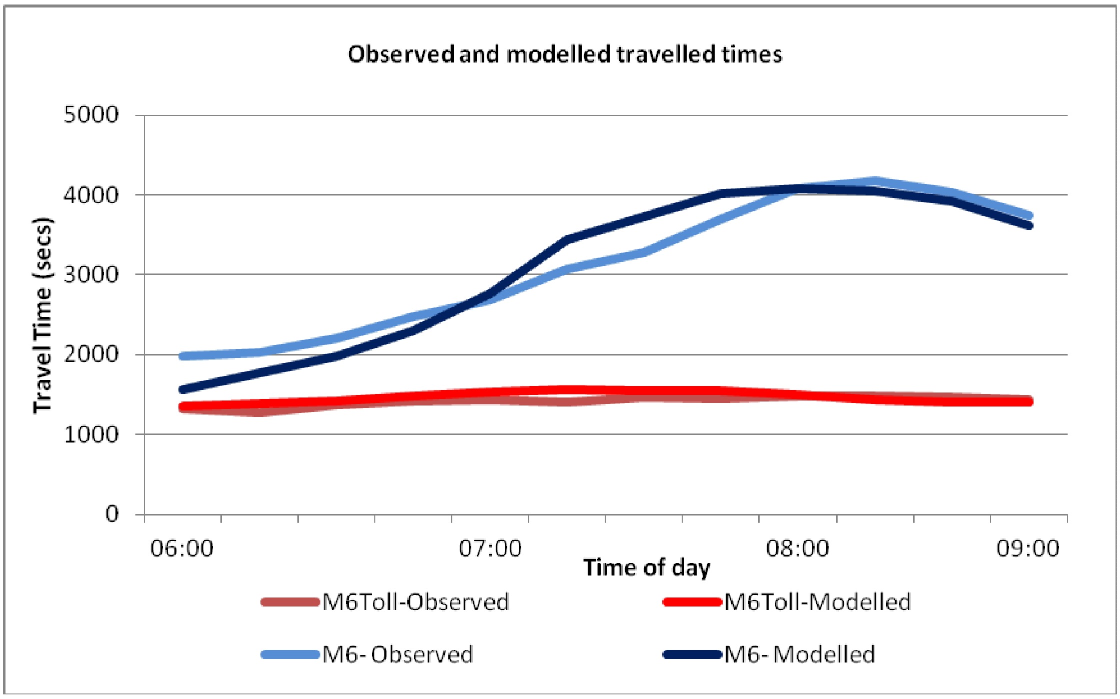

Figure 11. 14 January 2009: Observed and modelled travel times

5.3 Further validation: Travel time variability

For the purposes of this study, a further step in the validation of the model was undertaken. This consisted in establishing whether the variation in travel time between modelled runs reflected the day-to-day variations observed in reality.

In essence, the purpose of this base model would be to replicate day-to-day travel time variation in run-to-run travel times. Once this is achieved, this variation should be fed back to vehicles in the following runs so that they build a knowledge of how unpredictable the road is. Through a VOR term in the GCE, each vehicle should be able to weigh their chances of facing longer or shorter journeys and choose their route accordingly.

In order to calibrate the base model against TT variability, the first step was to determine how much travel times vary from one day to the next on both the M6 and the M6Toll. Observed travel times for 10 consecutive Wednesdays from January to March in 2009 are plotted in figure 12 below.

As it was expected, this analysis revealed a much wider variation in the results from the M6. Unsurprisingly, this variation is more exacerbated during the morning peak period. As can be seen in figure 12, traffic congestion starts building up at different times and peaks at different times. In the most extreme cases, travel times can double (e.g. the difference between the shortest and the longest travel times on 11 February and 18 March at 8.15 am is 2800 seconds (46 minutes)).

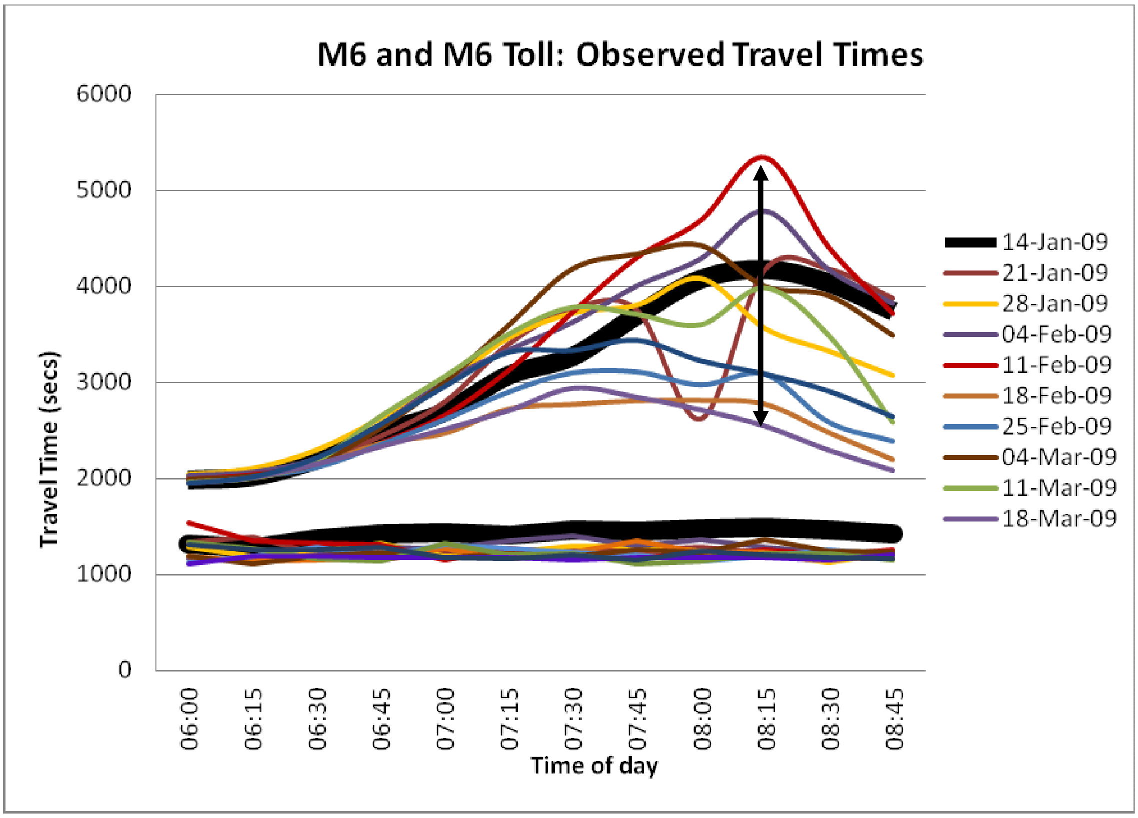

Figure 12. Observed Travel times (from JTDB)

The observed variation was found to contrast quite starkly with variation between modelled runs. As can be seen in figure 13, travel times between modelled runs are very similar to each other.

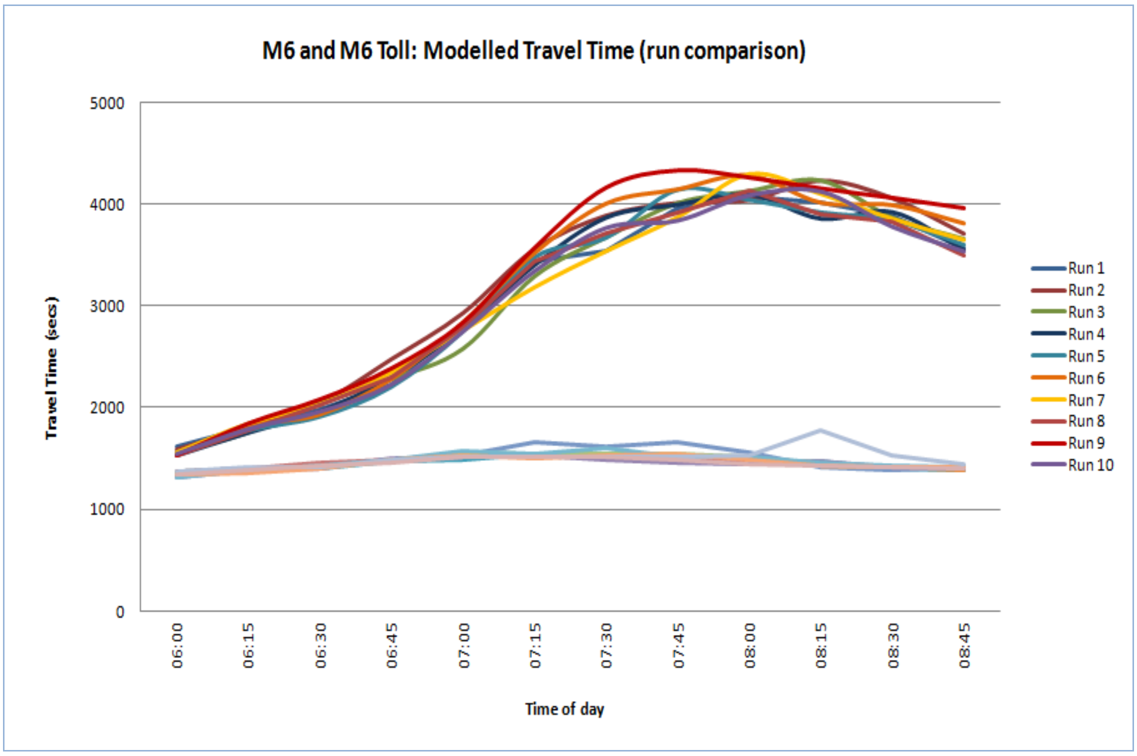

Figure 13. M6: Travel times from 10 model runs

Day-to-day variation in travel time on both the M6 and the M6 Toll was quantified by comparing the standard deviation, which reflects the dispersion of values from the mean. The standard deviation was calculated for travel times from 10 days' worth of data from the JTDB as well as for the TT from 10 runs of the base model. Results are presented in figure 14.

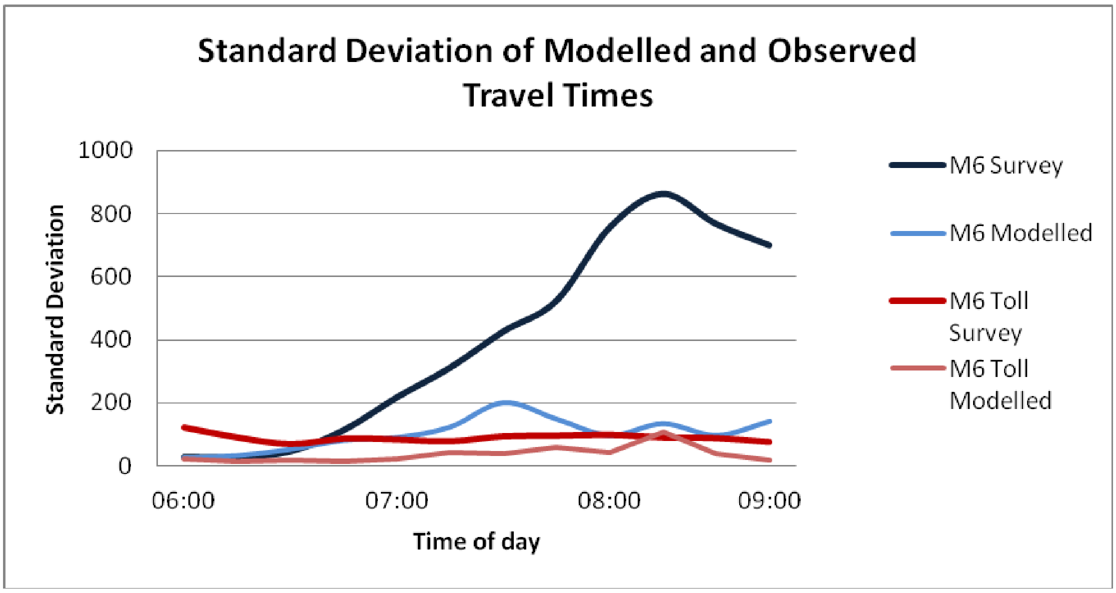

Figure 14. M6 and M6 Toll: Standard deviation of modelled and observed travel times

When considering results for the M6 Toll, standard deviation of both modelled and observed data are quite low, indicating similar travel times between runs of the same model as well as similar travel times from day to day in real life. The model did tend to underestimate variation slightly, but overall, these results are considered an acceptable match.

