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Incorporation of Departure Time Choice in a Mesoscopic Transportation Model for Stockholm

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Abstract

Travel demand management policies such as congestion charges encourage car-users to change among other things route, mode and departure time. Departure time may be especially affected by time-varying charges, since car-users can avoid high peak hour charges by travelling earlier or later, so called peak spreading effects. Conventional transport models do not include departure time choice as a response. For evaluation of time-varying congestion charges departure time choice is essential.

In this thesis a transport model called SILVESTER is implemented for Stockholm. It includes departure time, mode and route choice. Morning trips, commuting as well as other trips, are modelled and time is discretized into fifteen-minute time periods. This way peak spreading effects can be analysed. The implementation is made around an existing route choice model called CONTRAM, for which a Stockholm network already exists. The CONTRAM network has been in use for a long time in Stockholm and an origin-destination matrix calibrated against local traffic counts and travel times guarantee local credibility. On the demand side, an earlier developed departure time and mode choice model of mixed logit type is used. It was estimated on CONTRAM travel times to be consistent with the route choice model. The behavioural response under time-varying congestion charges was estimated from a hypothetical study conducted in Stockholm.

Paper I describes the implementation of SILVESTER. The paper shows model structure, how model run time was reduced and tests of convergence. As regards run time, a 75% cut down was achieved by reducing the number of origin-destination pairs while not changing travel time and distance distributions too much.

In Paper II car-users underlying preferred departure times are derived using a method called reverse engineering. This method derives preferred departure times that reproduce as well as possible the observed travel pattern of the base year. Reverse engineering has previously only been used on small example road networks. Paper II shows that application of reverse engineering to a real-life road network is possible and gives reasonable results.

Keywords: Transport Modelling, Departure Time Choice, Dynamic Traffic Simulation, Time-Varying Congestion Charges, Peak Spreading, Reverse Engineering

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Stockholm, May 2009

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List of Papers

I. Kristoffersson, I. and Engelson, L., 2009a. **A Dynamic Transportation Model for the Stockholm Area: Implementation Issues Regarding Departure Time Choice and OD-pair Reduction.** Accepted for publication in Journal of Networks and Spatial Economics. DOI 10.1007/s11067-009-9104-0.

II. Kristoffersson, I. and Engelson, L., 2009b. **Deriving Preferred Departure Times of Road Users in a Real-Life Network.** Submitted. First version in proceedings of the European Transport Conference 2008 at Leeuwenhorst Conference Centre/The Netherlands.

Contents

1 Introduction

1.1 Background

A vast majority of the world's citizens lives in urban areas. Advantages of urban living are among other things the range of services, workplaces and goods. Access to these advantages relies to a great extent on the possibility for people and goods to move easily in the urban area. Urban mobility is thus an important issue for both citizens' quality of life and the economic growth. The importance of urban mobility is also pointed out by the European Commission in their *Green Paper on Urban Mobility* (EC, 2007b). Urban mobility is no longer only about getting from point A to point B: there are nowadays new demands on the transport system. The Green Paper identifies five core elements: transport systems need to be *more fluid*, *greener*, *smarter*, *more accessible* and *safer*. Especially the first three of these are relevant to this thesis.

The core element *greener* originates from the insight that the urban transport system substantially contributes to emissions of greenhouse gases, air-pollution and noise. In the EU the transport sector is responsible for about 24% of total greenhouse gas emissions (EC, 2007a). Emissions from the transport sector are also increasing year by year whereas the other sectors (industry, households, services) remain more or less unchanged.

More fluid and *smarter* arises as goals since time, land and energy are all scarce resources. We want to move quickly, still consuming only a small amount of energy and land. The modern citizen struggles to find time to leave and pick up children at the day-care centre, work, buy groceries, go training etc. Time is thus a scarce resource that has a value (Mackie et al., 2001). Regarding land, transport facilities compete with housing, shops and workplaces for the expensive ground in city.

Commuting requires a transport system that performs well day after day with approximately equal travel times, i.e. a reliable transport system. Mean travel time is thus not the only thing valued by travellers; they also value a reliable travel time (Bates et al., 2001). Another core element is therefore added in this thesis: transport systems need to be *more reliable*.

To meet the above goals solely adding new transport capacity is not feasible. We cannot afford building roads that meet the peak hour traffic demand – neither from an economic point of view nor from a land-use and environmental perspective. Furthermore, expanding primary commuting roads is likely to attract traffic from alternative routes, time periods just before or after the peak hour and from public transport, thus cancelling out the benefits of the investment (Downs, 2004).

Cities and transport agencies have already realized that new policy measures are needed that focus on demand instead of supply, so called travel demand management (TDM) measures (US DoT, 2004). Examples of TDM measures include time-varying congestion charges, improvements of the competitiveness of public transport and information to travellers via intelligent transport systems (ITS). These measures all affect the behavioural response of the traveller. Table 1 shows which choices that are mostly affected by each TDM measure.

	Time-Varying Congestion Charges	Improve Public Transport	Information via ITS
Route Choice	x		x
Departure Time Choice	x	x	x
Mode Choice	x	x	x
Destination Choice			
Trip Chaining	x	x	
Trip/No Trip	x		

Table 1: TDM Measures and Travellers' Main Behavioural Responses

The use of new policy measures requires new analysis tools. We need to be able to evaluate the performance of an implemented TDM measure and to forecast effects of proposed measures. Table 1 gives guidance to which behavioural responses that need to be considered in evaluation and forecasting, depending on the analysed TDM measure.

As stated in Table 1, probable responses to congestion charges are route, departure time or mode changes, to chain trips or cancel the trip altogether. Trip chaining and cancellation of trips are more common responses for recreational trips than for work trips. Destination choice may in the long run be affected by congestion charges due to new locations of housing and workplaces. Studies of this phenomenon show however only small relocation effects, see for example Eliasson and Mattsson (2001). Destination choice can also change without changes in land-use, since congestion charges may influence people to shop and work on the same side of the cordon as they live. Studies from the Stockholm Trial show however none or only very small effects of decreasing retail trade inside the cordon (HUI, 2006).

Improvements of public transport has of course mainly an effect on mode choice, but also departure time choice can be affected since demand for public transport is more peaked (the frequency of public transport services during peak hour is higher). Trip chaining may also be affected, since it is more difficult to combine trips to perform several activities on the same tour using public transport.

Regarding information via intelligent transport systems, the behavioural response depends on whether information is given pre-trip or en-route. En-route information will mainly affect route choice, whereas likely responses to pre-trip information are route, departure time and mode changes.

Transport modelling and analysis is a tool that can be of great use in evaluation and forecasting of policy measure effects. Through the use of transport models effects on congestion, travel times, accessibility, the environment and number of accidents can be estimated. However, a conventional transport model only accounts for some of the behavioural responses in Table 1. Typically, departure time choice and trip chaining are left out. From Table 1 the conclusion can be drawn that transport model requirements are very dependent on application, i.e. which dimensions to include in the model depend on what the model shall analyse. It is for example very likely that a route choice model is enough for analysis of information given to car-users en-route by variable message signs (an ITS solution). For analysis of time-varying congestion charges the number of dimensions that need to be included in the transport model are, as can be seen in Table 1, many more.

