Modelling the effects of Stockholm Congestion Charges – A comparison of the two dynamic models: Metropolis and Silvester

Master Thesis
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Abstract

Congestion charging has drawn considerable attention of transport analysts and policymakers as a mean of relieving urban traffic congestion. Proper prediction of the impacts of charging is necessary for policy makers to take right decisions. A European project named SILVERPOLIS have been introduced in this connection to describe state-of-practice in modelling effects of congestion charging and to identify features of transport models that are crucial for reliable forecasting of effects of congestion charging. This master thesis is a part of the SILVERPOLIS project, where Stockholm congestion charging scheme has been analysed using two different types of dynamic simulators: METROPOLIS and SILVESTER.

The simulations are based on traffic data collected before and after the Stockholm congestion charging trial performed in spring 2006. The result of simulation suggests that METROPOLIS, which has been used for predicting effects of congestion charging in Ile-de-France, manages well to forecast the consequences of congestion charging for Stockholm. Comparison with SILVESTER model disclosed that, although calibration results of the two models differs in some respect, both models give similar results regarding impacts of congestion charging. The different modelling features and assumptions have been described for the two models. Despite the fact that the two models vary a lot in their assumptions and modelling style, both of them has proved to be good at describing the effect of congestion charging.

Keywords: Transportation modelling, Congestion charging, Dynamic traffic simulation, Departure time choice, METROPOLIS, SILVESTER.

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1. INTRODUCTION

1.1. Background

A transport system can be reliable when it performs efficiently day after day with approximately equal travel time. Congestion is one of the main obstacles behind a reliable transport system, especially in the morning and evening peak periods. One way to reduce congestion can be capacity expansion by building new roads or adding extra lanes beside the current congested ones. But building new roads or widening existing roads are always costly. Moreover it is not a sustainable solution because increased capacity will attract new demand and soon the situation will be the same as before.

For many years congestion charging has drawn considerable attention to transport analysts and policymakers as a means of relieving urban traffic congestion, although there have been few actual implementations. Congestion charging has a big advantage over other transportation demand management policies that it encourages traveller’s to adjust all aspects of their behaviour: number of trips, destination, mode of transport, departure time choice, route choice, and so on, as well as their long-run decisions on where to live, work and set up business.

Singapore was the first city to introduce full scale urban road pricing scheme in 1975. It was a manual coupon-based system in the beginning but in September 1998 they converted it to a fully automate electronic road pricing system. Following their example London, introduced congestion charging for central London on February 2003 and later extended it into parts of West London. Sweden introduced congestion charging scheme for greater Stockholm region in August 2007 following a full scale trial during spring 2006. The gradually accelerating pace at which congestion charging is being implemented or actively considered around the world suggests that congestion charging is an idea whose time may finally have come. Proper prediction of the impacts of charging is necessary for policy makers to take the right decision.

One of the difficulties in evaluating potential benefits of a congestion charging scheme is predicting motorist’s behavioural responses to direct charging - and in particular departure time choice adjustments. For a simple charging scheme involving a flat toll, estimates of traffic impacts can be made with knowledge of demand elasticity. However, even a flat toll may induce adjustments in departure time, since a more reliable travel time implies that drivers can reduce their head start. Rescheduling is even more important in case of time-variable charging, when motorists may change departure time to avoid or reduce the charge. This situation calls for explicit modelling of motorist’s choice making. There is however few transport models where a demand model includes traveller’s departure time choice within the peak and a dynamic assignment model that interact to predict how travellers react to new travel conditions. These models are in this thesis named “dynamic models”.

A study of available models (Algers, et al., 1998) suggests that most of them are research products, which have been developed for a particular city or based on some specific criteria. They also vary a lot in their modelling assumptions. As far as the author knows, two different dynamic models have never been calibrated for the same city, to compare their effectiveness in modelling congestion charging. It has therefore not been possible to evaluate which features of the models or assumptions are important for reliable prediction of congestion charging effects.

This research is a part of a European project named SILVERPOLIS which will review the transportation models used for predicting impacts of road user charging in European cities and carry out in-depth comparison of two such models: SILVESTER and METROPOLIS. Both models are dynamic and take into account route choice and departure time choice; however the theoretical basis and structure of the two models are different. SILVESTER (Kristoffersson & Engelson, 2009) developed at KTH Royal Institute of Technology (Stockholm, Sweden) is based on an existing dynamic assignment model called CONTRAM (Taylor, 2003), which has been in use for a long time in Stockholm. SILVESTER has been calibrated specifically for Stockholm and validated against the outcome of the road user charging trial of 2006. METROPOLIS (De Palma & Marchal, 2002) was developed at the University of Cergy-Pontoise (FRANCE). It has been calibrated for Ile-de-France, a major European area that includes Paris (De Palma & Lindsey, 2006). Road pricing for Ile-de-France has been evaluated using this software. In this thesis, METROPOLIS will be calibrated for the Stockholm road network and will be applied to test Stockholm congestion charging scheme.

1.2. Objective

The aim of this study is to evaluate the ability of METROPOLIS to predict the impacts of congestion charging in Stockholm and compare the results with the SILVESTER model for Stockholm congestion charging. To achieve this goal METROPOLIS will be calibrated for the same road network which has been used in SILVESTER using the same data, then the Stockholm congestion charging scheme will be evaluated in METROPOLIS, and finally the results of simulation will be compared with SILVESTER.

The comparison will be on both aggregate and disaggregate level. In aggregate level the network average travel time, speed, congestion percentage, number of cars and revenue collections will be compared for both the models. In disaggregate level total flow and its distribution for some selected links, and travel times for some selected road sections will be compared among both the models and also with the field measurements.

1.3. Limitations

Efforts have been made to achieve as much similarity in input data between the two models as possible, such that results will be comparable. Network representation in METROPOLIS is however not quite the same as SILVESTER. Some modification has been done to fit METROPOLIS requirement. It was also not possible to account for travel time variability in METROPOLIS, which led to a re-estimation of the SILVESTER demand model, but the same stated and revealed preference data was used for the estimation. Furthermore, METROPOLIS requires input data as individual travellers i.e. integer demand, whereas in SILVESTER it is possible to specify demand in fraction of flows.