When comparing results for the M6, it became apparent that observed TT variability was not replicated in the Paramics model. This meant that each run could not be taken to represent a separate day. This limitation has implications for the purposes of this study since it was expected to feedback run to run variations into the model's route choice mechanism.

5.4 Further model calibration to reproduce variability

Once established that natural run-to-run variations were not sufficient to replicate observed results, this study focused on attempting to artificially force variability into the model.

Typically, Paramics intends to model a typical day in each run. Each runs uses the same demand matrix and the same release profiles, however a limited amount of variation between runs is achieved by a combination of:

1. The use of stochastic release in conjunction with 5-minute interval profiles. The total number of vehicles to be released in an interval is dictated by the profile. However, under stochastic release, the probability of releasing a vehicle is calculated for every second in each 5-min interval in the profile. Thus, the use of a "seed" determines the exact time within each 5 minute interval at which each individual vehicle is released.

2. The combination and interaction of vehicles with different driver behaviour such as desired speed, lane changing behaviour or gap

acceptance as well as the combination of vehicle types (e.g. one run may include a cluster of HGVs). These affect the delays on the network.

3. The use of Stochastic Dynamic Assignment, which allows vehicles to reroute based on delays ahead. Again, the characteristics of some vehicles make them more likely to reroute than others.

Given that these factors were shown to have failed to achieve the extreme variations observed on the M6, this study tried to artificially create travel time variation in the model in order to match observed fluctuation. A series of attempts were made to reproduce variation by applying the following mechanisms to the M6 demand matrix:

1. Altering traffic flows by set percentages
2. Coding scheduled incidents on the network
3. Varying the release profiles

The process and results from each attempt are discussed in turn below.

1. Altering traffic flows by set percentages

The effect of flow on travel time was explored by increasing and decreasing demands on the base matrix by 5% and 10%.

This changes where only applied to movements within the M6 so as not to affect the M6 Toll. Two runs where undertaken with each perturbed matrix and results are presented in figure 15.

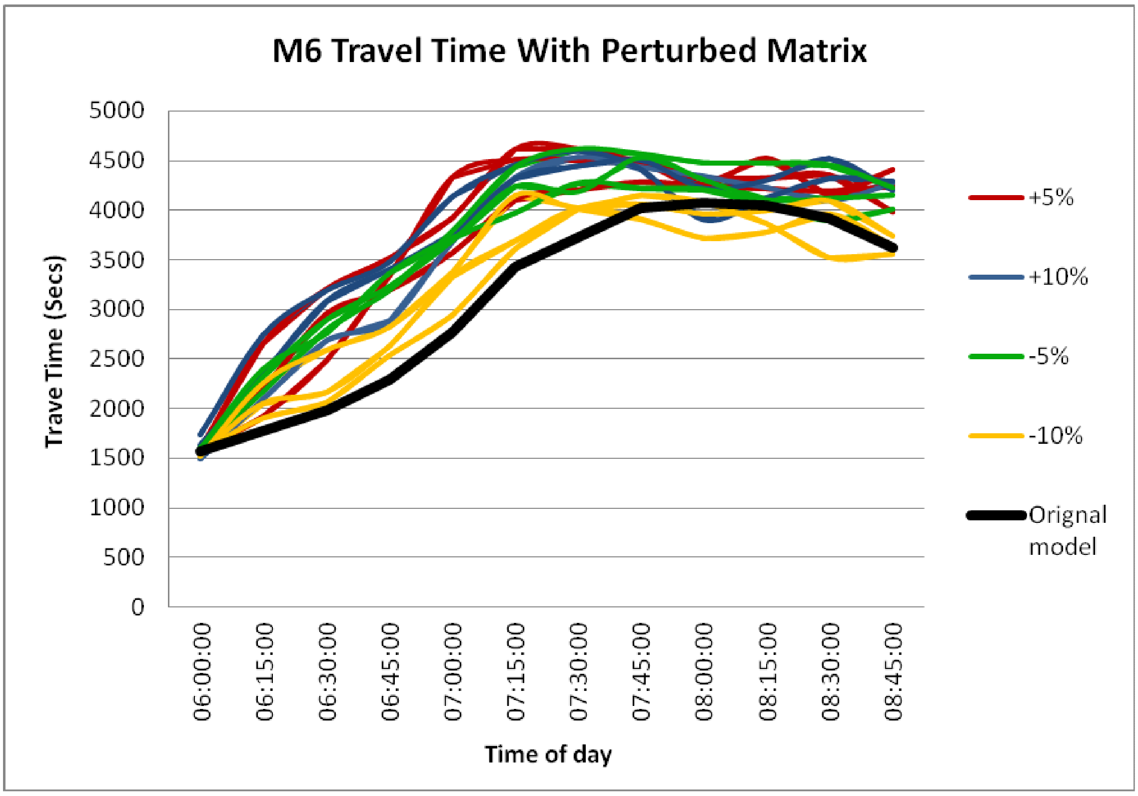

Figure 15. M6: Travel time with perturbed matrix.

(The 'Original model' series represents the average of the 10 model runs in the base model graphed in figure 13).

This attempt demonstrated that:

1. Perturbed matrices provoke variation in travel time over the whole time 6 am to 9 am period, while observed travel times vary more on the 7.30 to 8.30 am period as shown in figure 12.

2. The effect of increasing flows by 5% and 10% is not quite as severe as in observed travel times (up to 1,500 seconds in this model compared to up to 2,800 seconds in observed data).

These results revealed that, while flow has an impact on travel times, it is not responsible for all the variation shown in observed data. This finding is in line with results a comparison between observed data, which does not show a perfect correlation between higher flows and higher travel times or lower flows and lower travel times (see appendix 22).

2. Coding scheduled incidents on the network

Paramics has a mechanism that allows for incidents to occur at times and locations specified by the modeller. Examples of incidents that can be coded are vehicles having to stop on a lane or slowing down. These can be coded to affect single vehicles or percentages of the total flow, and to occur once or recurrently over a period of time.

A first test was made by adding an incident that would make a vehicle stop, thereby reducing the road to two lanes. These incidents were scheduled to happen at 30 minute intervals from 6.30 to 8 at two points on the M6 (one between junction 9 and 10 and another on the last third of the road).

Figure 16 shows the impact of such incidents with a duration of 2 minutes (i.e. the vehicle that causes the incident stops for 2 minutes thereby causing congestion)

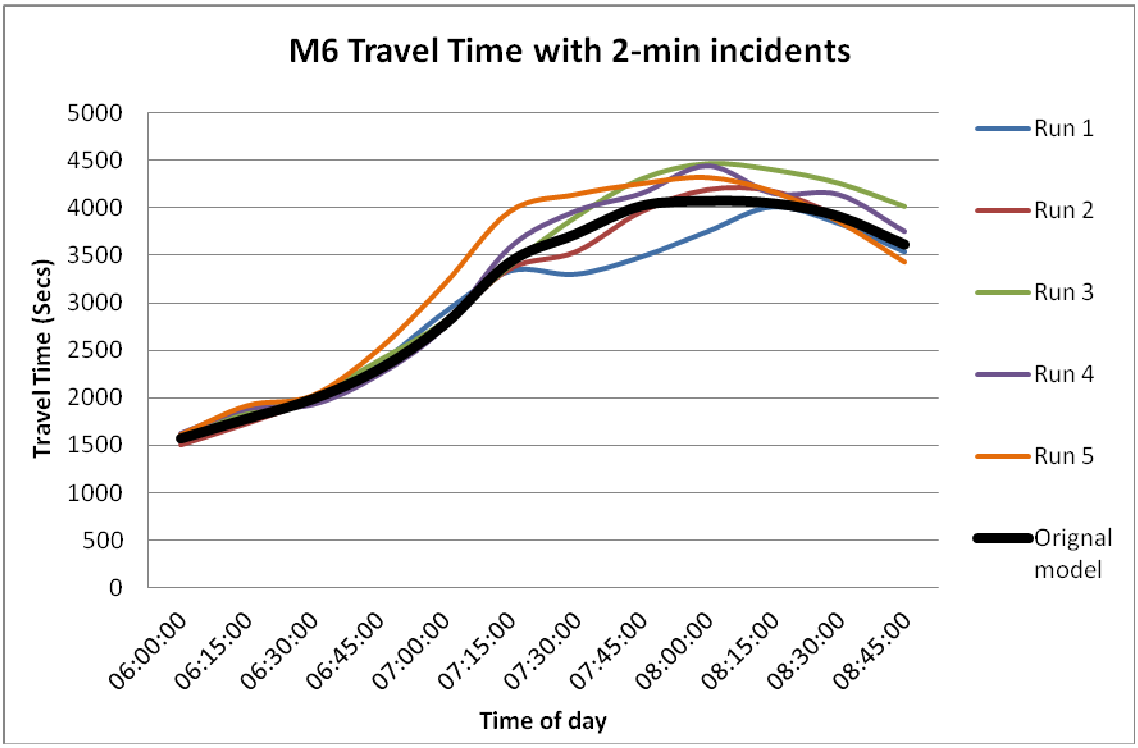

Figure 16. M6: Travel Time with 2 minute incidents.

(The 'Original model' series represents the average of 10 model runs in the base model graphed in figure 13)

Figure 17 shows the impact of the same incidents this time with a duration of 10 minutes (i.e. the vehicle that causes the incident stops for 10 minutes). Increasing the duration of the incident produces consistent congestion.