This thesis focuses on the development of an operational mode, departure time and route choice model for analysis and forecasts of time-varying congestion charges. Departure time choice has been included since it is essential in analysis of time-varying congestion charges. A transport model that includes departure time choice has been long in coming because of inherent difficulties in the development. Unlike for example mode choice alone, the choice of when to start a journey does not consist of discrete alternatives. Instead departure time is continuous and one must either use a continuous model or divide time into intervals. If one wants to model small shifts in departure time the intervals must be short and this in turn requires a dynamic traffic simulator when assigning traffic to the network. With the faster and more powerful computers available today dynamic traffic simulators that can manage large networks have been developed, i.e. the prerequisites for the development of a usable departure time choice model exist.

In Stockholm, the trial[1] implementation of a time-varying congestion charge (SNRA 2006) for car users raised the demand for an operational transport model that includes departure time choice. The charges were decided to be time-varying and aimed at rescheduling traffic from morning and afternoon peak hour when most congestion occur to time periods just before or just after the peak hour, so called peak spreading (see Section 2.3).

The congestion charge in Stockholm takes the form of a tax and is regulated in the congestion tax Act[2]. System design properties such as location of control points, length of time periods and charge levels are stated in an annex to the Act. The congestion charging system in Singapore (Phang and Toh, 1997) is revised every third month based on measurements of car speeds. The speeds should not be too low (too much congestion) or too high (roads are not used enough). This type of periodical revision is not possible in Stockholm since the tax is regulated by an Act. Probable 'lifetime' of the congestion charging system design is instead several years. Considering these circumstances it is even more important to conduct extensive modelling and analysis before a revision.

1.2 Objectives

This thesis is part of a larger project with the *overall objective* to develop a transport model (SILVESTER[3]) for Stockholm that is able to forecast effects of different congestion charging designs – how the charge varies during the day and where the control points are located – on car users choice of route, departure time and mode of transport. Using the transport model one shall be able to analyse changes in traffic flow data due to time-varying congestion charges, look into desired and undesired effects and make cost-benefit analyses.

A departure time and mode choice model has already been estimated for Stockholm at an earlier stage in the project (Börjesson, 2008). The objectives of the part of the project described in this thesis is to:

- Implement the departure time and mode choice model and connect it to a traffic assignment model that performs the route choice and calculates travel times.
- Adjust the resulting transport model to Stockholm conditions through derivation of preferred departure rates that reproduce locally observed travel demand.

The implementation is described in Paper I and the derivation of preferred departure rates in Paper II.

[1] The congestion charge system was made permanent in august 2007 without any changes in charge levels or location of control points.
[2] Lag (2004:629) om trängselskatt.
[3] SILVESTER is an acronym for "simulation of choice between starting times and routes".

1.3 Limitations

SILVESTER does not include car ownership, trip chaining, destination choice or the choice whether or not to make the trip at all (trip/no trip).

Car ownership is important in mode choice, since you are much more likely to travel by car if you own one. SILVESTER deals however with users who in the base case take the car, i.e. they have a car available (or at least a seat in a car). A car ownership model is therefore not necessary. Mode choice is in SILVESTER modelled in the sense that if car travel costs get too high the car-users have the possibility to switch to public transport. Travel times for public transport are assumed not to vary with time-of-day.

Trip chaining is possible to model in an activity-based framework where a tour can be modelled, which consists of for example a trip to work and a trip home via the shopping centre. A trip-based model as SILVESTER lack the possibility to model trip chaining, but is on the other hand less data intensive and has a shorter run time, which is very important when the objective is to apply the model to a real life city and compare a number of charging systems.

Another feature of activity-based models is the possibility to take into account interdependencies between outbound and return trip. In this thesis we focus on traffic flow changes *within* the morning peak period[4], in our case 6.30 a.m. to 9.30 a.m. Interdependencies between outbound and return trip thus do not play a central role.

SILVESTER should, due to the lack of destination choice and trip/no trip choice, be used for relatively short-term forecasts, such that the influence of changes in number of trips and their distribution are small and the most common responses from the travellers are to change route, departure time or mode. Even if SILVESTER is used for short-term forecasts, the lack of trip/no trip choice is a limitation since congestion charges can have a direct effect on whether the user makes the trip at all.

As mentioned above, the modelled period is in SILVESTER 6.30 a.m. to 9.30 a.m. It might be seen as a limitation that the whole day is not modelled. However, SILVESTER could in the future in principal be a sub-model to a larger modelling system, serving as a tool for analysts who want to take a closer look at changes within the morning peak period for car travel and get a more accurate representation of congestion.

Time is divided into fifteen-minute periods in both the demand and supply model. Resulting travel times and traffic flow quantities are thus averages over the fifteen-minute period. Discretization of time into periods is however partially justified by the fact that the congestion charges in Stockholm vary in steps that are multiples of fifteen-minute periods. Users thus have a choice of time periods in mind.

In the departure time and mode choice model travel time uncertainty is included in the utility function, meaning that not only long travel times but also uncertain travel times can cause the traveller to change departure time or mode. Route choice is however not affected by uncertain travel times, which is a limitation of our transport model. Choosing route considering also travel time uncertainty is not possible in the assignment model we use and travel time uncertainty is therefore calculated separately after assignment.

[4] The morning peak period is chosen for each modelling site such that the whole morning peak is included. Typically the morning peak period consists of three hours that roughly can be subdivided into: one hour build up phase, the peak hour itself and one hour dissipation phase.

2 Concepts

2.1 Time-Varying Congestion Charges

Time-varying congestion charges is a name for the direct charges to users of the transport system that aim at managing congestion without increasing supply and that varies over the day in accordance with variations in travel demand. It is thus more expensive to travel during peak hour than before or after the peak.

Related concepts are variable road pricing, dynamic congestion pricing and time-dependent tolls. The term road pricing is generally used broader than congestion pricing and includes fuel taxes, parking taxes, tolls and congestion charges. Depending on the context, road pricing thus has different objectives: to manage congestion or to generate revenues to finance road infrastructure. The term congestion tax is often used in the Stockholm context to emphasize that the charge is aimed at mitigating congestion and is implemented as a tax. However, this thesis will stick to the more general term congestion charge also for the Stockholm case.

2.2 Departure Time Choice

Users of the transport system make a departure time choice as they decide *when* to start a trip. There are many related concepts: time-of-day choice, trip timing choice, time period choice and others. In this thesis the term departure time choice will be used.

The term time-of-day choice is mainly used for choices between broad time periods when the whole day is modelled, e.g. a choice between a.m. peak, interpeak, p.m. peak and off-peak. In this thesis the morning peak period is modelled with focus on departure time choices within the peak period and on peak spreading (see Section 2.3). The term time-of-day choice is thus considered inconvenient for this thesis.

The term trip timing choice emphasizes that not only the departure time matters, it is the timing of the whole trip length in the user's daily schedule that is important. However, travel time is often uncertain and the choice under user control is in most cases the departure time choice.

Models of variations in traffic flow over time often include a discretization into time periods of different length depending on application. The term time period choice draws on this model feature and describes user choice as a choice between different time periods. However, differences between the time periods are in most cases not apparent to the user[5].

2.3 Peak Spreading

Cambridge Systematics, Inc. (1999) defines peak spreading as: 'Lengthening of the peak period, usually accompanied by a flattening of the peak'.

Peak spreading can be both active and passive (Bates, 1997). The extension of the peak period due to longer travel times in a congested network given unchanged departure times of users is called passive peak spreading. Active peak spreading is on the other hand extensions caused by *deliberate* departure time changes of the users to avoid congestion or charges.