Some vehicles were exempted from charging in the SILVESTER model, but this could not be modelled in METROPOLIS. Unfortunately U-turn restriction could not be implemented in METROPOLIS.
1.4. Outline

The rest of the report is organised as follows: A brief description of static and dynamic transportation models along with different types and features of dynamic models are presented in section 2. In section 3 a brief introduction to METROPOLIS and its different modelling features is described together with a brief description of SILVESTER and its modelling differences compared to METROPOLIS. Section 4 deals with the case study of Stockholm and the calibration procedure of METROPOLIS for the Stockholm network. Results of calibration are presented in section 5. Comparison of the results with SILVESTER is also described in this section. Finally conclusions are drawn in section 6.

2. Literature Review

In practice, the most widely used traffic planning tools are four stage models which include trip generation, trip distribution, mode choice and route choice. Most of them use a static assignment model, such as EMME/2 (Babin, Florian, James-Lefebvre, & Spiess, 1982). Although the static approach is successfully used in practice, it is not suited for addressing the following questions: What is the impact of a time-varying toll? How do flexible and staggered working hours influence traffic congestion? What is the impact of non-recurrent congestion? How do driver information systems modify route and departure time choice decisions? (De Palma, Marchal, & Nesterov, 1997). Moreover, several researches (Vickrey, 1969), (Arnott, De Palma, & Lindsey, 1993) have indicated that for many applications congestion cannot be treated adequately using only the total number of drivers that use a route during the peak period. Rather, an explicit description of the evolution of congestion over time is required. Dynamic transportation models were first initiated to understand the basics of congestion dynamics (De Palma, Ben-Akiva, Lefevre, & Litinas, 1983). But now-a-days dynamic models are used for emission modelling; to understand the effects of congestion charging, the effect of ITS applications and so on.

Many dynamic models exist today. Algers, et al., (1998) found fifty eight micro-simulation models and reviewed thirty-two of them. The authors discovered that most of the models were used only for research, just nine of them were found to be commercial products. Most of them attempt to provide a local picture of evolution of traffic congestion over a given time period (rush hour). However, few of them address the problem of departure time modelling and day-to-day variability.

Conventional static models can find the static equilibrium situation where the flow conservation laws are satisfied and where no user can decrease his/her (deterministic or stochastic) travel cost by choosing another route. It is assumed that the travel time on a link is a function of an average occupancy on that link during the given time period. On the contrary, dynamic models assume that the travel time on a given link at time \( t \) depends on the instantaneous occupancies on that link. Consequently, the travel time from an origin to a destination becomes variable over time and depends on the time of the day. For example, in the peak period (e.g. morning or evening commuting peak) there may be longer travel time resulting from high occupancies. As travel time is no more constant in dynamic models, travellers change their departure time to minimise travel cost. It is often assumed that drivers departure times are distributed on a time interval that includes the two extreme situations: arrive at some inconvenient time and enjoy little or no congestion, or travel during rush hour and arrive at their destination on time experiencing high level of congestion.
Preferred time (arrival or departure) plays an important role in dynamic modelling. Estimating preferred time is therefore crucial, but data on preferred departure or arrival times are rarely collected in travel surveys.

In a dynamic system, a stationary dynamic regime occurs when no user can modify his/her departure time and route choice in order to decrease the generalized cost. The generalised cost in a static model depends mainly on users travel time costs, but in a dynamic model it may also depend on their schedule delay costs i.e. the difference between actual arrival time and preferred arrival time (normally used to simulate morning peak) or the difference between actual departure time and preferred departure time.

Some dynamic models use time dependent origin-destination (O-D) matrices; they are specially called Dynamic Traffic Assignment Models (DTA). DTA models (Ran & Boyce, 1994) (Wu, Chen, & Florian, 1998) assume that the splitting of the O-D matrix is exogenously given. This models fits better in real-time information systems with online data acquisition, however, their scope of applicability is questionable by the fact that the input flows of the network are not consistent with dynamic traffic conditions, since there is no feedback on departure time decision (De Palma & Marchal, 2002).

2.1. Microscopic, macroscopic or mesoscopic model

Traffic models usually have two sides: a supply side and a demand side. The supply side describes vehicles’ movements through the network and calculates the travel costs. The network components i.e. link capacity, maximum permitted speed, no of lanes, signal plan and capacities, charging plan, etc. belong to the supply side. The demand side on the other hand describes user’s behaviour given travel costs of different modes etc.

According to the level of detail of the modelled phenomena, models have been classified into macroscopic, mesoscopic and microscopic categories. Macroscopic models use fluid properties e.g. flow and density to describe congestion. Individual vehicles are not modelled here. On the contrary, microscopic models describe vehicles individually. These models try to reproduce vehicle characteristics for acceleration and deceleration, driving behaviour e.g. route choice, gap acceptance, lane change, overtaking, etc. (see for instance the models of (Liu, Van Vliet, & Watling, 1995)and (Mahmassani, Pillai, & Stevens, 2001)). The objective of micro-simulation models (Algers, et al., 1998) is essentially to quantify the benefits of Intelligent Transportation Systems (ITS), Advanced Traveller Information Systems (ATIS) and Advanced Traffic Management Systems (ATMS). They also play an important role in studies of dynamic traffic control, incident management schemes, real time route guidance strategies, signal controls, ramp and mainline metering, toll plazas and lane control system, etc. Unfortunately, a microscopic simulation often requires large computing resources and time consuming calibration procedures and it is therefore practical only for small networks. Recent advancement in parallel computing and cloud computing may help to simulate larger networks (Nagel & Rickert, 2001), but is yet expensive.

The mesoscopic level of detail falls in between the microscopic and macroscopic model. Sometimes, mesoscopic models assume that packets of vehicles are moved together or that some “patterns” of decisions are modelled instead of individual decisions (e.g. (Ben-Akiva, Bierlaire, Koutsopoulos, & Mishalani, 1998) describes a completely mesoscopic model).With the growing popularity of discrete choice models (mainly introduced in the field by (Ben-Akiva & Lerman, 1985)) for the demand
description, demand models often use disaggregate (microscopic) approach to describe individual decisions. Therefore, we will refer to “mesoscopic” model which will combine a microscopic representation of traffic where each individual vehicle is represented, and a macroscopic model will capture the traffic dynamics. SILVESTER and METROPOLIS both fall in mesoscopic category.