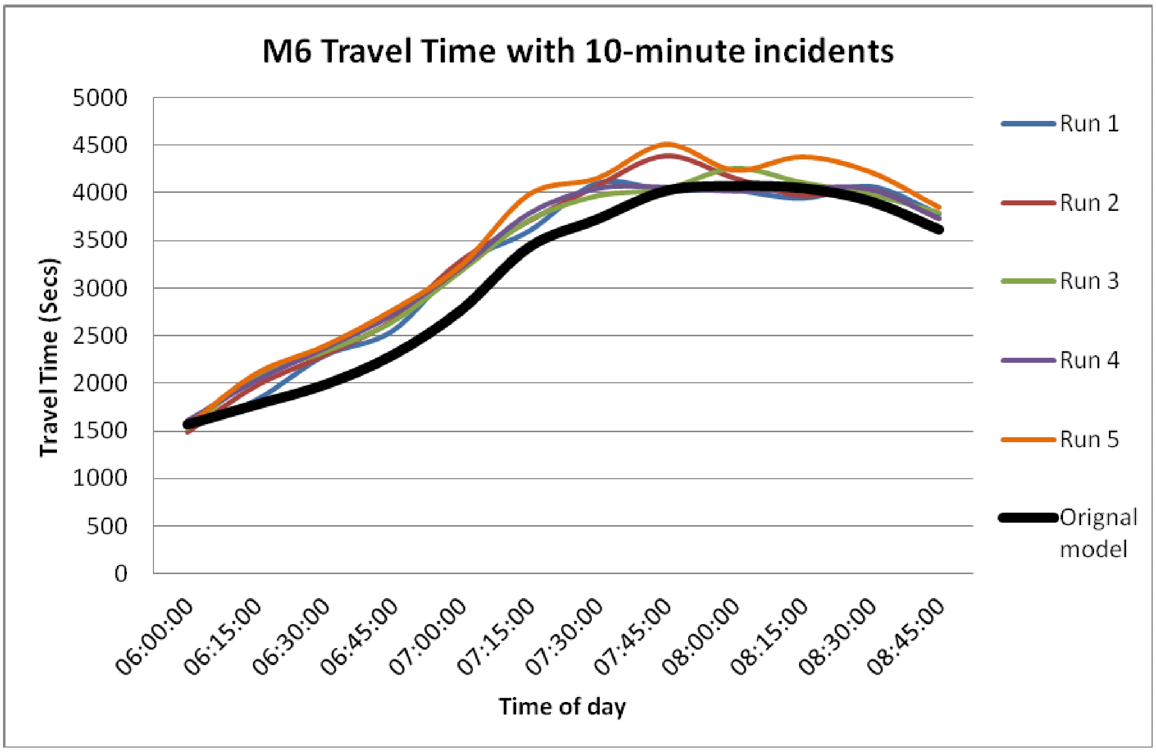

Figure 17. M6: Travel Time with 10 minute incidents.

(The 'Original model' series represents the average of the 10 model runs in the base model graphed in figure 13).

From the above graphs, it can be seen that incidents have a very limited impact on journey times. The most likely cause for this is that while the incident causes a hold up by reducing the road by one lane, this gives the opportunity for traffic downstream to flow more freely during the duration of the incident (e.g. traffic on the otherwise congested on-ramps downstream can join the M6 more easily while the flow on the M6 is diminished by the incident). Both events then cancel out and therefore overall travel times are not increased by the incidents.

In order for an incident to increase journey times, it would have to outweigh the effect of current congestion, which in a road like the M6 is quite severe. This could be done by significantly increasing the rate and duration of the incidents and locating them significantly further downstream from the most congested on-ramps.

In any case, the impact of incidents is very difficult to predict, and as in the butterfly effect, they can manifest at unexpected times and locations. As an example, a study carried out by SIAS indicated that a 20-minute incident on one point on the network could still generate a queue within a short wave over a 1 hour later at a point 5 kilometres away from the original incident (SIAS manual). As a result, incidents are difficult to calibrate and validate.

3. Varying the profiles

In Paramics the release profile controls the percentage of vehicles released in 5 minute intervals. In this experiment, the demand matrix of the 14th January base model was combined with the profile of observed demands on a similar day the following month (Wednesday 18 February 2009). The 14th January and the 18th February profiles are shown in figures 18 and 19.

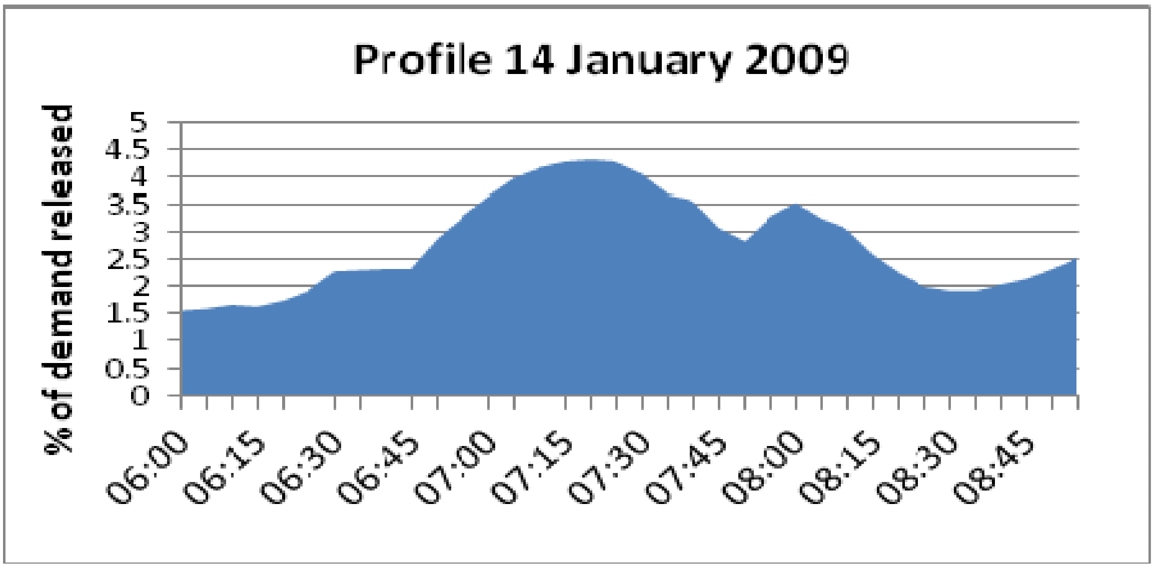

Figure 18. M6: release profile for 14th January 2009

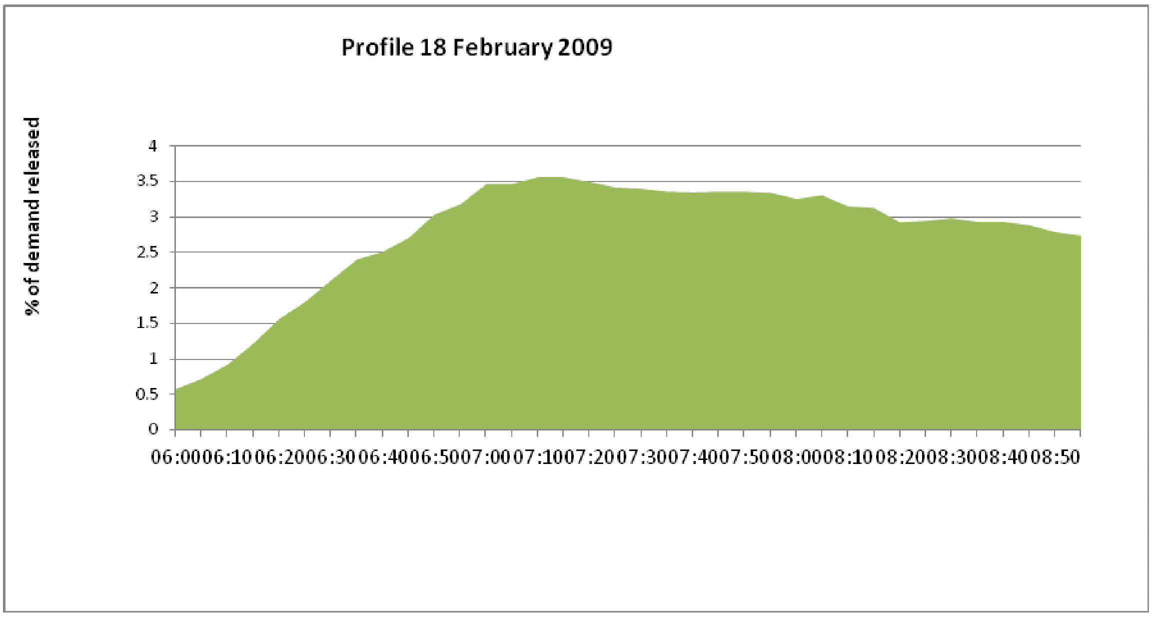

Figure 19. M6: release profile for 18th January 2009

This combination of the 18 February profile with the demands of the 14th January base model produced the highest variability of all attempts, as shown in figure 20. This brought forward the onset of congestion, which built up earlier and quicker that in the observed data.

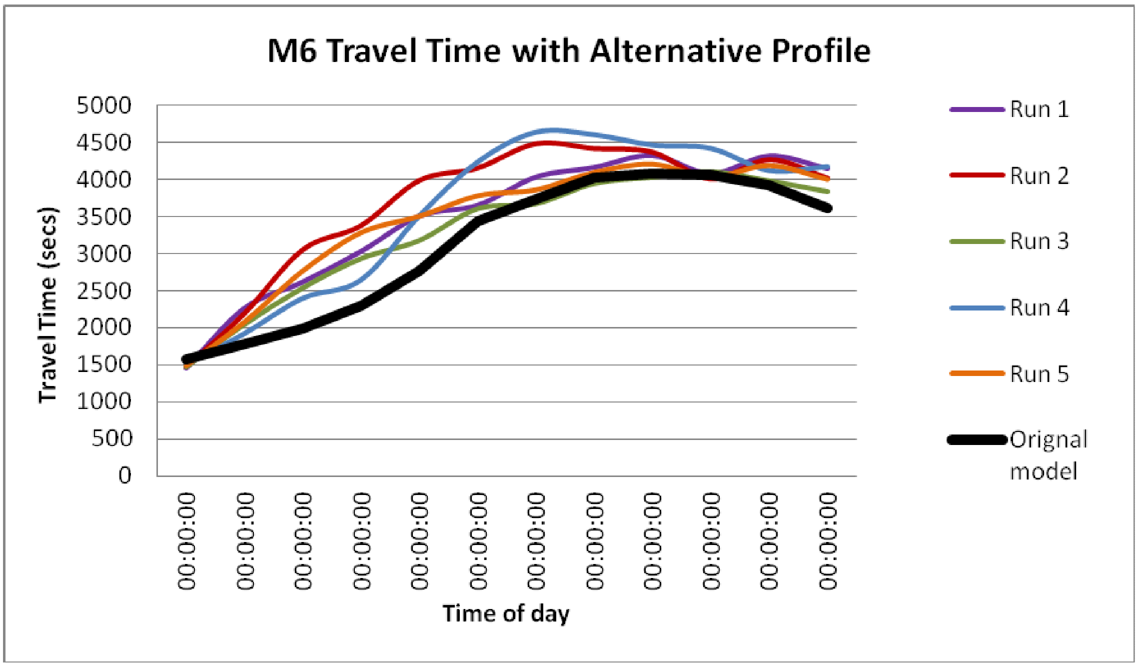

Figure 20. M6 and M6 Toll: Travel time with alternative profiles

(The 'Original model' series represents the average of the 10 model runs in the base model graphed in figure 13).

None of these three attempts at reproducing day to day travel time variability in run-to-run variations produced the desired results. They either didn't have a limited impact or they altered the congestion pattern. This was an important set back in the possibility of modelling travel time variations and using it to inform a VOR term in Paramic's GCE .

5.5 Conclusions

This research has established that drivers base a choice between a free congested route and a tolled free-flowing alternative on a personal valuation of their time. This is quantified as a Value of Time and a Value of Reliability, which are defined respectively as the money a driver would be willing to pay to reduce their total journey time by one hour, and to reduce travel time uncertainty by one hour. A review of the literature available concluded that it would be necessary to derive UK-specific values, and chapter 4 undertook the formulation of a base microsimulation model of the M6Toll and M6 motorways around the Birmingham, which is intended to be used in future research to derive VOT and VOR values specific to the UK context.

This chapter focusing on validating this base model against three criteria:

1. Traffic flows at decision point;
2. Vehicle type proportions;
3. End-to-end travel time; and
4. Day-to-day travel time variability

The model was successfully validated against the first three criteria, which are measures commonly used in modelling practice. The validation against day-to-day variability proved more challenging. A comparison of observed travel times in 10 days on both the M6 and the M6 Toll revealed that travel times are quite stable in the case of the M6 Toll but vary widely from one the day to the next in the case of the M6.