Peak spreading is often one of the objectives when implementing time-varying congestion charges. Road capacity is better utilized and congestion reduced if the peak is flattened but occurs during a longer period of time. To stimulate peak spreading the charges can take the form of shoulder pricing, where charge levels are raised in steps before the peak and lowered in steps afterwards.

[5] An exception is users in a city with time-varying congestion charges, where the user is aware that choosing a certain time period implies a certain level of charge.

2.4 Travel Time

Travel time is the length in time of the trip. Using the term travel time implies a risk for misunderstandings in the departure time choice context, since the term might be interpreted as the point in time when you start your trip. Travel time is however the accepted usage and will be used further on.

2.5 Preferred Departure Time

Long or uncertain travel times and time-varying congestion charges are likely to affect travellers' choice of departure time. Some may deliberately travel earlier or later to avoid these unpleasant features of the transport system. This suggests that there is some kind of preferred time of travel from which the traveller can deviate if the benefits of deviating are large enough.

Suppose that in the morning the marginal utility, i.e. utility per unit of time, of being at home and the marginal utility of being at work are decreasing and increasing functions of time respectively (see Figure 1). Given that the travel time to work is zero, preferred time of travel will occur at E. Travelling later than E would mean that the user stays at home even though the marginal utility of being at work is higher. Travelling earlier than E would mean that the user goes to work even though the marginal utility of being at home is higher. Now consider a trip to work, which has a travel time. There is no utility attached to time spent travelling. Maximum utility now occurs when the marginal utility at C is equal to the marginal utility at D.

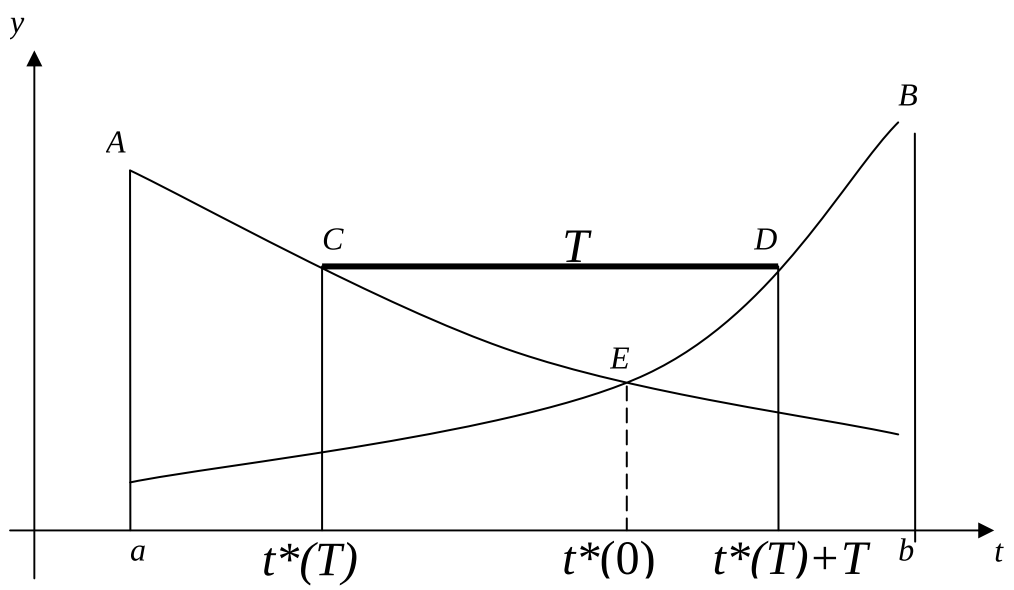

Figure 1: Preferred Time of Travel Depending on Travel Duration

(Courtesy of Dr. Leonid Engelson, CTR, KTH)

In Figure 1 t*(T) is the time the traveller would choose to leave home if there are no congestion or charges. This point in time is dependent on the travel time of the trip. The two marginal utility functions in Figure 1 capture how important it is to be at home and at work respectively. These functions differ among individuals and even from day to day for the same individual and are therefore very difficult to estimate. An attempt to estimate the home and work marginal utility functions is made in Tseng and Verhoef (2008). The authors note however that a rich data set is needed for the estimation. When such a data set is not available it is common to simplify the marginal utility functions: either the marginal utility at home or at work is modelled as a step function, while the remaining one is kept constant. If the marginal utility of being at home is modelled as a step function and the marginal utility on the 'work-side' is kept constant, then a preferred departure time (PDT) arises at the point in time when the step occurs. Modelling the functions the other way around results in a preferred arrival time (PAT).

A deviation from PDT or PAT is said to imply a *scheduling cost*. In this thesis scheduling deviation is defined with respect to departure time, i.e. deviation from PDT. In an uncongested situation there is no difference defining scheduling costs around PDT or PAT, since a shift from PDT then corresponds to similar shift from PAT. Given congestion the definitions differ and scheduling cost should be defined at the end where the traveller has the most crucial time constraint. The stated preference survey conducted prior to estimation of the departure time and mode choice model implemented in this thesis indicated constraints at both origin and destination (Börjesson, 2006) and thus does not give further guidance.

A disadvantage of defining scheduling costs with respect to PDT is that disutility of travel time uncertainty (TTU) is not taken into account. It is therefore advisable to include TTU as a separate variable. Apart from that defining scheduling costs with respect to PDT has advantages from an implementation point of view; it can also be argued that it is more adequate to define scheduling costs around PDT since PDT is what the traveller can control.

2.6 Schedule Deviation

Schedule delay is the common term, but in this paper deviation will be used instead of delay, since for many traffic engineers delay is defined as extra travel time in addition to the travel time under free-flow conditions. Shifting departure time from ones preferred departure time implies a schedule deviation but does not necessarily result in any delay. *Schedule deviation early* (SDE) is the time interval between early departure and PDT[6] and *schedule deviation late* (SDL) is the time interval between late departure and PDT. SDE is zero for late departure and SDL is zero for early departure. Both SDE and SDL are zero for a departure at PDT.

Given a time discretization into for example fifteen-minute periods, departures in the whole PDT time period get zero SDE and SDL. For other time periods SDE and SDL are multiples of the time period length.

2.7 Micro-, Meso- and Macroscopic Simulation

Traffic simulation models are often subdivided into three categories: micro-, meso- and macroscopic models. Common for the three types of models is some kind of route choice model and calculation of important network state variables such as travel times. The difference between the categories is mainly a question of level of detail.

Microscopic simulation models work with individual vehicles, which implies that different vehicle types and driver behaviour can be modelled explicitly. Also the properties of the network are modelled in great detail including roundabouts, traffic signal cycles and number of lanes. Microscopic simulation is mainly suitable for analysis of intersections and smaller part of a city. Whole cities are difficult to model due to the extensive number of parameters to calibrate. *Macroscopic* simulation work with aggregate traffic measures, such as mean traffic flow on a link. The network is typically modelled as consisting of only nodes and links. Traffic is often seen as a fluid propagating through the network. Macroscopic simulation is suitable for traffic analysis of whole cities and even countries. The development of *mesoscopic* simulation models has been driven by the desire to combine some of the detail

[6] SDE and SDL can also be defined around PAT, see discussion in Section 2.5.

from microscopic models with the ability of macroscopic models to be applied to a whole urban area.