2.2. Dynamic modelling

Many dynamic models use time discretization. Quasi-dynamic models use time slices and assume that traffic variables are constant during some time chunks (typically 15 minutes or more) (for example see the paper (Taylor, 2003)). These models have to deal with the complexity of journeys that span more than the given time slice (e.g. 30 minutes journeys), which often makes them inconsistent. Models with an explicit time modelling are either “time-based” or “event-based” models.

2.2.1. Time based models

In time based models, the time scale is divided into time steps that are one or few seconds long. During a time step, each vehicle keeps its variables constant (position, speed and acceleration). After each step, a “motion” phase computes the vehicle variables for all vehicles and a “decision” phase where drivers decides to do or do not alter the motion of their vehicle. Drivers change their driving decisions and behaviour in a given time step according to their driving environment. The algorithm can have different strategies: either it refresh all drivers every time steps or only partially according to some probabilistic law. De Palma and Marchal (2002), summarize that, every time based model must have (a) a supply component (or motion phase) that updates the state variables of vehicles: location, speed and acceleration and (b) a demand component (or decision phase) that updates the state variables of drivers. The two phases proceed iteratively in a closed loop: vehicle motions impact on driving decisions and conversely.

2.2.2. Event based models

In the event-based approach, system variables are only affected when an “event” occurs. An event can be any change to the model environment: a vehicle entering a link or leaving a link, a driver taking a route decision or making a lane change, etc. The occurrence of those events can be either probabilistic or deterministic. Each event has a timestamp and the list of events is processed chronologically. The computational complexity is highly dependent on the level of details of vehicle and drivers interactions (De Palma & Marchal, 2002). The difficulty of the event-based approach is to limit the interaction between drivers and vehicles to a realistic level so that not too many events are produced: if the single decision of a driver impacts on many others, the system will obviously explode with amass of events to process.

The two dynamic models METROPOLIS and SILVESTER which will be reviewed below use different time span for their simulation. SILVESTER is basically a quasi-dynamic model because it uses 15 minutes time slices and assumes that traffic variables are constant during that time interval. METROPOLIS is a fully dynamic model and use event based architecture for its simulation.
3. **MODEL DESCRIPTION**

3.1. **METROPOLIS**

METROPOLIS is a traffic planning software designed for dynamic simulations. It includes a mesoscopic traffic simulator that can handle large networks, a graphical user interface (GUI) to visualize the data and a database to manage them. METROPOLIS GUI is coded in Java while the simulator core is coded in C/C++ (METROPOLIS 1.5 manual, 2002).

METROPOLIS proposes an interactive environment that simulates vehicle traffic flow and congestion in urban areas. The core of the system is a dynamic simulator that integrates commuters’ departure time and route choice behaviour over large networks. Drivers are assumed to minimize a generalized travel cost function that depends on travel time and schedule delay (De Palma, Marchal, & Nesterov, 1997). The simulator uses event based simulation process; an event can be any change in the model environment: a vehicle entering a link or leaving a link, a driver taking a route decision or making a lane change, etc. De Palma & Marchal (2002) have predicted that the combination of mesoscopic supply description with an event-based architecture, such as that of METROPOLIS, can yield dynamic models that outperform time-based micro-simulators by one or two order of magnitude without sacrificing a detailed demand description.

3.1.1. **Important modelling features of METROPOLIS**

METROPOLIS describes the joint departure time and route choice decisions of drivers. Route choices are undertaken sequentially by drivers during the journey. The system is based on a disaggregated description of commuter behaviour: Each commuter is characterized by specific parameter values, and at each moment his or her location on the network is known. A heuristic procedure describes a day-to-day adjustment process toward a stationary user equilibrium regime.

Each vehicle is described individually by the simulator. However, the modelling of congestion on the links is carried out at the aggregate or macroscopic level. The congestion laws, which provide the travel delays of the links, depend on variables specific to each link: the incoming flow during a time period and the average rate of occupancy.

**Travellers’ Choices**

The travellers’ choices¹ are described at the individual level. For practical purposes, the users are partitioned into segments. In each segment, individuals have parameter values drawn from the same distribution. Individuals having different origin and/or destination can belong to the same demand segment. The VOT is specific to the user segment and are allocated for all users at the beginning of the simulation. The travellers’ choices are described by METROPOLIS in the following way:

- Mode choice,
- Departure time choice (from the origin),
- Route and direction choice (if the selected mode is car)

¹For details of traveller’s choice modelling please see the modelling section of (METROPOLIS 1.5 manual, 2002)
Mode choice

Mode choice is described by a discrete choice model. The generalised cost associated to public transport (VB) is defined as:

\[ V_B = VOT_{PT} \cdot t_{PT} + C_{PT} \]

Where,
- \( VOT_{PT} \) = Value of time spent in public transport (PT),
- \( t_{PT} \) = Generalised travel time in PT (specified externally by an O-D matrix of travel times),
- \( C_{PT} \) = fixed penalty associated to PT.

The generalised cost associated to the car alternative (VC) can have two forms: short term choice or long term choice (METROPOLIS 1.5 manual, 2002). In short term choice, it is assumed that, the user is aware of his/her potential departure time and can calculate the cost of car alternative associated with that departure time. Lastly the user compares \( V_C \) to \( V_B \) and chooses the mode for travel. In long term choice option, the user is unaware of his/her potential departure time, therefore, the cost associated with car mode is aggregated in time and equal to the accessibility which depends on the characteristics of the user: origin, destination and behavioural parameters. It is also possible to disable the mode choice for some user types if necessary. Long term choice option was used for this study.