It was hoped that day-to-day variability could be replicated in run-to-run results. However, when observed travel times were compared to travel times produced by the different runs of the Paramics model, it became apparent that simulation did not achieve extreme variations observed on the M6. Although simulation runs do produce some variation, this is due to 1) the use of stochastic release, 2) the combination and interaction of vehicles types and vehicles with different driver behaviour, and 3) the use of stochastic dynamic assignment. These produce moderate differences, typical of most UK roads on any ordinary day.

However, conditions on the M6 are extraordinary probably due to variations in demand, demand pattern, or incidents on the road. It was the purpose of this study to manipulate the model to replicate these and observe their impact on TT.

Three alternative models were set up, on which 1) demands were altered, 2) incidents were added and, 3) alternative demand profiles were used. Although these showed some impact on travel times, in no case did they match the TT variations observed in reality. Increasing or decreasing traffic demands did not produce enough variation. Altering the release patterns had the unwanted effect of moving the onset of congestion forward. The inclusion of incidents had the counterintuitive effect of balancing the queues caused by the incidents with the easing of congestion downstream during the holdup caused by the incident.

These experiments demonstrate that the wide variation in journey times observed in the M6 is most probably not caused by one single factor but by a combination of factors. However it is practically impossible to empirically determine the cause or causes from the data available (surveys, ATC counts). In the case of the M6, possible factors responsible for observed day to day variations may include differences in traffic composition (e.g more or less slow vehicles on the network), differences in traffic patterns (e.g. the share of drivers departing earlier or later), incidents (e.g. broken down vehicles), total demands or even the weather conditions. A combination of any of these factors would have an impact, which would be even more pronounced in the context of high density traffic, such as is the case in the M6, which are particularly sensitive to the smallest disturbances (SIAS manual).

Therefore, it follows that, just as in real life, variability would probably be best modelled through a combination of representation of the above factors. However, such model would be extremely difficult to calibrate due to the difficulty to ascertain which the causes were and to control the effect of the mechanism used.

A further caveat is that even if variation could be successfully modelled, at present Paramics does not count with a mechanism to feed travel times from previous runs to vehicles in a given run. Ideally, a mechanism similar to dynamic feedback, but using delays from previous runs would need to be used for day-to-day variation to be modelled.

Finally, from a more pragmatic point of view, even in the case that variability could be modelled, the cost of doing so may be preventative. It would be necessary to collect data on a number of days for each model in order to establish the range of day-to-day variation. If this was to be done though surveys it may be commercially unviable.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Over the past few decades there has been a renewed interest in road pricing through a variety of forms. Similarly, the forecasting and evaluation of transport schemes has become reliant on the careful consideration of all possible outcomes, very often by means of computer-based modelling packages. The aim of this research was to contribute to the advancement of the modelling of behavioural responses to tolls in microsimulation models.

In order to understand the context of road tolling, chapter 1 started by presenting an introduction of the principles of road tolling and a brief overview of the different ways in which it has been introduced across different countries. This review concluded that different tolling scenarios can be classified according to the availability of alternatives to paying the toll. In urban scenarios, area and cordon tolls around cities and city centres are mainly designed to move drivers onto alternative modes of transport rather than alternative routes. In inter-urban context, tolled facilities such as point tolls at bridges and tunnels offer shorted routes by saving natural obstacles, while alternative routes mean a longer detour. In many other instances, tolled routes run parallel to free alternatives, the only difference being the level of congestion in each one. This is the case of HOT/FAIR lanes and many tolled motorways in Europe, where tolled roads offer shorter journey times and travel times do not vary much from one day to the next as an alternative to a congested stretch of free road. This last scenario is the main focus of this research.

When forecasting demand for a road facility, existing traffic models base route choice on a GCE that is a combination of travel time, distance of each route and monetary costs (the plain toll cost), which are tangible variables. When presented with a scenario where there is a congested free alternative to the tolled facility, drivers make their route choice based on a trade-off between time and money. The driver’s willingness to pay is a subjective decision but it can be quantified into behavioural Values of Time - VOT (defined as the amount of money drivers are willing to pay to save travel time) and Values of Reliability - VOR (defined as the amount of money drivers are willing to pay to be able to predict how long the journey is likely to take). To model route choice under tolls in a computer simulated model, the route choice system must account for both VOT and VOR values.

Chapter 2 set out to review of available literature that has derived VOT and VOR values with a view to using them in a simulation model as a variable that affects route choice. The point of principle of this review was that, notwithstanding the fact that values differ between individuals, there must be some personal and trip characteristics that account for general valuation trends. By deriving values that apply certain driver groups or types of journey, these could be used to apply weight to the monetary term of a model's GCE.

The literature review collected and reviewed values from available studies with the aim of deriving either one value or a distribution of values that could be used in simulation in the UK. The review found studies from a variety of countries and years, in a variety of currencies, from a variety of tolling contexts and elicited using different methods. In an attempt to establish the impact of all these variables, values from the literature were made comparable by converting them to a common currency in a common year and then a regression analysis was attempted. Unfortunately, most studies did not provide enough details about the tolling context from which values were derived, which meant that the regression analysis was not possible.

It was not possible to use the literature to derive a value or range of values that could be applied to the UK context. The literature did however unveil that there are certain trip and socioeconomic characteristics that seem to share similar values. The review concluded that a different VOT and VOR value should be derived by 1) vehicle type (cars and HGVs); 2) trip purpose (commuting trips, non- commuting trips); and 3) day of the week (weekdays v. weekends).

Chapter 3 turned the focus onto the transport models used in current transport practice in order to determine their suitability to model tolls. Since the main difference between a toll road and its free alternative is travel time and delays, the detailed representation of travel time, the build-up of congestion and the network where traffic queues and blocks the road were seen as essential features of any candidate model. Moreover, in order to apply VOT and VORs by segment, as identified in chapter 2, a model needs to be able to represent demand in a disaggregate manner, where vehicles can be assigned individual characteristics. As a results chapter 3 identified dynamic traffic assignment with microsimulation as the most suitable technique for the modelling of road choice in the context of road tolling.

Chapter 4 undertook the construction of a model of a tolling scenario in the UK that could be used to derive UK-specific VOT and VOR values. At present there is only one tolled road in the UK: the M6 Toll that bypasses the Birmingham conurbation in England. Chapter 4 detailed the formulation of an S-Paramics model of the M6 Toll and the parallel free section of the M6, which is one of the most congested roads in Europe. This model represented a weekday during the morning commute from 6am to 9am. Data was extracted from the Highways Agency's JTDB which provided figures for traffic flows and speed on both the M6 Toll and the equivalent section of the M6, as well as travel times from the beginning to the end of both routes. This model was run using Stochastic Dynamic Assignment, whereby vehicles are capable of rerouting in real time by basing their decision on actual delays on their route.

The model formulated in this study is regarded as a base model, calibrated and validated to replicate observed proportions of vehicles choosing each route alternative. This choice is based on a typical GCE in which the cost of each alternative is calculated by means of a weighted combination of time, distance and monetary costs (tolls). For this base model the weighs applied to these costs were derived in accordance with TAG 3.5.6. The purpose of this model is to provide a tool to be used in future research to derive VOT and VOR values in the UK by adjusting the weights applied to the monetary cost of the GCE.

Chapter 5 successfully validated against travel time by using three criteria commonly used in modelling practice: 1) end-to-end travel time on each route in order to replicated real conditions under which drivers could make a choice to pay a toll or not; 2) traffic flow immediately after the decision point in order to ascertain that the number of vehicles choosing each alternative route reproduced observed proportions; and 3) the proportion of cars and HGVs choosing each route in order to be able to test different time and cost coefficients in future research.

A further validation against day to day travel time fluctuation was attempted, with a view to having each model run replicate the wide variations observed in the M6. All attempts in this respect were unsuccessful. This was due to the fact that the combination of parameters in Paramics that allow for run-to-run variations are intended for the validation of a model against average daily variations. The wide variation observed on the M6 could only be achieved by calibrating and validating each day as an independent model.

6.2 Recommendations for future work

The main challenge that microsimulation faces when modelling tolls is that it does not account for the subjective choice to pay a toll or not. At present microsimulation models forecast demand based on the response of drivers to the length of the route (where it is assume that drivers will favour shorter routes), the time it takes to complete the journey (where it is assumed that drivers favour shorter travel times) and the actual toll applied to the route. However, to accurately model road tolls we need a variable that tells are how likely an individual is to pay the tolls, and this is based on how much they value their own time.

Values of time recommended in The Highways Agency' Transport Assessment Guidance (TAG) are based on the cost of delays to the general economy. This in effect calculates the money that the country's economy loses when an individual is stuck in traffic and unproductive as opposed to being at work. While this valuation of time is useful in calculating the economic benefit of a new transport scheme, it is completely unrelated to how an individual makes the choice to pay to shorten their travel time, which is commonly based on the rate of substitution between time spent in traffic and time spent doing some other pleasurable activity, this could be something like staying in bed longer or having more time to play with the kids at night, etc.

While this value is highly subjective, the review in this study showed that it is possible to find groups that share common values. The review recommended values according vehicle type (cars and HGVs), trip purpose (commuting trips, non-commuting trips); and day of the week (weekdays v. weekends). Other segments such as gender or socioeconomic status were dismissed due to the practicalities or commercial traffic assessment such as the costs of data collection and availability and reliability of data. Out of these, this research recommends investigating further the effects of congestion in route choice. Studies such as Hensher (2001), Koenig, Abay and Axhausen (2003), Jovicic and Hansen (2003), Zhang, Xie and Levinson's (2004) and Cantos and Alvarez (2009) found the VOT to be higher in congested circumstances. This means that as travel time increases on the free alternative, the probability of choosing the tolled option can be expected to increase. It is therefore recommended to gather further evidence in literature and to investigate the possibility of using a cost equation in microsimulation that reflects this correlation. Options could be based on the traditional BPR and the Akçelik equations presented in appendix 23.

The second issue encountered in this study was the difficulty to replicate day to day fluctuation in the microsimulation model. A comparison of observed travel times over 10 consecutive days revealed that journey times on the M6 can vary widely between days, while they are very similar on the M6 Toll. These findings are in line with the expected benefits of a toll road, and as such it was considered that there should be a term in the GCE that reflects the effect of unpredictable travel times on route choice. It was therefore necessary to validate the model against travel time variability and this was done by assuming that each model run represents a different day.

Three techniques were used to instigate journey time changes: 1) demands were altered, 2) incidents were added and, 3) alternative demand profiles were used. Although these showed some impact on travel times, in no case did they match the TT variations observed in reality. Increasing or decreasing traffic demands did not produce enough variation. Altering the release patterns had the unwanted effect of moving the onset of congestion forward. Finally, the coding of incidents had the counterintuitive effect of balancing the queues caused by the incidents with the easing of congestion downstream during the holdup caused by the incident. Therefore, it follows that, just as in real life, variability would probably be best modelled through a combination of representation of the above factors, which would be practically impossible to reproduce in a model.

A further caveat identified was that even if variation could be successfully modelled, Paramics does not count with a mechanism to feed travel times from previous runs to vehicles in a given run. Ideally, a mechanism similar to dynamic feedback, but using delays from previous runs would need to be used for day to day variation to be modelled. As a result, the validation of the base model against travel time variability was unsuccessful and any attempt in further research to introduce a VOR in the GCE would need to be calculated from observed travel time data and would not be based on a feedback mechanism. As shown in the literature review, day to day fluctuations in travel time are however decisive in route choice and therefore, this study recommends carrying out further research into its inclusion in modelling.