3 Description of the SILVESTER Modelling System

SILVESTER is a transport modelling system that extends conventional car travel modelling by:

- Modelling not only the peak hour, but the whole morning peak period from 06:30-09:30
- Introducing departure time choice, which depends on travel time, travel time uncertainty, scheduling cost, distance cost, and congestion charge (if any).
- Including queuing dynamics when calculating travel times

The modelling system consists of two main parts: a demand model and a supply model (the bold boxes in Figure 2). The demand model calculates probabilities to start in each of the departure time periods depending on travel costs, whereas the supply model calculates travel costs depending on departure time period. The process is thus iterative and a general equilibrium is sought.

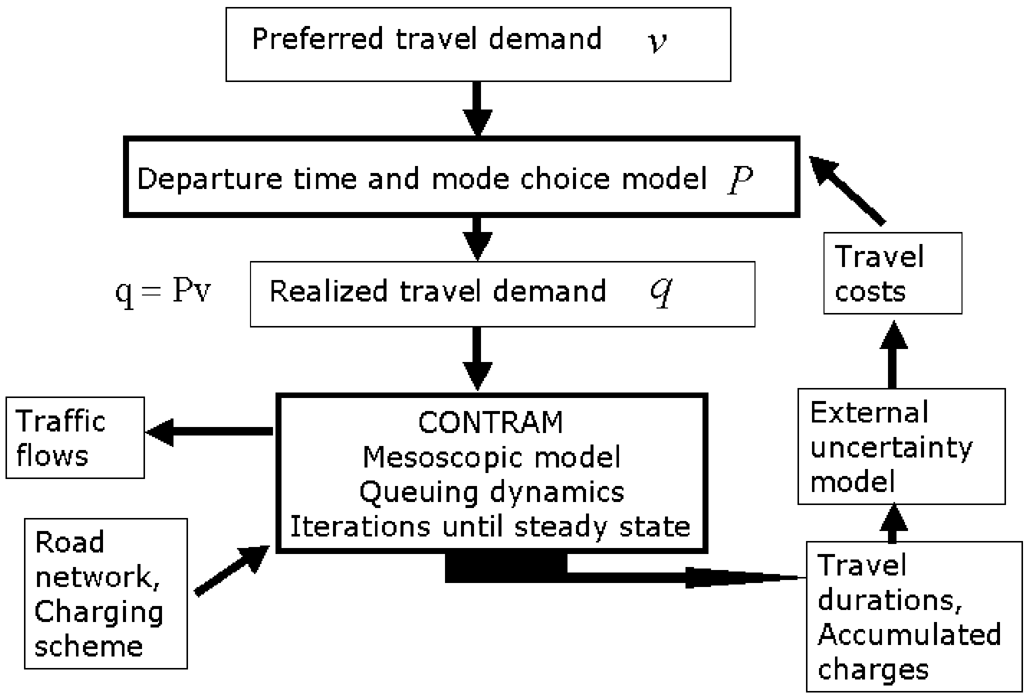

Figure 2: Overview of the SILVESTER Modelling System

3.1 Demand Model

The demand model was developed at an earlier stage within the project (Börjesson, 2008). It is a mixed logit model in which car users trade off travel time, travel time uncertainty, scheduling cost, distance cost, and congestion charge in order to decide which departure time period to start in or if they should switch to public transport instead. The demand model is subdivided into three trip purposes (see Table 2).

	Percent of users
Commuters with fixed schedule and school trips (short: fixed)	29
Business trips (short: business)	11
Commuters with flexible schedule and other trips (short: flexible)	60

Table 2: Description of Trip Purpose Segments

For the fixed and flexible segments the utility functions are on the form shown in Equation 1.

$$U_{CAR,t} = \beta_1 SDE_t + \beta_2 SDL_t + \beta_3 (D_t + Z_t) + b_1 T_t + b_2 \sigma_t + \varepsilon_t$$
$$U_{PT} = C_{PT} + b_3 T_{PT} + b_4 \delta_{card} + \varepsilon_{PT} \qquad (1)$$

The attributes of the utility functions are: *SDE* – schedule deviation early, *SDL* – schedule deviation late, *D* – distance travelled, *Z* – congestion charge, *T* – travel time, σ – travel time uncertainty, C_{PT} – alternative specific constant for public transport, T_{PT} – public transport travel time and δ_{card} – share of population that also has a public transport monthly travel card. The departure time period is indexed by *t* and ε is a Gumbel distributed error term. The utility function for the business segment equals Equation 1, except that there is no public transport alternative[7]. Constant parameters are labelled *b*, whereas the β-parameters are randomly distributed in the population according to the Johnson's S_B distribution, which is bounded between [-1,0]. A draw from the distribution represents an individual in the population. Draws are made on beforehand and are constant during iterations between demand and supply.

Table 3 shows parameter values for the three models. The parameter values differ somewhat from those in Börjesson (2008) since some changes had to be made to the demand model during implementation.

	Flexible		Fixed		Business	
Parameter	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev
β_1	-2.19	1.14	-1.93	-1.01	-2.45	-1.09
β_2	-1.83	0.75	-1.25	0.87	-1.74	0.03
β_3	-1.77	-1.20	-2.08	2.04	-3.35	2.03
b_1	-0.24		-0.19		-0.19	
b_2	-0.06		-0.06		-0.11	
b_3	-0.18		-0.22		NA	
b_4	10.90		13.49		NA	
C_{PT}	-5.65		-7.10		NA	

Table 3: Parameter values for the three trip purposes. Mean and standard deviation of random parameters correspond to the underlying normal distributions.

Firstly, the demand model had to be re-estimated without the extra penalty for starting earlier than 07:30, since this penalty led to shaky PDT-profiles using reverse engineering (Paper II)[8].

[7] In the survey which the demand model is estimated on almost no business travellers chose to switch to public transport and this alternative was therefore excluded.

[8] A likely reason for the shaky PDT-profiles is that the extra penalty for starting earlier than 07:30 belonged to the specific group of car-users crossing 'Tranebergsbron', where the observations for the demand model estimation was made. The realized demand for the whole city of Stockholm does not show a corresponding early penalty. When reverse engineering was applied to the whole city the method compensated by making changes in the PDT-profiles.

Furthermore, the randomly distributed parameters are in SILVESTER represented by only 50 draws per parameter and per trip purpose for computational capacity reasons. In the original demand model the utility function for public transport included a normally distributed error term with large spread. Using only 50 draws, the effect of this parameter depended too much on the specific draws made. The solution was to remove the public transport extra error term and adjust the alternative specific constant (C_{PT}) correspondingly.

Since the travellers modelled are frequent car users, C_{PT} is negative in the models, implying that if everything else is equal they will choose car.

Each draw from the cost parameter distribution (β_3) corresponds to a certain value of time (VOT). This is utilized in road network assignment to divide users into classes depending on their VOT (Section 3.2).

3.2 Supply Model

In SILVESTER we use the supply model CONTRAM (Taylor, 2003), which is a mesoscopic simulation model (Section 2.7). One important reason for using CONTRAM is that a calibrated origin-destination matrix already exists for Stockholm, which saves a lot of time-consuming work. Furthermore, the mesoscopic level is suitable since we want to model a whole city (Stockholm), but need detailed information on how congestion levels change during the morning peak period on individual routes. Information on changes in congestion levels is needed as input to the mode and departure time choice model. Detailed modelling of changes in congestion levels requires modelling of build up and dissipation of queues, which is possible using mesoscopic simulation.