Departure time choice

Car users have to select their departure time. The choice of departure time for public transportation is not described by the model, since the public transportation travel times are external inputs to METROPOLIS. The departure time choice model for car is a continuous logit model, either deterministic or stochastic. The deterministic version of the departure time choice has been used for the current project. Here the individual selects the departure time that minimizes the generalized cost function. The generalised cost function is given by:

\[ V_C(t) = \alpha \cdot tt_c(t) + \beta \cdot MAX \left[0, \left\{t^* - \Delta/2\right\} - \left\{t + tt_c(t)\right\}\right] + \gamma \cdot MAX \left[0, \left\{t + tt_c(t)\right\} - \left\{t^* + \Delta/2\right\}\right] \]

Where,
- \( V_C(t) \) = Generalised cost for car user whose departure time is \( t \) from the origin
- \( tt_c(t) \) = travel time for a departure at \( t \) from the origin
- \( t^* \) = desired arrival time at destination
- \( \alpha \) = value of time
- \( \beta \) = penalty associated to early arrival
- \( \gamma \) = unit penalty associated to late arrival
- \( \Delta \) = flexible time period without penalty

The first term in the above equation represents the travel time penalty; the second and third term represents early or late arrival penalty respectively. Typically, the user faces the following trade-off: either he arrives close to the desired arrival time and incurs a lot of congestion or he avoids the congestion and arrives too early or too late compared to his desired arrival time. Details about desired arrival time (preferred time of travel) have been described in section 3.2.1.
Route choice and direction choice

METROPOLIS uses a model of route choice based on point-to-point dynamic travel times. The user selects the dynamic shortest path from the origin node to the destination node. Two types of information are available to the users: **Historical travel time** which is the result of a learning process, and **instantaneous travel time** which reflects the situation of the day (i.e. from current iteration).

The choice of a route at the origin is only based on the minimization of historical travel times. Consider a user whose origin zone is $O$ and who is reaching the intersection $N$. Intersection $N$ has 3 downstream links whose directions are $D_1$, $D_2$ and $D_3$. The final destination of the user is zone $D_f$. In METROPOLIS, it is assumed that the user chooses the direction $D_i$ ($i = 1, 2$ or $3$) that minimizes the remaining travel time to destination. That travel time is the sum of the current travel time on the link downstream of $N$ plus the historical travel times from $D_i$ to $D_f$. The situation is described in **Figure 1**.

![Figure 1: Route choice decision (Source: METROPOLIS manual 1.5, 2002)](image)

It is assumed that the travel time on the next link to take is observable and anticipated by the user. It is expressed by the following equation:

$$t_{t_j D_f} (t) = t_{t_j}^S (t) + t_{t_j D_f}^H (t + t_{t_j}^S (t))$$

In this expression, H-indices refer to historical travel times and S-indices refer to the simulated travel times (i.e. current) on the links downstream from $N$. Historical travel times are those used to reach $D_f$ by using the routes $P_1$, $P_2$ and $P_3$ from nodes $D_1$, $D_2$ and $D_3$. This combination of current and historical values allows:

- To model that users perform route diversion if any disturbance (e.g. incident) occurs,
- To avoid an all-or-nothing route choice model: the situation is different for each user since the simulated conditions vary from one vehicle to another in the same intersection and over a very short time.

Each node is considered as an intersection in METROPOLIS, which can be a problem if not modelled properly. For example, if it finds a node in a straight road (may be inserted to make a curve road) it will revise its route choice decision and sometimes a high percentage of u turn is observed. Some computation time is also consumed for this unnecessary decision making. The problem is described in **Figure 2**. In the left picture of **Figure 2** about 600 vehicles going north changed their decision at the intersection and took the U-turn during the simulation period. To ban the U-turn the network can be re-designed as shown in the right picture, where the unnecessary node has been omitted using a direct connection with the next intersection. The network taken from CONTRAM was modified and updated for METROPOLIS to overcome this type of problems.
Learning model

It is assumed that travel times experienced one day by the users affect their decisions the next day. For this reason, METROPOLIS uses an iterative process where one iteration corresponds to one day. This process is a learning process where users acquire knowledge about the congestion of the network and adapt their choices accordingly. This process operates as follows:

- The first day, the users have a naive knowledge: they make the assumption that there is no congestion in the network. If the users have preferred arrival time, they leave relatively late, all attempting to arrive at the preferred time, and select the route that is fastest under the free flow conditions. The congestion caused by this concentration phenomenon is very high.
- The second day, they leave much earlier or later in order to avoid this congestion. They also select longer routes. Consequently, the congestion is reduced. Yet, the arrivals are still too far away from the schedule time.
- The process continues until it reaches a stable state. At each stage (iteration), the users acquire information about their experienced route. After one complete iteration, collected information’s are either stored as historical travel data or update the previous data.

METROPOLIS requires similar data as a static model, i.e. a coded network with static congestion laws and demand in the form of a static OD-matrix. In addition to the static data, METROPOLIS also requires data related to the dynamic features of the model, i.e. behavioural parameters for departure time choice and some parameters for the day-to-day adjustment process (De Palma & Marchal, 2002).
3.2. SILVESTER

The implementation of SILVESTER is made around an existing route choice model called CONTRAM, for which a Stockholm network already exists. The CONTRAM network has been used for a long time in Stockholm. Also a time sliced origin-destination matrix which was calibrated against local traffic counts and travel times was available for use in CONTRAM. On the demand side, an earlier developed departure time and mode choice model of mixed logit type is used. The data preparation and Calibration for SILVESTER model was done in another project which was completed before starting this project. The interested readers may see the report of Kristoffersson & Engelson, (2009) and Kristoffersson & Engelson, (2008) for detail information. A brief idea about SILVESTER modelling process can be visible from SILVESTER data flow diagram as shown in Figure 3.

![SILVESTER data flow](image)

Figure 3: SILVESTER data flow
Source: (Kristoffersson & Engelson, 2008)

3.2.1. Differences Compared to METROPOLIS

A major concern of this study is comparison of the two dynamic simulators. We want to investigate differences in forecasts when using different dynamic simulators. The two simulators use different assumptions, also different calibration procedure was followed for each of them. But, both were calibrated for the same network and we have tried our best to make sure that the input parameters are the same. But we could not keep everything similar mostly because of different model assumptions and time constraint. Some important differences for the two simulators are described below:

**The network**

SILVESTER use a quasi-dynamic model called CONTRAM for which Stockholm network already exists. CONTRAM uses a detail network of Stockholm where every intersection has been designed separately i.e. every turning percentage and capacity, banned turn, signal plan etc. are described in the model. Here each links are assigned as single lane. One road section can have several links depending on the number of lanes available in reality.