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APENDICES

Appendix 1. VOT by income (Steimetz and Brownstone, 2005)

Study and type of data	Segmentation	Quantitative outcomes		% increase
		Income<$80K	Income>$80K	
Steimetz and Brownstone (2005)	Work trips	21.52	64.9	202%
	Non-work trips	9.6	14.35	50%

Appendix 2. Relationship between VOT for males and females (Ghosh, 2000)

STUDY, DATA and CURRENCY	SEGMENTATION	QUANTITATIVE OUTCOMES		
		Males	Females	% female VOT exceed male VOT
Ghosh (2000) I-15 Hot lane (US) $	Morning	22.8	29.79	30%
	Afternoon/evening	14.25	16.73	17%

Appendix 3. Relationship between the VOT of commuting and business travel

STUDY, DATA and CURRENCY	SEGMENTATION	Commuting	Business	% business is higher
Radovich and Foster (2000) Tauranga Harbour Birdge (NZ) NZ$/hr		8.35	17.66	112%
Axhausen *et al.* (2006) Switzerland CHF/hr		19.04	27.66	45%
Jovicic and Hansen (2003) DKK/hr		18.7	46.8	150%
Gunn and Rohr (1996 in Wardman 2001) f/hr	0-1500 f/month	7	9.1	30%
	1501-2500	7	9.1	30%
	2501-4000	7.7	12.2	58%
	4001-6000	10.3	12.7	23%
	6001-8000	10.4	14.5	39%
	8000+	12.2	31.4	57%
Gunn *et al.* (1998 in Wardman 2001) f/hr	<2500	9.03	7.53	-17%
	2500-4000	9.37	11.8	26%
	4000-6000	10	14.36	44%
	>6000	10.56	28.4	69%
Hague Consulting Group (1999 in Wardman 2001)	£ 0-10000	1.56	4.2	169%
	10-20000	1.86	5.22	181%
	20-30000	2.46	6.18	151%
	30-4000	3.3	7.74	135%
	40-50000	4.62	8.7	88%
	50-60000	6.84	9.96	46%
	Above 60000	8.4	11.94	42%
Tretvik (1993) Trondheim toll road Kr/hr	0-100000	47.51	57.25	21%
	101-150000	52.32	62.28	19%
	151-200000	52.65	59.31	13%
	201-250000	57.6	59.85	4%
	251-300000	66.75	65.43	-2%
	>300000	67.14	71.96	7%

Appendix 4. Relationship between the VOT of commuting and leisure/shopping/other purpose travel

STUDY, DATA and CURRENCY	SEGMENTATION	Commuting	Leisure/shopping/other	% commtng is higher than leisure/other
Radovich and Foster (2000) Tauranga Harbour Bridge (NZ) NZ$		8.35	Leisure 7.53	10
			Social/recreation 10.49	-26
			Personal business 9.64	-15
Cantos and Alvarez (2009) A3 National Highway (Spain) €		11.76	6.49	
Axhausen *et al.* (2006) Switzerland CHF		19.04	Leisure 18.83	1
			Shopping 17.84	6
Fosgerau, Hjorth, Lyk-Jensen 2007 DKK		78	75	4
Gunn and Rohr (1996 in Wardman 2001) f/hr	**0-1500 f/month**	7	6.3	10
	1501-2500	7	7.4	-6
	2501-4000	7.7	7.9	-3
	4001-6000	10.3	8.9	14
	6001-8000	10.4	10.4	0
	8000+	12.2	12.3	-1
Gunn *et al.* (1998 in Wardman 2001) f/hr	**<2500**	9.03	6.26	31
	2500-4000	9.37	6.86	27
	4000-6000	10	7.31	27
	>6000	10.56	9.55	10
Hague Consulting Group (1999 in Wardman 2001)	**0-10000**	1.56	4.2	-169
	10-20000	1.86	5.22	-181
	20-30000	2.46	6.18	-151
	30-4000	3.3	7.74	-135
	40-50000	4.62	8.7	-88
	50-60000	6.84	9.96	-46
	Above 60000	8.4	11.94	-42
Tretvik (1993) kroner/hr	**0-100000**	47.51	57.25	-21
	101-150000	52.32	62.28	-19
	151-200000	52.65	59.31	-13
	201-250000	57.6	59.85	-4
	251-300000	66.75	65.43	-2
	>300000	67.14	71.96	7
Radovich and Foster (2000)	**<20**	4.1	4.68	-14
	20-30	6.99	4.26	39
	30-50	9.97	12.21	-22
	50-70	8.29	11.17	-35

Appendix 5. Relationship between VOT for morning and afternoon commute

STUDY, DATA and CURRENCY	SEGMENTATION	QUANTITATIVE OUTCOMES		
		Morning	Afternoon/ Evening	% morning VOT is higher than afternoon VOT
Ghosh (2000) I-15 Hot lane (US) $	Males	22.8	14.25	60%
	Females	29.79	16.73	78%
Cirillo and Axhausen (2006) Germany DM	Working days	3.2	18.8	-83%
	Non-working days	20.7	5	314%

Study, data and currency	Quantitative outcomes ($/hr)									
Liu, He and Recker (2007) SR91 Hot lane (US) $	5:00-5:30 am	5:30-6:00 am	6:00-6:30 am	6.30-7:00 am	7:00-7:30 am	7:30-8:00 am	8:00-8:30 am	8:30-9:00 am	9:00-9:30 am	9:30-10:00 am
	16.5	**18.53**	**22.02**	**22.97**	**27.66**	**24.66**	**24.23**	**23.18**	**19.58**	**6.82**

Appendix 6. Relationship between the VOT of weekdays and weekends

Study, data and currency	Quantitative outcomes (€/hr)		
	Weekday	Weekend	% weekday VOT is higher than weekend VOT
Cantos and Alvarez (2009) A3 National Highway (Spain) €	**10.28**	**8.49**	**21%**

Appendix 7. Relationship between the VOT in free-flow and congested conditions

<table>
<tr><th rowspan="2">Study and currency</th><th rowspan="2">Segmentation</th><th colspan="6">Quantitative outcomes</th></tr>
<tr><th colspan="2">Free flow</th><th colspan="2">Congested</th><th colspan="2">% VOT in congestion is higher than free flow</th></tr>
<tr><td>Calfee and Winston (1998) $</td><td>Commuting</td><td colspan="2">-</td><td colspan="2">3.88</td><td colspan="2">-</td></tr>
<tr><td rowspan="3">Koenig, Abay and Axhausen (2003)
CHF/h</td><td>Route choice-1</td><td colspan="2">29.82</td><td colspan="2">38.44</td><td colspan="2">129</td></tr>
<tr><td>Mode choice</td><td colspan="2">31.97</td><td colspan="2">34.16</td><td colspan="2">107</td></tr>
<tr><td>Route choice-2</td><td colspan="2">29.68</td><td colspan="2">51.88</td><td colspan="2">175</td></tr>
<tr><td rowspan="4">Jovicic and Hansen 2003
DKK/h</td><td>Commuter</td><td colspan="2">18.7</td><td colspan="2">64</td><td colspan="2">342</td></tr>
<tr><td>Leisure</td><td colspan="2">23</td><td colspan="2">59.4</td><td colspan="2">258</td></tr>
<tr><td>Education</td><td colspan="2">9.1</td><td colspan="2">26.4</td><td colspan="2">290</td></tr>
<tr><td>Business</td><td colspan="2">46.8</td><td colspan="2">130.8</td><td colspan="2">280</td></tr>
<tr><td rowspan="3">Hensher 2001
NZ$</td><td></td><td colspan="2"></td><td>Slowed down time</td><td>Stop-start time</td><td>Slowed down time</td><td>Stop-start time</td></tr>
<tr><td>Model 2</td><td colspan="2">4.93</td><td>13.37</td><td>22.79</td><td>271</td><td>462</td></tr>
<tr><td>Model 3</td><td colspan="2">4.22</td><td>16.45</td><td>20.90</td><td>390</td><td>476</td></tr>
<tr><td rowspan="2">Fosgerau et al.(2007)
DKK/hr</td><td></td><td><= 25 km</td><td>> 25 km</td><td colspan="2">Additional driving time due to congestion</td><td colspan="2"></td></tr>
<tr><td></td><td>98</td><td>78</td><td colspan="2">0.88/min</td><td colspan="2"></td></tr>
</table>

Appendix 8. Values of Time compiled by Zamparini and Reggiani (2007)

Study and year of data	QUANTITATIVE OUTCOMES ($/hr in 2002) values)
Transek (1990) Sweden	**2.69**
Bergkvist (2000)(data of 1991) Sweden	**1.72**
Transek (1992) Sweden	**3.60**
Bergkvist and Johansson (1997) Sweden	**5.4**
Kurri *et al.* (2000) Finland	**8.15**
Bickel *et al.* (2005) (data of 2002) Finland	**17.95**
De Jong *et al.* (1995) Denmark	**37.27**
Bickel *et al.* (2005) (data of 2002) Denmark	**21.43**
Waters *et al.* (1995) Norway/Sweden	**14.22**
De Jong *et al.* (1995) United Kingdom	**45.36**
Bickel *et al.* (2005) (data of 2002) United Kingdom	**11.19**
Bickel *et al.* (2005) (data of 2002) Ireland	**17.11**
NEA (1991) Netherlands	**28.08**
De Jong *et al.* (1992) Netherlands	**41.79**
De Jong *et al.* (1992) Netherlands	**28.92**
De Jong *et al.* (1995) Netherlands	**46.87**
Gwilliam (1997) (data of 1995) Netherlands	**47.21**
De Jong (2000) Netherlands	**20.13**
Bickel *et al.* (2005) (data of 2002) Netherlands	**26.41**
De Jong *et al.* (1995) France	**38.39**
Massiani (2003) France	**27.63**
Bickel *et al.* (2005) (data of 2002) France	**26.04**
Bickel *et al.* (2005) (data of 2002) Austria	**23.97**
Bickel *et al.* (2005) (data of 2002) Belgium	**29.33**
Bickel *et al.* (2005) (data of 2002) Germany	**21.43**
Fehmarn Belt Traffic Consortium (1999) Denmark/ Germany	**23.71**
Bickel *et al.* (2005) (data of 2002) Switzerland	**43.43**
Bickel *et al.* (2005) (data of 2002) Malta	**7.14**
Bickel *et al.* (2005) (data of 2002) Portugal	**7.99**
Bickel *et al.* (2005) (data of 2002) Spain	**27.54**
Bolis and Maggi (2001) Switzerland/Italy	**16.3**
Bickel *et al.* (2005) (data of 2002) Czech Republic	**6.39**
Bickel *et al.* (2005) (data of 2002) Hungary	**15.89**
Bickel *et al.* (2005) (data of 2002) Lithuania	**10.43**
Bickel *et al.* (2005) (data of 2002) Slovak Republic	**9.02**
Waters *et al.* (1995) USA	**14.1**
Waters *et al.* (1995) USA	**9.05**
Haning and McFarland (1963) USA	**22.07**
Kawamura (2000) USA	**28.35**
Wilbur Smith Associates (2000) USA/Canada	**27.72**
Waters *et al.* (1995) Canada	**17.82**

Appendix 9. Other values of time

Study and year of data	QUANTITATIVE OUTCOMES ($/hr in 2002) values)
Smalkoski and Levinson (2004) data in $2003-USA	49.42
Richardson (2004, cited in Walis 2005) data from 2004 ($-NZ)	14.77