CONTRAM allows for several user classes that differ in their generalized cost functions, if they are affected by charges or not and resulting route choices and travel costs. Four user classes are implemented in SILVESTER. Class 4 represents the vehicles that are exempted from congestion charges9. The remaining vehicles are subdivided into three user classes depending on their VOT, (see Table 4).

	Range (SEK/h)	**Median VOT (SEK/h)**	**Percent of users**
Class 1 (low VOT)	VOT <62	36	23
Class 2 (medium VOT)	62=< VOT <175	102	23
Class 3 (high VOT)	VOT >=175	405	26
Class 4 (exempted)	Whole range	109	28

Table 4: Description of User Classes in Assignment

This assures more realistic modelling of reactions to congestion charges, since users with high VOT have incentives to choose a fast but expensive route, whereas users with low VOT have incentives to choose a slower but cheaper route. High VOT users are assumed to have a value of time of 175SEK/h or more. The limit between class 1 and 2 is found assuming equal number of users in these classes.

[9] During the Stockholm trial the exempted vehicles amounted to 28% (SNRA, 2006). The 28% consisted of taxis (8%), cars driving to and from Lidingö without stopping in the charged zone (9%), environmental cars (3%), buses (2%), cars with parking permit for disabled people (1,5%) and 'other' (4,5%). The category 'other' included motorcycles, foreign cars and emergency vehicles among others.

4 Model Implementation: A Trade-Off between Level of Detail and Manageability

4.1 General Implementation Issues

In the development of any operational transport model the researcher at some point comes across the trade-off between level of detail and manageability. A more accurate representation of reality can often be achieved by increased level of detail. However, if model complexity is increased there is a risk that one becomes less aware of how uncertainties in input data affect the results. A detailed model is also very data intensive and is therefore likely to have a longer run time.

Run time is an important issue in evaluation of scenarios. A short run time means that many forecasts can be made. The model must however be detailed enough that the traveller responses are included which are likely to be affected by the policies the model should be able to evaluate. It is therefore advisable to consider first the application areas of the model, state the main behavioural responses (compare Table 1) and then decide which choices to model in detail.

Important for run time is also the geographical resolution, i.e. the number of zones the study area is subdivided into. A large number of zones gives a high level of detail, but can cause excessive run times. Just as in the case of which demand responses to consider, the choice of number of zones is dependent on application area. Analysis of local and regional trips requires higher geographical resolution than analysis of long distance and international trips. Larger zones means that more trips occur within the zone. These intra-zonal trips are treated in different ways depending on assignment model. One should be aware of that some assignment models completely disregards intra-zonal trips. In this case a high geographical resolution is important in areas where travel demand is composed by many short trips.

4.2 Implementation Issues Regarding Temporal Effects

Most metropolitan planning organizations tackle the trade-off between level of detail and manageability in the temporal aspect by using simple time-of-day factors, i.e. fixed ratios of peak-period demand to total daily demand. If the time-dimension is present in a transport model for an urban area, it is almost always a time-of-day choice between broad time periods such as peak and off-peak, not changes within the peak period (see e.g. Van Vuren and MacDonald, 2005). This has lead to a large gap between state-of-the-art in theoretical departure time choice modelling and state-of-practice.

Time-of-day factors may be a reasonable simplification for some applications of transport models. However in networks that suffer from congestion more advanced modelling of temporal aspects are advisable since time-of-day factors are independent of congestion levels. A model that uses time-of-day factors will tend to overestimate peak hour congestion levels in future years: demand increases but is in the model not allowed to spread outside the peak hour, because the percent of trips simulated during peak hour is fixed. If simulation of car trips is part of a larger modelling system the result may also be an overrating of number of users switching to public transport, due to the very long peak hour car travel times. Also, this kind of model may overrate the benefit of adding capacity in a congested area, since temporal effects that result in car-users switching back to the peak hour are not accounted for.

If one wants to undertake air quality analysis, accurate modelling of temporal effects is very important because emission levels depend on vehicle speeds, which vary significantly during the day.

Furthermore, policies that bring about peak spreading are becoming more and more common (congestion charging, flexible working hours, pre-trip information to travellers etc.).

These policies affect when trips occur, which also supports the development of operational models that can handle peak spreading effects in real life networks.

4.3 Temporal Implementation Issues and Existing Applications

Existing attempts to model daily differences in travel demand more accurately than by simple peak hour factors can be divided into three implementation categories (Barnes, 1998): (1) the traditional four-step modelling process[10] is adjusted to give assignments that are sensitive to congestion, (2) a peak spreading model is developed as a sub-model within the four-step modelling process and (3) a stand-alone peak spreading model is developed which is independent of the four-step modelling process. SILVESTER belongs to category (3). This review of existing applications will therefore mainly concentrate on stand-alone models.

4.3.1 Peak spreading adjustments

The first category represents minor adjustments of the traditional four-step modelling process in order to capture some effects of peak spreading. The main advantage of methods in this category is that the implementation is rather straightforward and all changes are incorporated in the existing modelling system. The category includes two types of methods: link-based and trip-based adjustments. In the link-based method demand that exceeds link capacity is removed from the peak hour. A major limitation of this approach is that the removed demand may differ substantially in quantity between adjacent links, i.e. flows on adjacent links are not consistent. In the trip-based method, the origin-destination matrix is adjusted such that demand does not exceed capacity on any link. Flows on adjacent links are thus consistent. Removed demand is however in most cases neglected, assuming that these trips occur before or after the peak hour or by another mode.

Peak spreading implementations in category (1) have been applied to several regions. Barnes (1998) reviews applications in Arizona (link-based) and Tri-Valley[11], Boston (downtown), Washington DC, Trafford Park[12] and East Anglia[13] (trip-based).

4.3.2 Peak spreading sub-models

Modelling of peak spreading is more sophisticated in this second category than in the first. Instead of rough link or trip adjustments to cope with excess demand, departure time choice models are built that retime trips when travel costs are perceived as too high to the user. The peak spreading models in this category are developed within the four-step modelling process and are therefore called sub-models.

In Purvis (1999) a rather simple peak spreading model for the San Francisco Bay Area is described. The model is developed within the MTC[14] travel model system. A hybrid approach is taken where traditional peak factors are used for non-work trips, whereas a binomial logit model, with choices peak or off-peak, is used for work trips. A problem with the model is that it tends to move too many trips to the shoulders of the peak, resulting even in travel times that are longer in the shoulders than in the actual peak.

Clark et al. (2007) describes an activity-based peak spreading model that was implemented within the Gloucestershire[15] sub-regional model. In this peak spreading model

[10] The traditional four-step modelling process consists of trip/no trip choice, destination choice, mode choice and route choice.
[11] Tri-Valley is a triangle-shaped region in the San Francisco Bay Area with a population of about 300,000.
[12] Trafford Park is an industrial estate in Manchester where 1,400 companies are situated, employing about 35000 people.
[13] East Anglia is a peninsula in eastern England. The region has a population of about 2.2 million.
[14] The Metropolitan Transportation Commission (MTC) is the metropolitan planning organization in the San Francisco Bay Area.
[15] Gloucestershire is a region in south-west England with about 800,000 inhabitants.

every individual is simulated and the individual chooses in which fifteen-minute time period to depart.

4.3.3 Stand-alone peak spreading models

Just as the peak spreading sub-models of category (2), the stand-alone models of category (3) represent a more sophisticated attempt to model peak spreading. The advantage over category (2) models is that implementation is not limited by the need to fit into the four-step process. It is therefore possible to combine choices, for example a simultaneous choice of departure time and route as in METROPOLIS (see below). Also, stand-alone models can be more customized to the specific peak spreading policy under evaluation, i.e. only relevant behavioural responses have to be accounted for.