Capacity of each link is the only governing factor to circulate flow in METROPOLIS. One link can contain several lanes going the same direction. It is not possible to assign more than one link between the same start and end of a road section. In this study METROPOLIS used the network from
CONTRAM, therefore, to be consistent with METROPOLIS specification, all the links between the same start and end were merged together before uploading the network in METROPOLIS.

**Route choice model**

In CONTRAM vehicles are combined into packets. A packet consists of demand with the same origin and destination, which belongs to the same user class and starts in the same time period. Each packet follows its minimum cost route in each iteration, and provides information about the current network as it experiences it. Minimum cost routes are found using a time-dependent link-based all-or-nothing tree-building method (Whiting & Hillier, 1960). Packet re-assignment consists of first deducting the packet’s flow from the network, and updating the network state, then finding its new route, loading it onto this and updating the network again (Taylor, 2003).

METROPOLIS uses a model of route choice based on point-to-point dynamic travel times. The user selects the dynamic shortest path from the origin node to the destination node based on instantaneous travel time (travel time experienced by the user so far) and historical travel time (which will give an indication about the situation of different alternative paths experienced by previous users). The detail of this process is described in section 3.1.1 under the title “Route choice and direction choice”.

**Preferred time of travel**

Travellers want to reach their destination in a safe, fast and cheap way. Long or uncertain travel times are likely to affect their choice of departure time and even decision to travel. Moreover time varying congestion charge also affects departure time and mode choice. From their day to day experience some may intentionally choose to travel earlier or later to avoid unnecessary travel time and cost. 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.

In De Palma and Lindsey (2001), the authors discover that keeping everything identical and with sufficient heterogeneity in preferred travel times, in a Vickery’s bottleneck model (Vickrey, 1969) the evening model (scheduling preferences are defined in terms of departure time from work) shows lower congestion than the morning model (scheduling preferences are defined in terms of arrival time at work). Naturally the differences persist between morning and evening travel cost. Another important finding is that, many individuals may depart on time in the evening, while no one departs early.

In an uncongested situation there is no difference defining scheduling costs around a preferred departure time (PDT) or preferred arrival time (PAT), since a shift from PDT then corresponds to similar shift from PAT. Kristoffersson and Engelson, (2008) argue that scheduling costs should be defined at the end where the user has the most critical constraint. Since data underlying the SILVESTER estimations showed important constraints at both ends this did not give any further advice. Travellers can however control departure time but not arrival time, so PDT was chosen in the SILVESTER model.

The focus of this study is to simulate the morning peak. According to De Palma & Lindsey (2001), morning model should use scheduling preferences as arrival time at work i.e. preferred arrival time (PAT). Based on simulation result and discussion of the paper by De Palma & Lindsey (2001), the morning model is used for simulation in METROPOLIS.
3.2.2. Mixed logit estimation for SILVESTER

The original departure time choice model is a mixed logit model estimated in 2005 on stated and revealed preferences data from car users in Stockholm, taking into account also that car users face an uncertain travel time (Börjesson, 2008). Mode choice is considered partially, by modelling the propensity to switch from driving. The model does not, however, take into account that public transport travellers may switch to driving.

In the stated choice experiment the respondent $n$ faces a sequence of $k$ choices. Each choice $k$ includes three alternatives: two car alternatives ($i = 1$ and 2), with different departure times, arrival time intervals and monetary costs, and one public transport (mode shift) alternative (PT). There were also bike, walk and cancelling the trip alternatives but they were not included in the estimation because too few respondents chose them. The indirect utility functions of these alternatives are defined as

$$U_{\text{car}1nk} = \beta_{1} \text{COST}_{1nk} + \beta_{2} \text{SDE}_{1nk} + \beta_{3} \text{SDL}_{1nk} + b_{1} \text{TIME}_{1nk} + b_{2} \text{TTV}_{1nk} + \epsilon_{1nk}$$

$$U_{\text{car}2nk} = \beta_{1} \text{COST}_{2nk} + \beta_{2} \text{SDE}_{2nk} + \beta_{3} \text{SDL}_{2nk} + b_{1} \text{TIME}_{2nk} + b_{2} \text{TTV}_{2nk} + \epsilon_{2nk}$$

$$U_{\text{PT}nk} = C_{\text{PT}} + b_{3} \text{TIME}_{\text{PT}} + b_{4} \text{SeasonTicket}_{n} + \eta_{n} + \epsilon_{\text{PT}nk}$$

$$\text{SDE}_{ink} = \max(PDT_{n} - DT_{ink}, 0)$$

$$\text{SDL}_{ink} = \max(DT_{ink} - PDT_{n}, 0)$$

In the above equation, $\text{COST}$ is the monetary cost of the trip. $\text{SDE}$ and $\text{SDL}$ stands for Schedule delay early and Schedule delay late respectively. $\text{TIME}$ is the mean travel time and $\text{TTV}$ represents travel time variability. $C_{\text{PT}}$ is a public transport constant and $\text{TIME}_{\text{PT}}$ is the public transport travel time. It is assumed that public transport travel times are independent from departure time, within the extended morning peak. $\text{SeasonTicket}$ is a dummy variable indicating if the respondents have season ticket, and thus zero marginal cost, for public transport. $\eta$ is a normally distributed error component with zero mean. This element induces a larger variance in the error difference between the car and public transport alternatives relative to the error difference between the two car alternatives. This is equivalent to specifying a separate nest for each of the two modes in a nested logit frame work. $PDT$ is preferred departure time and $DT$ is actual departure time.

Parameters labelled $\beta$ are randomly distributed in the population according to the Johnson SB distribution. The estimated parameters could not be used for METROPOLIS due to the fact that it does not support mixed logit formulation. Nested logit re-estimation was performed in estimating behavioural parameters for METROPOLIS (described in Section 4.4). The results of the mixed logit estimation are not presented in this thesis. The interested readers are encouraged to see the paper by Kristoffersson (2011) for more details of the mixed logit estimation and results for SILVESTER.
4. **CASE STUDY OF STOCKHOLM**

4.1. **Description of the Study Area and Charging Scheme**

Stockholm is the capital and the largest city of Sweden. It is also the most populated urban area in Scandinavia\(^2\). It is located in the middle of Scandinavia. At present Stockholm county has a population of about 2 million inhabitants\(^3\) (March 31, 2011) and 3 millions live within a daily commuting distance. The city of Stockholm is extremely mono-centric (Armelius & Hultkrantz, 2006). Within the inner city there is a compact central business district with numerous workplaces within one kilometre walking distance from the central railway station. Downtown Stockholm has suffered from traffic congestion for years. A large fraction of the morning rush hour traffic is directed to the central areas and is concentrated on a few main roads from the south and the north. A map of our study is presented in the following Figure 4.