Appendix 10. VOT according to cargo

Study and currency	Segmentation	Quantitative outcomes (£/hr)
Fowkes, Nash and Tweddle (1989, in Fowkes, 2001) £	Fertiliser	1.3
	Cement	4
	Domestic appliances	3.2
	Chocolate	6.5
	Beer	7.7
	Oil	7.5
	Tubes	13
	Paper products	15

Appendix 11. VOT for HGVs and LGVs according to vehicle ownership

		HGV OWN	HGV HIRE	LGV OWN	LGV HIRE	Av HGV	Av LGV	Av all
Fowkes 2001 (values £1994)	Model 1	21.3	28.26	21.3	26.1	24.78	23.7	24.24
	Model 2	19.98	11.7	12.48	11.58	15.84	12.03	13.94
	Model 3	35.58	12.3	10.62	9.06	23.94	9.84	16.89

VOR

Appendix 12. Comparison between the VOR of males and females

Study, data and currency	Segmentation	VOR ($/h)		% female VOR is higher
		Male	Female	
Lam and Small (2001) SR91 (RP) $	Route	10.90	28.72	164%
	Route and mode	12.85	33.92	164%
	Transponder and route	14.23*	26.74*	88%
	Transponder, mode and route	15.12	31.91	111%

Appendix 13. VOR values by arrival time

Value of average travel time*(€/hour)*	
Full sample	14.7
Value of delayed arrival time *(€/hour)*	
Full sample	34.4
Fixed start time (possible delay up to 10 min.)	51.1
Fixed start time (possible delay of more than 10 min.)	21.4
No fixed start time	1.4
Value of early arrival time *(€/hour)*	
Full sample	7.0
Fixed start time	8.9
No fixed start time	not stated

Appendix 14. VOR median values

	Median values ($/hr)	
Study and type of data	Morning commute (before 7:30am)	Afternoon commute
Ghosh's (2000) I-15 HOT lane (RP)	33.15 (s.d. 26.20)	Travel time variability is not relevant

Appendix 15. VOR per morning commute segments

Study and type of data	Quantitative outcomes ($/hr)									
	5:00-5:30 am	5:30-6:00 am	6:00-6:30 am	6.30-7:00 am	7:00-7:30 am	7:30-8:00 am	8:00-8:30 am	8:30-9:00 am	9:00-9:30 am	9:30-10:00 am
Liu, He and Recker (2007) SR91 Hot lane (SP)	39.24	25.66	23.60	23.30	20.25	23.61	21.00	22.53	17.49	22.68

Appendix 16. VOR compiled by De Jong et al. (2004)

Study and data	Quantitative outcomes
Accent and HCG, 1995 SP	A 1% increase in the probability of delay of 30 or more min. is equivalent to €0.45 – 1.8 (Euro of 2003) per transport
Bruzelius, 2001, based on Transek, 1990, 1992 (Sweden) SP	A 1% increase in the frequency of delays is equivalent to €3.5-32.6 for road transport
Bruzelius, 2001, based on INREGIA, 2001 (Sweden) SP	The value of the risk of delay is €6.1 per pro mille per transport for road
Fowkes et al., 2001 (UK) SP	The value of the difference between the earliest arrival time and the departure time is on average €1.18 per min. per transport (more or less the free-flow time); for the time within which 98% of the deliveries takes place minus the earliest arrival time, the value is €1.44 ('spread'); for deviations from the departure time (schedule delay) the value is €1.12.
RAND Europe et al., 2004 (The Netherlands) SP	A change of 10% in the percentage not on time (e.g. from 10% to 11%) is equivalent to €1.77 per transport for goods transport by road.

Appendix 17. Conversion to British Pounds (£)

VOT by trip purpose in 2002 British Pounds (£)

Study and data	Segmentation	Quantitative outcomes (£/hr in 2002 values)			
		Commuting	Business	Leisure/shopping	Education
Richardson (cited in Walis 2005) ALPURT B2 (NZ)	-	4.78			4.78
Radovich and Foster (2000) Tauranga Harbour Birdge (NZ)	-	2.89	6.12	Leisure 2.61 Social/recrea. 3.63 Prsnal business 3.34	1.56
Cantos and Alvarez (2009) A3 National Highway (Spain)		8.07		4.45	
Axhausen *et al.* (2006) Switzerland	-	8.16	11.85	Leisure 8.01 Shopping 7.65	-
Jovicic and Hansen (2003)		2.26	5.65	2.78	1.10
Algers *et al.* (1995) Sweden	<50km	3.60	-	-	-
Fosgerau, Hjorth, Lyk-Jensen 2007		6.72		6.47	-
Gunn and Rohr (1996 in Wardman 2001) f/hr	0-1500 f per month	3.17	4.12	2.85	-
	1501-2500	3.17	4.12	3.35	
	2501-4000	3.49	5.52	3.58	
	4001-6000	4.66	5.75	4.03	
	6001-8000	4.71	6.56	4.71	
	8000+	5.52	14.21	5.57	
Gunn et al. (1998 in Wardman 2001) f/hr	<2500	3.16	2.64	2.19	-
	2500-4000	3.28	4.13	2.40	
	4000-6000	3.50	5.03	2.56	
	>6000	3.70	9.94	3.34	
Hague Consulting Group (1999 in Wardman 2001)	0-10000	1.803	4.854	1.595	-
	10-20000	2.150	6.033	2.011	
	20-30000	2.843	7.142	2.774	
	30-4000	3.814	8.945	2.982	
	40-50000	5.339	10.055	4.161	
	50-60000	7.905	11.511	4.785	
	Above 60000	9.708	13.799	9.916	
Tretvik (1993) kroner/hr	0-100000	6.25	7.53	6.83	-
	101-150000	6.89	8.20	7.49	
	151-200000	6.93	7.80	7.78	
	201-250000	7.58	7.88	7.96	
	251-300000	8.78	8.61	9.19	
	>300000	8.84	9.47	8.25	
Beca (cited in Walis 2005)	low VTTS	4.42	-	-	-
	medium VTTS	4.78			
	high VTTS	5.12			
Radovich and Foster (2000)	<20	1.42		1.62	-
	20-30	2.42		1.48	
	30-50	3.45		4.23	
	50-70	2.82		3.87	
Algers *et al.* (1995)	Other trips<50km	-	-	2.86	-
	Other trips<50km	-	-	8.58	-

*Derived together

VOT by departure time in 2002 British Pounds (£)

Study and data	Quantitative outcomes (£/hr in 2002 values)									
	5:00-5:30 am	5:30-6:00 am	6:00-6:30 am	6.30-7:00 am	7:00-7:30 am	7:30-8:00 am	8:00-8:30 am	8:30-9:00 am	9:00-9:30 am	9:30-10:00 am
Liu, He and Recker (2007) SR91 Hot lane (US) SP	21.11	11.73	13.17	15.65	16.32	19.66	17.52	17.22	16.47	13.91

VOT by day of the week in 2002 British Pounds (£)

Study and data	Quantitative outcomes (£/hr in 2002 values)	
	Weekday	Weekend
Cantos and Alvarez (2009) A3 National Highway (Spain)	7.05	5.82

VOT by daytime segment in 2002 British Pounds (£)

Study and data	Segmentation	Quantitative outcomes (£/hr in 2002 values)			
		Morning	Afternoon	Evening	Main pattern
Ghosh (2000) I-15 Hot lane, San Diego (US)	Males	14.99	9.33		
	Females	19.51	10.96		
Cirillo and Axhausen (2006) Germany	Working days	1.14		6.71	4.53
	Non-working days	7.39		1.79	6.32

VOT by trip length in 2002 British Pounds (£)

Study and year of data	Quantitative outcomes (£/hr in 2002 values)				
	<=25km	<50km		>25km	>50km
		Commuting	Other		
Algers *et al.* (1995) Sweden SP		3.60	2.86		8.50
Fosgerau *et al.* (2007)	8.45			6.72	

VOT in congestion in 2002 British Pounds (£)

Study and data	Segmentation	Quantitative outcomes (£/hr in 2002 values)				
		Original in:	**Free flow**		**Congested**	
Calfee and Winston (1998)	**Commuting**	$	-		3.20	
Koenig, Abay and Axhausen 2003	**Route choice-1**	CHF/h	12.78		16.47	
	Mode choice	CHF/h	13.70		14.64	
	Route choice-2	CHF/h	12.72		22.23	
Jovicic and Hansen 2003	**Commuter**	DKK/h	2.26		7.74	
	Leisure	DKK/h	2.78		7.18	
	Education	DKK/h	1.10		3.19	
	Business	DKK/h	5.66		15.81	
Hensher 2001					Slowed down time	Stop-start time
	Model 2	NZ$	1.71		4.63	7.89
	Model 3	NZ$	1.46		5.70	7.24
Fosgerau *et al.*(2007)		DKK/h	<= 25 km.	> 25 km	Additional driving time due to congestion 0.08	
			8.45	6.72		

VOT for freight in 2002 British Pounds (£)

Study and year of data	Quantitative outcomes (£/hr in 2002 values)
Transek (1990) Sweden	1.79
Bergkvist (2000)(data of 1991) Sweden	1.15
Transek (1992) Sweden	2.40
Bergkvist and Johansson (1997) Sweden	3.60
Kurri *et al.* (2000) Finland	5.43
Bickel *et al.* (2005) (data of 2002) Finland	11.96
De Jong *et al.* (1995) Denmark	24.83
Bickel *et al.* (2005) (data of 2002) Denmark	14.28
Waters *et al.* (1995) Norway/Sweden	9.47
De Jong *et al.* (1995) United Kingdom	30.22
Bickel *et al.* (2005) (data of 2002) United Kingdom	7.45
Bickel *et al.* (2005) (data of 2002) Ireland	11.40
NEA (1991) Netherlands	18.71
De Jong *et al.* (1992) Netherlands	27.84
De Jong *et al.* (1992) Netherlands	19.27
De Jong *et al.* (1995) Netherlands	31.22
Gwilliam (1997) (data of 1995) Netherlands	31.45
De Jong (2000) Netherlands	13.41
Bickel *et al.* (2005) (data of 2002) Netherlands	17.59
De Jong *et al.* (1995) France	25.57
Massiani (2003) France	18.41
Bickel *et al.* (2005) (data of 2002) France	17.35
Bickel *et al.* (2005) (data of 2002) Austria	15.97
Bickel *et al.* (2005) (data of 2002) Belgium	19.54
Bickel *et al.* (2005) (data of 2002) Germany	14.28
Fehmarn Belt Traffic Consortium (1999) Denmark/ Germany	15.79
Bickel *et al.* (2005) (data of 2002) Switzerland	28.93
Bickel *et al.* (2005) (data of 2002) Malta	4.76
Bickel *et al.* (2005) (data of 2002) Portugal	5.32
Bickel *et al.* (2005) (data of 2002) Spain	18.35
Bolis and Maggi (2001) Switzerland/Italy	10.86
Bickel *et al.* (2005) (data of 2002) Czech Republic	4.26
Bickel *et al.* (2005) (data of 2002) Hungary	10.59
Bickel *et al.* (2005) (data of 2002) Lithuania	6.95
Bickel *et al.* (2005) (data of 2002) Slovak Republic	6.01
Waters *et al.* (1995) USA	9.39
Waters *et al.* (1995) USA	6.03
Haning and McFarland (1963) USA	14.70
Kawamura (2000) USA	18.89
Wilbur Smith Associates (2000) USA/Canada	18.47
Waters *et al.* (1995) Canada	11.87

Median VOR values in 2002 British Pounds (£)