Only a pocketful of stand-alone peak spreading models exists. The remainder of this section reviews four of them. For each model, comparisons are also made with implementation choices made in SILVESTER.

METROPOLIS

One of the few stand-alone peak spreading models applicable to real life networks is METROPOLIS, presented in de Palma and Marchal (2002). The paper also describes an illustrative application of the transport model to the greater Paris area. METROPOLIS is however not developed with a certain urban area in mind; rather it attempts to be flexible enough to be used for any city. In application this requires calibration of parameters to local conditions.

Features of METROPOLIS are that departure time and route choices are performed simultaneously and that an event-based mesoscopic simulation approach is used which is fast and applicable to whole cities, while still able to have a higher level of detail than macroscopic models. The choice to model departure time and route choice simultaneously simplifies implementation since input is *one* static origin-destination matrix, whose demand the departure time choice model spread on different departure times. The choice of event-based simulation decreases run time since variables are only updated if they are affected by an event.

Just as in SILVESTER, the developers of METROPOLIS have chosen to model travel as trips not tours and to work with a fixed OD-matrix. Changes in the generation and distribution of trips are thus not modelled, neither is trip chaining and relationships between outbound and return trip.

Other implementation decisions that must be taken when developing this kind of transport model are the kind of choice model to use and how to model the dynamic link travel times. In METROPOLIS the continuous logit model is used for choice of departure time (for cars) and binary logit for mode choice between car and public transport. The two logit models are combined into a hierarchical (nested) logit with departure time choice at the lower level. The dynamic link travel times are implemented using Vickrey's bottleneck model (Vickrey, 1969) with capacities equal to the static capacities. Using the simple bottleneck model simplifies calibration, since the model includes only one parameter that needs to be calibrated.

In the illustrative application of METROPOLIS to the greater Paris area several simplifications are made. These are for example inconsistent assumptions about travellers' preferred arrival times (PAT) and calibration of congestion laws only at aggregate level. The assumptions made about the PATs are that they are uniformly distributed over the time period 8 a.m. to 9 a.m. for commuters and 8 a.m. to 11 a.m. for non-commuters. The PAT assumptions are based on estimations from Paris and other cities in Europe. It is however not certain that these PATs are consistent with traffic flows in the network under consideration. Regarding calibration of congestion laws the authors state that calibration should be made not only at aggregate level but also road by road, since model travel times for individual roads differ significantly from reality. A further simplification made in the application process is the use of historic values of schedule deviation and travel time parameters. These are not estimated for the local conditions at the specific application area. In SILVESTER schedule deviation, travel time parameters etc. are estimated using travel times from the assignment model that will be used in application, which guarantees consistency and credibility.

DIADEM

Another transport model that has the ability to model peak spreading is DIADEM (MacDonald and UK Department for Transport, 2008). Just as in the case of METROPOLIS, the approach taken by DIADEM is to provide the user with a flexible model framework in which it is possible to use the tool for any area. Given sufficient local calibration DIADEM can be applied to give results for a specific area.

DIADEM's strength is the various demand responses that can be modelled using this tool. Not only mode, route and departure time choice can be modelled, but also the generation and distribution of trips. Furthermore, unlike SILVESTER and METROPOLIS, in DIADEM it is possible to choose either simulation of tours or trips, allowing for more realistic modelling of relationships between outbound and return trip using the tour formulation. However, regarding implementation difficulty, the choice to include tour modelling had severe consequences for the complexity of the departure time choice modelling.

DIADEM and SILVESTER are similar in the respect that they consist of a model for demand responses connected to an already existing assignment model for calculation of car travel times. This implementation choice has the advantage that for many cities networks and calibrated dynamic OD-matrices already exists. As described in Chapter 3, SILVESTER uses CONTRAM as assignment model. In DIADEM the user can choose between CONTRAM and SATURN (ITS Leeds et al., 2008).

The departure time choice model in DIADEM is of incremental logit form. Correlations between time periods are thus not accounted for. Time periods in departure time choice can be of different length, but not shorter than the time periods in assignment. With time periods of five to thirty minutes in assignment it is thus possible to model peak spreading. Modelling of peak spreading requires fairly many time periods in the peak period, e.g. as in SILVESTER twelve fifteen-minute time periods between 6.30 a.m. and 9.30 p.m. To model peak spreading using DIADEM's tour-based approach becomes practically infeasible, since data must be available for proportions of trips in each combination of outbound and return time period, i.e. for (number of time periods)^2 combinations. During one day with two peaks this leads two over 500 combinations for which data on proportions of car-users that leave and return must be supplied. Thus, in practice if DIADEM is used to model peak spreading the trip-based approach will be used, just as in METROPOLIS and SILVESTER. As regards modelling of peak spreading DIADEM thus holds no major advantage over other existing departure time choice models.

MODEL FOR SINGAPORE

Olszewski and Xie (2005) develop a peak spreading model for prediction of motorists' responses to time-varying charges at a *single* control point. The model is a multinomial logit model where motorists choose between a number of departure time periods, along with a re-routing/mode-change alternative. Travel time on the road segment under consideration is calculated using a speed-flow equation calibrated for Singapore expressways.

In the paper, application of the model to one expressway and two arterial roads is shown. These applications are however mainly of illustrative character, because of major simplifications. For example preferred arrival times are assumed to be the same as observed arrival times in the uncharged situation, i.e. it is assumed that no serious congestion existed before the introduction of charges. Furthermore, travel times on alternative routes are assumed constant, independent of number of motorists switching to these routes.

The choice to study only one control point facilitates implementation, since travel time calculations is made for a road segment instead of solving a network equilibrium problem. This simplification introduces however a new question: since total journey time cannot be calculated, which part of the trip is affected by the charge and should be taken into consideration?

An objective of SILVESTER is that the model shall be able to forecast and compare effects of different charging system designs (cordon-based, area-based) for a whole city. The implementation approach taken in Olszewski and Xie (2005) to model effects of a single control point was thus not feasible in our case.

ALBATROSS

As discussed in Section 1.3, activity-based models have great possibilities to model temporal aspects of travel. In activity-based models, demand for travel is a result of the will to participate in a number of activities that occur at different destinations. *When* people travel is then a natural consequence of when and for how long the activities occur, even though the scheduling process is a complex task as it needs to take into account spatial, temporal, institutional and household constraints and preferences of the individual.

In Algers et al (2005) ALBATROSS (a learning-based transportation oriented simulation system) is highlighted as an operational activity-based model which is an interesting candidate for application. The authors emphasize ALBATROSS' ability to handle the many constraints a household has to obey when deciding which activities to take part in and deciding the sequence of these activities.

ALBATROSS is a rule-based model for daily scheduling of activities conducted by an individual in a particular household (Arentze, and Timmermans, 2004). Choices made by other persons in the household affect the individual decisions. For example if there is only one car in the household, the choice of one of the household members to use it implies that car is not a possible mode choice for another household member. Working at household level is an advantage over SILVESTER which works at individual level.

In ALBATROSS the selection, location, duration and departure time of so called fixed activities (work and school) are assumed to be given. The fixed activities form an activity skeleton, within which so called flexible activities (e.g. shopping) are scheduled. This is a big difference compared to SILVESTER where the departure time of work and school trips are not fixed, on the other hand small changes in departure time as a reaction to congestion or charges are in focus. The departure time choice in ALBATROSS is more of a time-of-day choice between broad time periods. The model is thus not yet ready to be used for analysis of peak spreading effects.