![Figure 4: Stockholm divided into inner-city (I), northern suburbs (N+L) and Southern suburbs (S)](image)

A time-dependent congestion charging system has been made permanent in Stockholm from August 1, 2007. Before that a full-scale road pricing seven months trial was performed in 2006. The charging system is implemented as a cordon around the city. The cordon is approximately a circle with radius three kilometres and 280,000 people live inside the cordon. Stockholm is situated on islands with water in-between, which makes it convenient to install most tolling stations on bridges that connect the inner city of Stockholm with the suburbs, resulting in a toll ring build up by only 18 tolling stations.

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\(^2\)Scandinavia is a cultural, historical and ethno-linguistic region in northern Europe that includes the three kingdoms of Denmark, Norway and Sweden, as well as Iceland.

\(^3\)As mentioned in the website of Stockholm Municipality (www.stockholm.se)
as shown in Figure 5. In this figure one toll location corresponds to several tolling stations in some cases. The red x-marks represent toll locations and the green line shows the motorway “Essingeleden” which is currently free of charge. The location of the toll gates, the toll timetable and the toll levels are the same now as they were during the trial.

Figure 5: The toll ring in the Stockholm CONTRAM simulation network. 
Source: (Kristoffersson, 2011)

The aim of Stockholm congestion charging system was to reduce road traffic to and from the city centre by about 15 percent during the peak periods, partially by peak spreading (Stockholmsförsöket (Stockholm trial), 2006). A step toll has been introduced which was charged from 6:30 in the morning to 6:30 at evening, with a minimum of 10SEK during off-peak periods and a maximum of 20 SEK during peak-period. The charge scheme is shown in Table 1. The same map and charging scheme has also been implemented for METROPOLIS model.

<table>
<thead>
<tr>
<th>Time</th>
<th>Congestion charge (SEK⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td>06:30–06:59</td>
<td>10</td>
</tr>
<tr>
<td>07:00–07:29</td>
<td>15</td>
</tr>
<tr>
<td>07:30–08:29</td>
<td>20</td>
</tr>
<tr>
<td>08:30–08:59</td>
<td>15</td>
</tr>
<tr>
<td>09:00–15:29</td>
<td>10</td>
</tr>
<tr>
<td>15:30–15:59</td>
<td>15</td>
</tr>
<tr>
<td>16:00–17:29</td>
<td>20</td>
</tr>
<tr>
<td>17:30–17:59</td>
<td>15</td>
</tr>
<tr>
<td>18:00–18:29</td>
<td>10</td>
</tr>
<tr>
<td>18:30–06:29</td>
<td>0</td>
</tr>
</tbody>
</table>

⁴ 1 SEK is equivalent to 0.109 Euro
4.2. Supply Data

SILVESTER uses CONTRAM (Taylor, 2003) as assignment model. The Stockholm network (see Figure 6) coded in CONTRAM has been transferred into METROPOLIS, including links with location, number of lanes, free-flow speed and capacities. Capacities are taken from the base scenario in SILVESTER, i.e. before charging, and thus include effects of traffic signals, conflicting flows at intersections and blocking back of upstream links. The final network which has been uploaded in METROPOLIS consists of 315 zones which can also be described as trip origin or destination, 2232 nodes and 5366 links.

![Figure 6: Stockholm network in CONTRAM](image)

4.3. Demand Data

A time-sliced (15 minute) origin-destination demand matrix (OD-matrix) for car travel between 6:30 a.m. and 9:30 a.m. for situation before the charges exists for the Stockholm network in CONTRAM. SILVESTER has been calibrated such that it reproduces this car demand matrix using a reverse engineering approach (Kristoffersson & Engelson, 2008). The reverse engineering approach estimates demand for travel in each time-slice in a hypothetical uncongested situation, i.e. demand in so called preferred departure time (PDT) intervals.

4.3.1. Demand distribution

Demand is, both in SILVESTER and METROPOLIS, divided on three trip purposes: (1) work trips with fixed working hours and school trips (short: fixed), (2) business trips (short: business) and (3) work trips with flexible working hours and other trips including leisure and shopping trips (short: flexible). Furthermore, demand is segmented by the region in which the trip starts: inner city (I), northern suburbs (N+L) or southern suburbs (S) (see Figure 4). A total of nine demand matrices have been
produced where each of them has different distribution based on their preferred arrival time (PAT). But each of these nine demands has unique distribution which is tough to describe with one single standard distribution (e.g. logarithmic, exponential, etc.) as required by METROPOLIS. Therefore, each of these nine demand matrices has been sub-divided to 4-5 separate matrices with simplified uniform distribution depending on the variation in original distribution. An example of simplified uniform demand distribution is shown in Figure 7.

4.3.2. Bucket rounding

In CONTRAM demand is allowed to be input as fractions of vehicles, such as 0.01veh/h. In fact, the Stockholm demand matrix for CONTRAM consists of a large number of origin-destination pairs with very little demand. Aggregation of demand has in the Stockholm case the tendency to reduce congestion (Kristoffersson & Engelson 2009), but this effect can be remedied with an appropriate choice of aggregation method. METROPOLIS requires aggregation of demand, since demand cannot be input as fractions. SILVESTER demand has been aggregated using bucket rounding, which goes through the list of OD-pairs, rounding the demand of an OD-pair and adjusting the next OD-pair accordingly to preserve overall demand. The bucket rounding algorithm is presented in the form of a flow chart in Figure 8 below:

Figure 7: Simplified uniform distribution of demand

![Figure 7: Simplified uniform distribution of demand](image)

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Figure 8: Bucket Rounding Flow-chart

![Figure 8: Bucket Rounding Flow-chart](image)
4.4. Nested logit re-estimation for METROPOLIS

For implementation in METROPOLIS the departure time choice and mode switch model described in section 3.2.2 was re-estimated without the travel time variability component and as a nested logit model instead of a mixed logit model. The re-estimation is done using BIOGEME (Bierlaire, 2009), which was also used in the mixed logit estimation. The dummy for a public transport season ticket is removed, since it does not fit the specification of METROPOLIS. Finally, to match the specification of the morning model in METROPOLIS, schedule delays are now defined around PAT instead of PDT.