Study and data	Segmentation	Quantitative outcomes (£/hr in 2002)
Ghosh's (2000) I-15 HOT lane	Morning commute	21.71
Brownstone *et al.*(2003) I-15 HOT lane (RP)	-	13.72
Liu, Recker and Chen (2004) SR91 (SP/RP)	-	13.50
Small *et al.*(2005) SR 91 (RP)	Base model	12.80
	With time of day dummy	15.91
	With occupancy and transponder choice	16.10

VOR by day segment in 2002 British Pounds (£)

Study and data	Quantitative outcomes (£/hr in 2002 values)	
	Morning commute	Afternoon commute
Ghosh's (2000) **I-15 HOT lane**	**21.71**	**Not relevant**

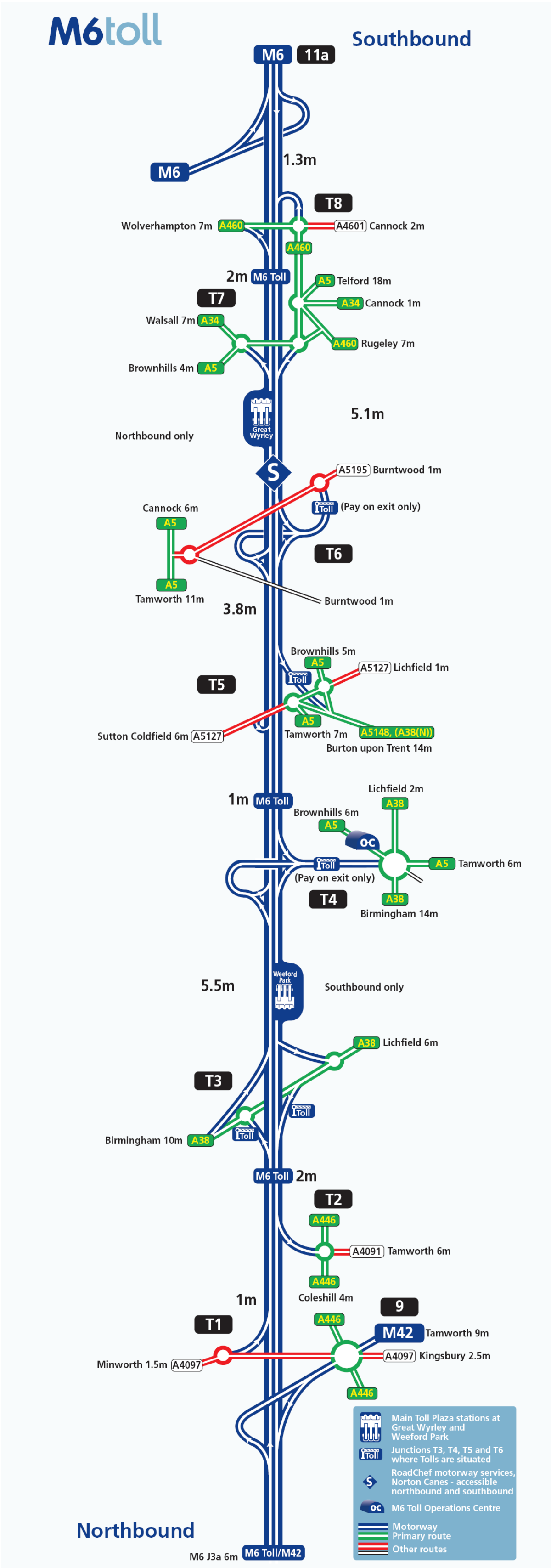
VOR by departure time in 2002 British Pounds (£)

Study and data	Quantitative outcomes (£/hr in 2002 values)									
	5:00-5:30 am	5:30-6:00 am	6:00-6:30 am	6.30-7:00 am	7:00-7:30 am	7:30-8:00 am	8:00-8:30 am	8:30-9:00 am	9:00-9:30 am	9:30-10:00 am
Liu, He and Recker (2007) SR91 Hot lane (US) SP	27.88	18.23	16.77	16.56	14.39	16.78	14.92	16.01	12.43	16.12

VOR by gender in 2002 British Pounds (£)

	Model	Choice	(£/hr in 2002 values)	
			Male	***Female***
Lam and Small (2001) SR91	1	Route	7.13	18.78
	3	Route and mode	8.40	22.18
	4	Transponder and route	9.30	17.48
	5	Transponder, mode and route	9.89	20.86

Appendix 18. The M6 Toll: entry and exit points (Source: M6Toll website)



Appendix 19. Entry and exit points along the M6 Toll

	ENTRY	EXIT	TOLL STATIONS
T1	Northbound from A4097 Southbound from M42	Northbound to M42	
T2	None	Southbound to A446/A4091	
T3	Northbound from A38 Southbound from A38	Northbound to A38 Southbound to A38	On entry (S) On exit (N)
T4	Northbound from A5/A38 Southbound from A5/A38	Northbound to A5/A38 Southbound to A5/A38	On exit
T5	Northbound from A5127	Southbound to A5 148 (A38)	On exit
T6	Northbound from A5 Southbound from A5127	Northbound to A5 195 Southbound to A5 195	On exit
T7	Southbound from A5/A34/A460	Northbound to A5/A34	
T8	Southbound from A460	Northbound to A460	

Appendix 20. Vehicle classes ***(Source: M6Toll website)***

Vehicle Class	Number of Wheels	Number of Axles	Height at 1st Axle*
Class One	under 4		Any
Class Two	4 or more	2	under 1.3m
Class Three	4 or more	more than 2	under 1.3m
Class Four	4 or more	2	1.3m or more
Class Five	4 or more	more than 2, 6 or less	1.3m or more
Class Six	4 or more	more than 6	1.3m or more

* If your vehicle has 2 axles and is under 1.3 metres at the first axle, it will be Class 2.

Appendix 21. M6 Toll rates ***(Source: M6Toll website)***

Opening prices on the 9th December 2003; These discounted prices applied to the first 10 million vehicles to use the new M6 Toll. They benefited from a discount of £1 off standard day and night tolls

	Day	Night
Motor Bike	£1	50p
Car	£2	£1
Van	£5	£4
HGV	£10	£9

‡Langley Mill toll was half the launch toll (minimum toll 50p).

Changes on the 23 July 2004: The tolls for HGVs were reduced from £10 to £6

Prices as of 16th August 2004: the 10 million vehicles figure was reached so standard toll rates were introduced.

	Mainline Plazas		Intermediate Plazas	
	Day rate	Night rate	Day rate	Night rate
Motorbikes	£2.00	£1.00	£1.00	£0.50
Cars	£3.00	£2.00	£2.00	£1.00
Vans	£6.00	£5.00	£6.00	£5.00
HGV***	£6.00	£5.00	£6.00	£5.00

Langley Mill were half the standard toll (minimum toll 50p).

Prices as of 14th June 2005:

	Mainline Plazas		Intermediate Plazas	
	Day rate	Night rate	Day rate	Night rate
Class 1: Motorbikes	2.50	1.50	1.50	1
Class 2: Cars	3.50	2.50	2.50	1.50
Class 3: Car & trailer	7	6	7	6
Class 4: Vans	7	6	7	6
Class 5: HGV or coach	7	6	7	6
Class 6: HGV with more than 6 axles	35	25	35	25

Prices as of 1st January 2007:

	Mainline Plazas		Intermediate Plazas	
	Day rate	Night rate	Day rate	Night rate
Class 1: Motorbikes	2.50	1.50	1.50	1
Class 2: Cars	4	3	3	2
Class 3: Car & trailer	7	6	7	6
Class 4: Vans	8	7	8	7
Class 5: HGV or coach	8	7	8	7
Class 6: HGV with more than 6 axles	8	7	8	7

Prices as of January 2008:

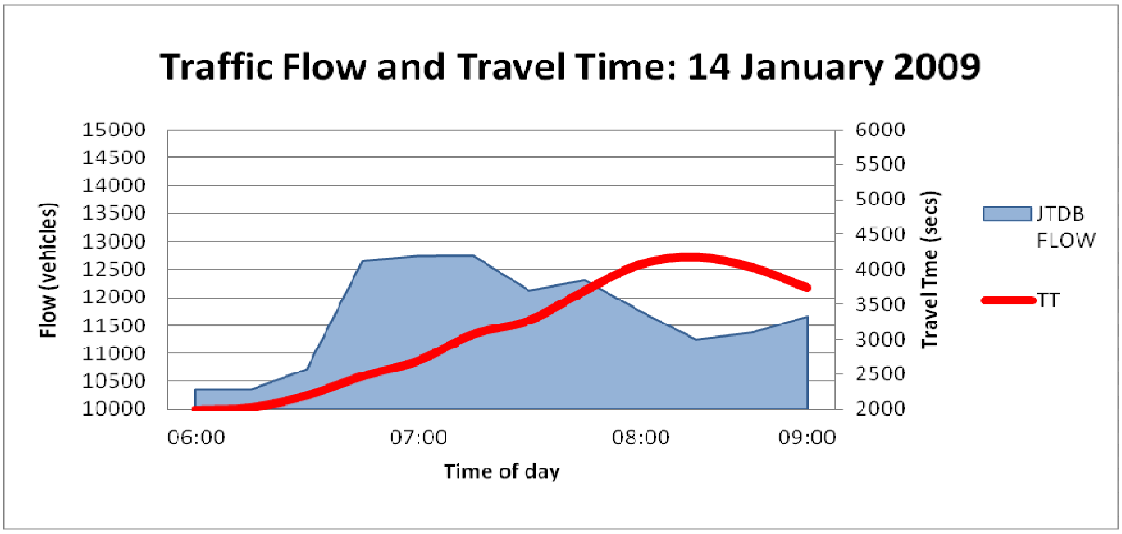
	Mainline Plazas		Intermediate Plazas	
	Day rate	Night rate	Day rate	Night rate
Class 1: Motorbikes	2.50	1.50	1.50	1
Class 2: Cars	4.50	3.50	3.50	2.50
Class 3: Car & trailer	8	7	8	7
Class 4: Vans	9	8	9	8
Class 5: HGV or coach	9	8	9	8
Class 6: HGV with more than 6 axles	9	8	9	8

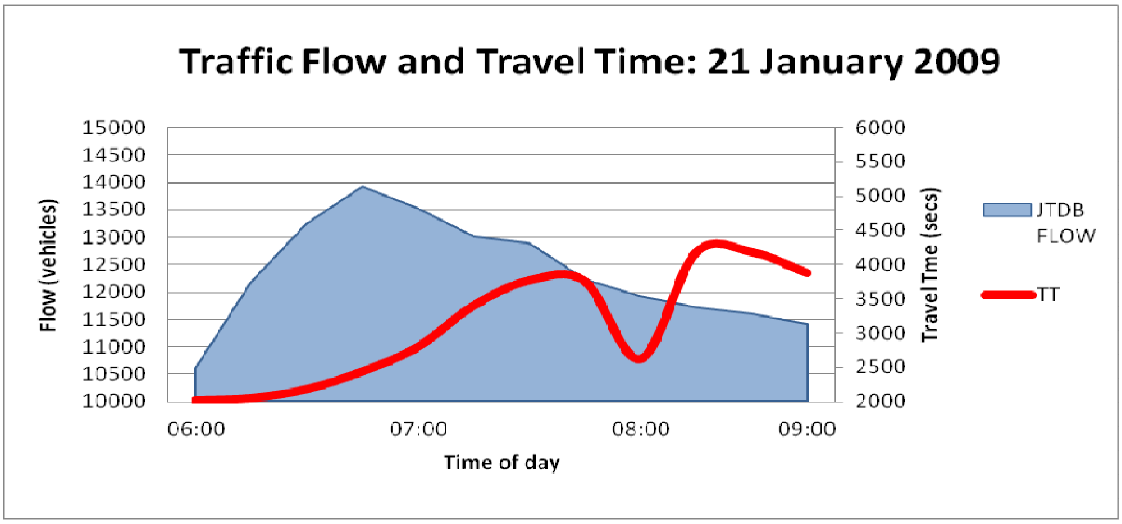
Prices as of January 2009:

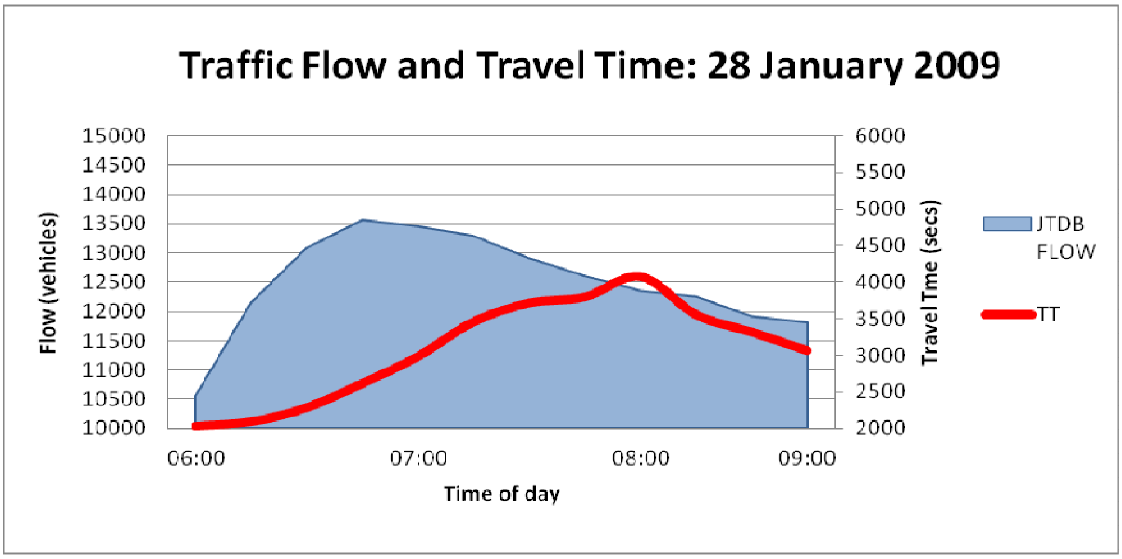
Mainline Plazas	**Mon - Fri (06:00 - 23:00)**	**Sat - Sun (06:00 - 23:00)**	**Night (23:00 - 06:00)**
Class 1: Motorbikes	£2.70	£2.50	£1.50
Class 2: Cars	£4.70	£4.50	£3.50
Class 3: Car & trailer	£8.40	£8.00	£7.00
Class 4: Vans	£9.40	£9.00	£8.00
Class 5: HGV or coach	£9.40	£9.00	£8.00
Class 6: HGV with more than 6 axles	£9.40	£9.00	£8.00

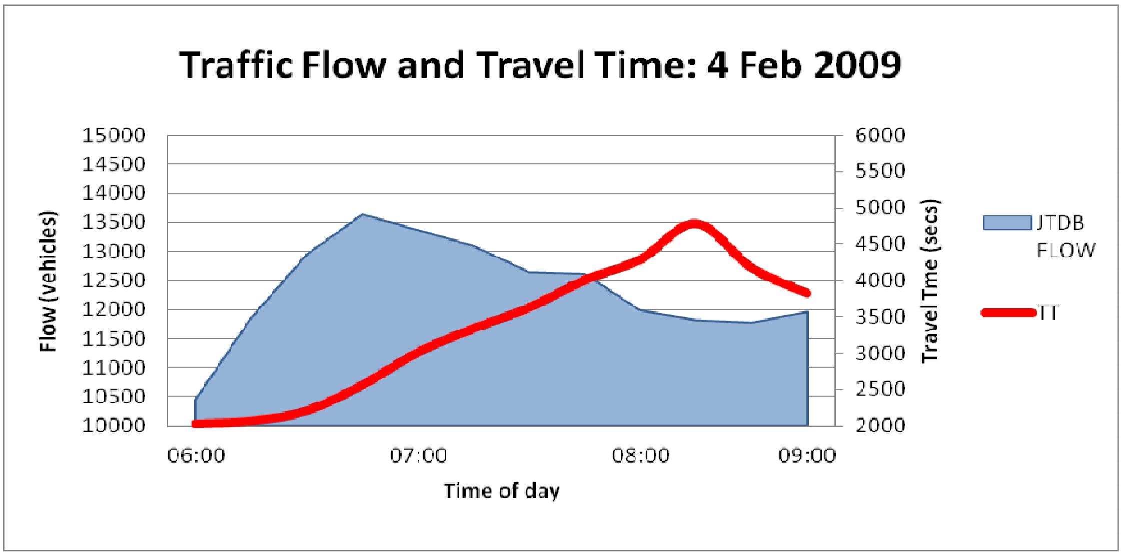
Intermediate Plazas	**Mon - Fri (06:00 - 23:00)**	**Sat - Sun (06:00 - 23:00)**	**Night (23:00 - 06:00)**
Class 1: Motorbikes	£1.70	£1.50	£1.00
Class 2: Cars	£3.70	£3.50	£2.50
Class 3: Car & trailer	£8.40	£8.00	£7.00
Class 4: Vans	£9.40	£9.00	£8.00
Class 5: HGV or coach	£9.40	£9.00	£8.00
Class 6: HGV with more than 6 axles	£9.40	£9.00	£8.00

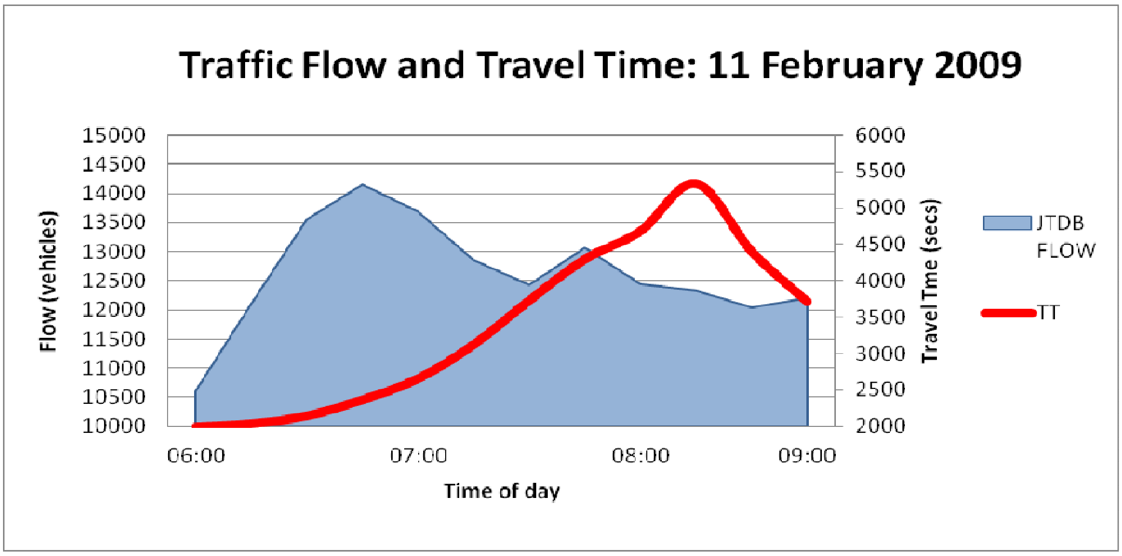
Appendix 22. Traffic flows and travel time in the M6

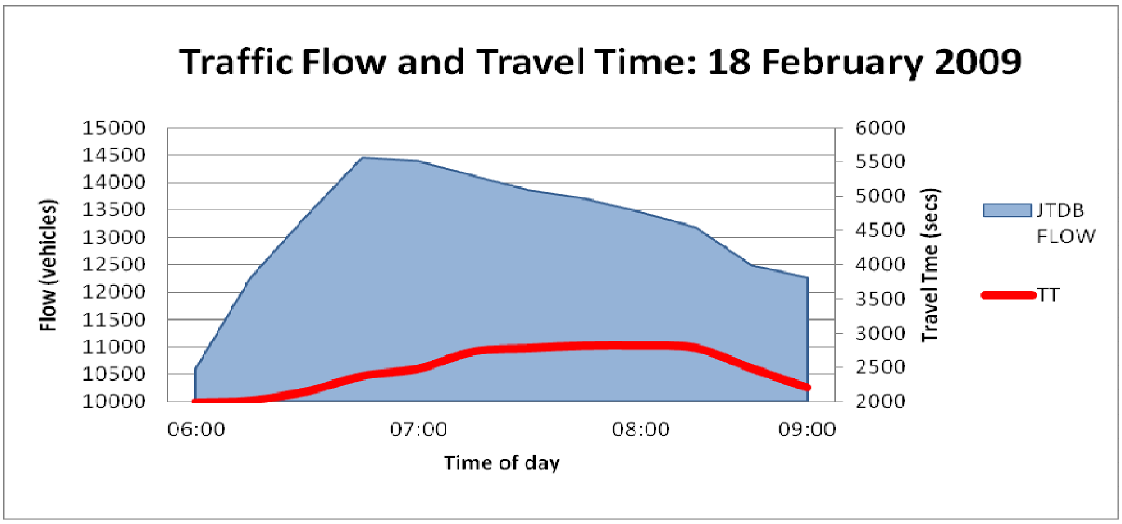







Traffic Flow and Travel Time: 4 Feb 2009
Flow (vehicles)
15000
14500
14000
13500
13000
12500
12000
11500
11000
10500
10000
06:00
07:00
08:00
09:00
Time of day
6000
5500
5000
4500
4000
3500
3000
2500
2000
Travel Tme (secs)
JTDB FLOW
TT


Traffic Flow and Travel Time: 11 February 2009
Flow (vehicles)
15000
14500
14000
13500
13000
12500
12000
11500
11000
10500
10000
06:00
07:00
08:00
09:00
Time of day
6000
5500
5000
4500
4000
3500
3000
2500
2000
Travel Tme (secs)
JTDB FLOW
TT


Traffic Flow and Travel Time: 18 February 2009
Flow (vehicles)
15000
14500
14000
13500
13000
12500
12000
11500
11000
10500
10000
06:00
07:00
08:00
09:00
Time of day
6000
5500
5000
4500
4000
3500
3000
2500
2000
Travel Tme (secs)
JTDB FLOW
TT

Appendix 23. Equations to represent the cost-flow relation

The following table shows equations that represent the cost-flow relation (following Dowling and Skabardonis, 2006). Oonly the BPR and Akçelik are unique to travel time and delay analysis, while the others are standard mathematical functions commonly used in data analysis.

Functional Form	Example
Linear	s = -a x + b
Logarithmic	s = -a ln x+b
Exponential	s = a s_0 exp(-bx)
Power	s = a /x^b
Polynomial	s = -ax^2 –bx + c
BPR	$s = \frac{s_0}{\left[1 + a\,(x)^b\right]}$
Akçelik	$s = \frac{L}{L/s_0 + 0.25\left[(x-1) + \sqrt{(x-1)^2 + ax}\right]}$

Where:

s is the predicted speed;
x is the volume/capacity ratio;
a,b,c are global parameters for equation;
L is the link length; and
s_0 is the link free-flow speed.

ENDS