5 Contributions of the Thesis

5.1 Paper I: A Dynamic Transportation Model for the Stockholm Area: Implementation Issues Regarding Departure Time Choice and OD-pair Reduction

Paper I (Kristoffersson and Engelson, 2009a) describes one of the first implementations of a departure time and mode choice model for evaluation of peak spreading effects in a real-world urban road network (Stockholm). A mixed logit specification is used for the departure time and mode choice model. Implementation of such an advanced logit model and connection of it to an assignment model in a real world application is rare. Furthermore, as Batley and Clegg (2001) points out, parameters for departure time choice are often extracted from historical studies (particularly from Small (1982)). The model implemented in this thesis uses new parameters estimated from a survey made in the area where the model will be applied (Börjesson, 2008). The paper thus attempts to reduce the gap discussed in Chapter 3 between state-of-the-art in theoretical departure time choice modelling and state-of-practice, to explore difficulties and propose more or less general solutions to them.

In large-scale dynamic modelling one of the main problems is model run time. The simulations are often time consuming and trade-off's between level-of-detail of the model and run time has to be made (see also Chapter 3.). A long run time is coupled with high costs and low flexibility since only a few scenarios and designs of a policy measure can be evaluated.

In Paper I the run time of the resulting transport model, containing both demand and supply submodels, was made acceptable by a reduction in number of origin-destination pairs (OD-pairs). The paper shows how a 75% cut down in run time was achieved by moving only 7% of the demand to remaining OD-pairs. It is brought up for discussion both how to select which OD-pairs to remove and how to redistribute demand from removed OD-pairs. The paper compares two selection methods and five redistribution methods. The selection methods are compared regarding changes in the average trip distance weighted by demand. The redistribution methods are compared regarding how well they preserve the trip distance distribution, the travel time profile and the link flows.

In conventional transport models travellers with the same trip purpose are modelled to have the same value of time (VOT). The estimation of the departure time and mode choice model used in this study showed that the VOTs differed within each trip purpose group. A contribution of Paper I is thus the implementation of three VOT-classes in assignment with a mixture of trips with different purposes. The proportion of a certain trip purpose in each VOT-class is decided by the VOT-distribution for that trip purpose. More than three VOT-classes in assignment could not be implemented because of an excessive run time.

Since demand model results depend on supply quantities (travel times and travel time uncertainties) the transport model must be iterated between demand and supply to form a convergence process. Also within the assignment model iterations are performed to reach network user equilibrium. In Paper I several measures are presented to evaluate these convergence processes. The tests show that the convergence between demand and supply is smooth and that the convergence process stabilizes. A contribution of Paper I is also that the performance of the method of successive averages (MSA) is compared with another damping specification, instead of just using MSA by tradition.

5.2 Paper II: Deriving Preferred Departure Times of Road Users in a Real-Life Network

The common way to model departure time choice is as a trade-off between schedule deviation and other travel costs, following the formulation in Small (1982). The traveller is prepared to change departure time if enough is gained in travel times, travel time uncertainties and/or reduced congestion charges. Given an uncongested traffic network without congestion charges the traveller has, with this model formulation, nothing to gain by changing departure time. The departure time chosen by the traveller in this free-flow situation is called the preferred departure time (PDT) (see also Section 2.5). Since most urban networks under analysis are congested, the PDTs cannot be observed directly from the field.

The accuracy of the PDTs strongly affects the predictive capability of the transport model. It is thus a major limitation that most earlier studies have relied on exogenous assumptions about the PDTs in application, for example assuming that all travellers have the same PDT, that PDTs are uniformly distributed on some time interval or that PDTs are equal to actual departure times even though the network is congested.

In Paper II (Kristoffersson and Engelson, 2009b) the PDTs of travellers are derived for the network of Stockholm. Instead of an exogenous assumption the paper uses an approach called reverse engineering, in which the probabilities of the departure time choice model and the actual departure rates given by the origin-destination matrix are used in order to find travellers' underlying PDTs. Paper II shows that it is possible to use the reverse engineering approach for revealing preferred departure times in a large network. The method is consistent with observed times of travel in the specific city the model is calibrated for. It is also consistent with the applied departure time choice model.

Travellers with flexible working hours or those undertaking a recreational trip are often more willing to change departure time because of weaker scheduling constraints. This is acknowledged in Paper II and separate PDT profiles are estimated for trip purposes that differ in schedule flexibility. Furthermore, Paper II also investigates other trip properties that could give rise to differing PDT profiles: trip distance, traveller income and geographic location of start and end zone, showing that in Stockholm location of start zone is important for two of the three trip purpose segments.

A contribution of Paper II is also that it looks into a problem with reverse engineering: the method may produce unrealistic solutions in the respect that the number of trips with preferred departure time in some time period can be negative. The paper shows that calculation of a common PDT profile for a group of OD-pairs can solve the problem of negative solutions. Even if the problem with negative solutions would not exist, aggregation of OD-pairs is advisable if the PDT profiles are similar.

Paper II shows a combined PDT profile for all trips which is in line with previous research: the PDT profile is more peaked and the peak occurs somewhat later than in the departure profile observed in the field. In other words, car-users have, according to the model, quite similar preferred departure times but spread out to avoid congestion (PDT profile more peaked than observed behaviour) and they rather change departure time to a time period earlier than later (peak of PDT profile occurs later than peak of observed behaviour).

6 Discussion and Future Research

The ability of transport models to perform reliable forecasts is often questioned. The criticism is partially justified by the fact that human travel behaviour is too complex for any model to be able to perfectly replicate and predict reality. There are however many situations in which transport models can help decision-makers select which long-term road investment or transport policy to concentrate on. When deciding whether or not to use transport models, the alternative must also be considered, which is a - hopefully experienced-based – guess.

Nevertheless, care should be taken when using transport models. The key is to be well aware of which factors are included in the model and which are disregarded. Beimborn and Kennedy (1996) capture this in a concise way:

"All models are limited by the assumptions, factors, and alternatives that are explicitly included in the equations used by those models."

The authors also exemplify the statement: a transport model that disregards bicycle and pedestrian trips will of course never show any positive effects of plans that improve bicycle and pedestrian paths.

With the discussion above in mind, emphasis is in this thesis put on the importance to select which demand responses that are modelled from an application perspective. The components of the transport model should be chosen considering which policies/investments the model is developed to analyse. It is argued that departure time choice is important for the analysis of time-varying congestion charges and the thesis thus attempts to develop a transport model that includes departure time choice. We also stress the importance of local calibration, since all cities have different structure and behavioural characteristics. Parameters for travel costs (travel time, travel time uncertainty, scheduling costs and congestion charges) and preferred departure time profiles are therefore all estimated on data for the city of Stockholm.

In Beser et al., (1996) four Swedish transport model systems are evaluated and the authors come to the conclusion that the systems all have a high modelling standard, but that they have not been validated enough. If any validation is undertaken, it tests how well the model reproduces data from the base year on which it was calibrated. Validation seems to be a neglected area for many transport models. Sufficient validation could increase the credibility of transport models among planners and decision-makers.