Since the morning model in METROPOLIS calculates scheduling costs at the destination i.e. Preferred Arrival Time (PAT), the PDT demand from SILVESTER has been translated into desired demand for arriving in each time slice using the PDT demand and free-flow travel times from CONTRAM. All departure time intervals for car are kept in one nest and the public transport alternative in another nest, to account for the similarities between car alternatives. Nest parameters are set to be equal for the two nests. The utility functions in the nested logit models\(^5\) are thus defined as

\[ U_{\text{car1nk}} = b_1 \text{COST}_{1nk} + b_2 \text{SDE}_{1nk} + b_3 \text{SDL}_{1nk} + b_4 \text{TIME}_{1nk} + \epsilon_{1nk} \]

\[ U_{\text{car2nk}} = b_1 \text{COST}_{2nk} + b_2 \text{SDE}_{2nk} + b_3 \text{SDL}_{2nk} + b_4 \text{TIME}_{2nk} + \epsilon_{2nk} \]

\[ U_{\text{PTnk}} = C_P + b_5 \text{TIME}_{\text{PT}} + \epsilon_{\text{PTnk}} \]

\[ \text{SDE}_{nk} = \max(PDT_n - DT_{nk}, 0) \]

\[ \text{SDL}_{nk} = \max(DT_{nk} - PDT_n, 0) \]

In the above equation, \( \text{COST} \) is the monetary cost of the trip. \( \text{SDE} \) and \( \text{SDL} \) stands for Schedule delay early and Schedule delay late respectively. \( \text{TIME} \) is the mean travel. \( C_P \) is a public transport constant and \( \text{TIME}_{\text{PT}} \) is the public transport travel time. \( \text{PDT} \) is preferred departure time and \( DT \) is actual departure time. The parameters of the nested logit model can be found for each trip purpose in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Flexible</th>
<th>Fixed</th>
<th>Business</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_1 )</td>
<td>-0.0372</td>
<td>-0.0145</td>
<td>-0.0262</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>-0.0200</td>
<td>-0.0152</td>
<td>-0.0339</td>
</tr>
<tr>
<td>( b_3 )</td>
<td>-0.0190</td>
<td>-0.0189</td>
<td>-0.0428</td>
</tr>
<tr>
<td>( b_4 )</td>
<td>-0.0494</td>
<td>-0.0124</td>
<td>-0.0688</td>
</tr>
<tr>
<td>( b_5 )</td>
<td>-0.0687</td>
<td>-0.0465</td>
<td>N.A.</td>
</tr>
<tr>
<td>( C_P )</td>
<td>-4.9416</td>
<td>-1.6404</td>
<td>N.A.</td>
</tr>
<tr>
<td>Nest parameter</td>
<td>3.98</td>
<td>4.77</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

Converting this to the METROPOLIS model formulation (METROPOLIS 1.5 manual, 2002) we get the behavioural parameters in Table 3.

\(^5\) For business, the estimated model is a multinomial logit model because very few respondents switched to public transport for this trip purpose and there PT alternative is omitted for business.
### Table 3: Parameter values of the nested logit models with METROPOLIS specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Flexible</th>
<th>Fixed</th>
<th>Business</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$(b_4/b_1)*60$</td>
<td>80</td>
<td>51</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$(b_2/b_1)*60$</td>
<td>32</td>
<td>63</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$(b_3/b_1)*60$</td>
<td>31</td>
<td>78</td>
</tr>
<tr>
<td>$\mu_t$</td>
<td>$(1/b_1)*60$</td>
<td>27</td>
<td>69</td>
</tr>
<tr>
<td>$\alpha_p$</td>
<td>$(b_5/b_1)*60$</td>
<td>111</td>
<td>193</td>
</tr>
<tr>
<td>$C_p$</td>
<td>$(C_{pt}/b_1)*60$</td>
<td>133</td>
<td>113</td>
</tr>
<tr>
<td>$\mu_m$</td>
<td>-Nest parameter/b_2</td>
<td>107</td>
<td>330</td>
</tr>
</tbody>
</table>

#### 4.5. Calibration of the Stockholm Network in METROPOLIS

When calibrating METROPOLIS to a city, the usual procedure is to use data from existing static models for that city (De Palma & Marchal, 2002). The situation is however somewhat different in our case. SILVESTER – a quasi-dynamic model for Stockholm – is already available, since the objective of the research is to compare two mesoscopic dynamic models. Data from SILVESTER could thus be used when calibrating METROPOLIS to Stockholm.

The first simulation was performed with all estimated parameters and without toll and mode choice. When we compare preferred arrival time (PAT) and actual arrival time, in a same graph as shown in Figure 9, we observe that actual arrival time is widely distributed over the time period of 8 hours (5:00 AM to 1:00 PM) whereas the PAT was only for 3.5 hours (6:30 AM to 10:00 AM). About 15% users are outside the PAT band. It indicates that a lot of people are arriving earlier or later than their scheduled arrival time. One of the reasons can be that, outside the PAT band there would be low volume of traffic and low congestion which would result in shorter travel times and lower travel costs. To overcome this problem the schedule delay penalty (early and late) has been calibrated to have more users arriving on time. In Table 4 and Figure 10 the result of different SDE and SDL parameters are shown.

---

**Figure 9:** Distribution of PAT and Actual arrival time for estimated delay penalty (SDE &SDL)

---

6The demand matrices in METROPOLIS simulation were only for 3.5 hours (6:30-10:00), therefore outside this time period there will only be users who tend to arrive early or late than their PAT.
Table 4: Vehicle arrival percentage between 6:30-10:00 AM

<table>
<thead>
<tr>
<th>Percentage of Vehicle arrived inside 6:30 AM to 10:00 AM</th>
<th>Estimated SDE &amp; SDL</th>
<th>2 times SDE &amp; SDL</th>
<th>2,5 times SDE &amp; SDL</th>
<th>2,75 times SDE &amp; SDL</th>
</tr>
</thead>
<tbody>
<tr>
<td>85,48%</td>
<td>94,56%</td>
<td><strong>96,09%</strong></td>
<td>97,82%</td>
<td></td>
</tr>
</tbody>
</table>

Observing the results for different SDE and SDL parameter from Figure 10, a value of 2.5 times estimated SDE and SDL have been selected. With this value about 96% users arrive inside the PAT band (6:30 – 10:00). The new $\beta$ and $\gamma$ parameters are given in Table 5.