The next step in this research will be to validate SILVESTER. In addition to tests regarding how well the model reproduces data from the base year (without congestion charges), we also have the rather unique possibility to compare model forecast of adding congestion charges to the system, with data from the Stockholm Trial regarding traffic flows, travel times and distribution of travellers on time periods and modes.

An often stated criticism of congestion charges is that those who can pay have access to more or less free-flow streets in the very popular city centre region. What is questioned here is the equity of congestion charging. Are some user groups, for example low-value-of-time users, priced off the road? This kind of equity questions will be investigated using the validated SILVESTER model. Also, different charging system designs will be analysed, e.g. impact of differences in level of charge, time period when the charge is applicable and if the system is cordon-, area- or distance-based. A long-term goal is to find charging system designs that reduce congestion and improve the environment, with only a minimal impact on user mobility.

References

Algers, S., Eliasson, J., Mattsson, L-G., 2005. Is It Time to Use Activity-Based Urban Transport Models? A Discussion of Planning Needs and Modelling Possibilities. The Annals of Regional Science, Vol 39, pp. 767-789.

Arentze, T. A. and Timmermans, H. J. P., 2004. A Learning-Based Transportation Oriented Simulation System. Transportation Research B, Vol 38, pp. 613-633.

Barnes, J., 1998. Peak Spreading Analysis: Review of Relevant Issues and Synthesis of Current Practice. Final Research Report, Washington State Transportation Center, University of Washington, Seattle, Washington.

Bates, J., 1997. Time Period Choice Modelling: a Preliminary Review. HETA Division, Department for Transport, UK.

Bates, J., Polak, J., Jones, P., Cook, A., 2001. The Valuation of Reliability for Personal Travel. Transportation Research E, Vol. 37, pp.191-229.

Batley, R., Clegg, R., 2001. Driver Route and Departure Time Choices: The Evidence and the Models. Proceedings of the 33rd Annual UTSG Conference, Cambridge, UK. http://www.richardclegg.org/pubs/utsg2001.doc 2009-02-17

Beimborn, E. and Kennedy, R., 1996. Inside the Blackbox: Making Transportation Models Work for Livable Communities. Citizens for a Better Environment, Milwaukee, WI, US. http://www.edf.org/documents/1859_InsideBlackBox.pdf 2009-02-20

Beser, M., Eliasson, J., Karlström, A., Mattsson, L-G., Rosenlind, S., 1996. Swedish title: Kan vi lita på trafikprognoser? (Can we trust traffic forecasts?) Dept. of Infrastructure, Royal Institute of Technology, Stockholm. Copyright: Swedish Environmental Protection Agency.

Börjesson, M., 2006. Issues in Urban Travel Demand Modelling: ICT Implications and Trip Timing Choice. Doctoral thesis in Infrastructure, Royal Institute of Technology, Stockholm. ISBN 10: 91-85539-04-X.

Börjesson, M., 2008. Joint RP-SP Data in a Mixed Logit Analysis of Trip Timing Decisions. Transportation Research E, Vol. 44, pp.1025-1038.

Cambridge Systematics, Inc., 1999. Time-of-day Modeling Procedures: State-of-the-Art, State-of-practice. US Department of Transportation.

Clark, P., Culley, R., Davidson, P., 2007. Using Activity Based Modelling to Implement a Peak Spreading Model in a Practical Multi-Modal Context. Proceedings of the European Transport Conference 2007 at Leeuwenhorst Conference Centre/The Netherlands.

de Palma, A., Marchal, F., 2002. Real Cases Applications of the Fully Dynamic METROPOLIS Toolbox: An Advocacy for Large-Scale Mesoscopic Transportation Systems. Networks and Spatial Economics, 2: (2002) pp. 347-369. Kluwer Academic Publishers, the Netherlands.

Downs, A., 2004. Still Stuck in Traffic: Coping with Peak-Hour Traffic Congestion. Brookings Institution Press.

EC, 2007a. Energy & Transport: Figures and Main Facts. European Commission. http://ec.europa.eu/dgs/energy_transport/figures/pocketbook/2007_en.htm 2009-02-09

EC, 2007b. Green Paper on Urban Mobility. European Commission. http://ec.europa.eu/transport/clean/green_paper_urban_transport/doc/2007_09_25_gp_urban_mobility_memo_en.pdf 2009-02-05

Eliasson, J. and Mattsson, L.-G., 2001. Transport and Location Effects of Road Pricing: A Simulation Approach. Journal of Transport Economics and Policy, Vol. 35, part 3, pp. 417-456.

HUI, 2006. Swedish Title: Stockholmsförsökets effekter på detaljhandeln i Stockholmsregionen (Effects of the Stockholm Trial on Retail Trade in the Stockholm Region). The Swedish Retail Institute (HUI), Stockholm.

ITS Leeds, Dirck Van Vliet, Atkins, 2008. SATURN Manual, Version 10.8. http://www.saturnsoftware.co.uk/saturnmanual/chapters.html 2009-02-19

Kristoffersson, I. and Engelson, L., 2009a. A Dynamic Transportation Model for the Stockholm Area: Implementation Issues Regarding Departure Time Choice and OD-pair Reduction. Accepted for publication in Journal of Networks and Spatial Economics. DOI 10.1007/s11067-009-9104-0.

Kristoffersson, I. and Engelson, L., 2009b. Deriving Preferred Departure Times of Road Users in a Real-Life Network. Submitted. First version in proceedings of the European Transport Conference 2008 at Leeuwenhorst Conference Centre/The Netherlands.

Mackie, P.J., Jara-Diaz, S., Fowkes, A.S., 2001. The Value of Travel Time Savings in Evaluation. Transportation Research E, Vol. 37, pp. 91-106.

MacDonald, M. and UK Department for Transport, 2008. DIADEM User Manual Version 3.0, Southampton, UK. http://www.diadem.org.uk/manuals/manuals.html 2009-02-17

Olszewski, P., Xie, L., 2005. Modelling the Effects of Road Pricing on Traffic in Singapore. Transportation Research A, Vol. 39, pp. 755-772.

Phang, S.Y., Toh, R., 1997. From Manual to Electronic Road Congestion Pricing: The Singapore Experience and Experiment. Transportation Research E, Vol. 33, pp. 97-106.

Purvis, C., 1999. Peak Spreading Models Promises and Limitations. Proceedings of the 7th TRB Conference on Application of Transport Planning Methods, Boston, Massachusetts.

Small, K. A., 1982. The Scheduling of Consumer Activities: Work Trips. The American Economic Review, Vol. 72, No. 3, pp. 467-479.

SNRA, 2006. Trial Implementation of a Congestion Tax in Stockholm. Swedish National Road Administration. http://www.stockholmsforsoket.se/upload/Infomaterial%20VV/Booklet%20eng.pdf 2009-02-09

Taylor, N. B., 2003. The CONTRAM Dynamic Traffic Assignment Model. Networks and Spatial Economics, No. 2003:3, pp. 297-322. Kluwer Academic Publishers, Netherlands.

Tseng, Y-Y., Verhoef, E., 2008. Value of Time by Time of Day: A Stated-Preference Study. Transportation Research B, Vol. 42, pp. 607-618.

US DoT, 2004. Mitigating Traffic Congestion – The Role of Demand-Side Strategies. US Department of Transportation, Federal Highway Administration.

Van Vuren, T., MacDonald, M., 2005. PRISM – a 21st Century Transport Model for the West Midlands Region. Final Report. Mott Macdonald, Birmingham. http://www.prism-wm.com 2009-02-17