Table 5: New schedule delay parameters adjusted in calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Flexible</th>
<th>Fixed</th>
<th>Business</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>80</td>
<td>51</td>
<td>158</td>
</tr>
<tr>
<td>$\beta$ (SDE)</td>
<td>75</td>
<td>158</td>
<td>195</td>
</tr>
<tr>
<td>$\gamma$ (SDL)</td>
<td>80</td>
<td>195</td>
<td>245</td>
</tr>
</tbody>
</table>

Figure 10: Arrival time distribution for different values of SDE and SDL

In the next step of calibration, mode choice has been introduced to the model. The first run with mode choice showed that around 27.6% of users choose public transport (PT). But no verified data are available to calibrate the PT share directly from field result, because the original model was estimated for mode switch from car ignoring switchers to car from PT. The only available data that could help is the number of cars recorded in some links before and after introduction of congestion charging. It should be mentioned here that traffic flow has been recorded for 59 links in various important places all through the Stockholm network. They are named as 'validation links' for the rest of this report. Their positions are located in Figure 11.
The demand matrix in METROPOLIS was taken from the SILVERSTER network which was based on the data from car users only. The PT share was only 1.6% in the situation without toll in SILVERSTER model, and the demand matrices were raised to compensate for this loss of car drivers. Whereas the first run with METROPOLIS showed 27.6% PT share. Therefore current METROPOLIS network will experience lower car flow than SILVERSTER and also compared to field measurements, because of the high PT share. A major part of the calibration process will cover the adjustment of car flow to match the real situation in the field. Basically we have to increase car flow. We can increase the flow either by increasing the population or by modifying the public transport parameters.

We have measurement of car flow before and after introducing congestion charge for all the validation links. We took the advantage of using these data for calibration. Hence, the change in car flow after implementation of congestion charge was also considered during calibration. It is time consuming to observe the effect of one parameter at a time. For example we have to increase population to have correct car flow, change PT parameter to have correct change in PT share after implementing congestion charge, etc. Hence the population and PT constant (which may also be named as PT fare) have been modified at the same time. An approximate mathematical formula was established to change these two parameters together, based on the result of current simulation and the target value. The whole calibration procedure is described by a flow chart as shown in Figure 12.
When simulated flow matches with observed field flow, both before and after the charges; the network was set for travel time check. In this step the travel time for some routes or part of different routes were compared to field observations. The simulated travel times in most of the sections were reasonably closer to the collected field data. Therefore, calibration process was terminated at this point. The results of calibration are presented in next section.
5. RESULTS

5.1. Validation of METROPOLIS Simulation

After calibration METROPOLIS has successfully reproduced almost similar situation as observed in the field for most of the validation links (Figure 11) in both the situations with and without charging for Stockholm network. Two scatter plots have been formed (Figure 13) to show the relation among field observation and simulation flow for all 59 validation links. The scatter plots suggest that the simulated flow through these links are highly correlated with field flow (R² value of 0.957 and 0.921 for the simulation without charging and with charging respectively, suggest high correlation). Also the trend line equation for both the simulation cases suggests that the simulation flows are very close to the observed field flow.

![Figure 13: Observed Flow Vs Simulated Flow before and after congestion charging](image)

The above scatter plots show the total flow between 6:30-9:30. During the calibration process in METROPOLIS only the total flow was raised to match the field flow and it was done by increasing the whole population with a factor so that it would not affect the original distribution of flow.
Simulation flow has been recorded for all links in every 15 minutes interval as it was done for the field data. One thing we should keep in mind is that, demand data for simulation was for 3.5 hours (from 6:30AM to 10:00 AM), but we have the field observation for only 6:30-9:30 period. During the simulation period (5:00 AM to 11:00 AM), users arrive to their destination according to their PAT distribution, and some people arrive early or late to minimize travel cost. Because outside the band of 6:30-9:30, there will be less or no congestion due to the fact that, no demand has been assigned on that time. So the only traffic outside 6:30-9:30 band is due to those who changed their journey time and started either very early or late. We also checked the situation with some added demand before and after 6:30-10:00AM period, but it had negligible effect to the flow distribution. Hence, no extra demand was used. Figure 14 below shows the distribution of flow for all validation links for the entire simulation period. In this figure the field flows are also presented to observe the difference in their distribution against simulation flow.

![Figure 14: Distribution of flow for all validation links](image)

The figure shows that, simulation flows are almost at the same level as the field flow, but the distribution does not match exactly the field flow distribution for both the situations with and without charging. There may be several reasons behind that. It was mentioned in Section 4.3.2 that SILVESTER demand has been aggregated using bucket rounding, which goes through the list of OD-pairs, rounding the demand of an OD-pair and adjusting the next OD-pair accordingly to preserve overall demand. Although this procedure gives integer demand matrices for METROPOLIS, but it modifies the original demand matrices to some extent and it may affect the flow pattern in the simulation. METROPOLIS took the network from CONTRAM where all the link capacities were modified to reflect real situation i.e. capacity adjustment for calibration of CONTRAM. As the demand has been re-arranged, capacity constrain may change the flow pattern.
To understand the decrease in car flow due to charging, 37 of the validation links are selected where flow has been recorded both before and after introduction of congestion charging. These 37 links are positioned around the inner-city like a circle. They are specially named as ‘cordon links’. Field observation shows that car flow decreases by about 18% on the cordon links mainly due to congestion charging. Simulation should show a similar effect. At the end of calibration 15.1% decrease in car flow has been observed on the cordon links from simulation.

Despite of all the shortcomings in the network, simulation results that are presented above, suggest that the calibrated network has succeeded to represent the real situation well. An overview of the calibrated network performance is presented in Table 6 below:

<table>
<thead>
<tr>
<th>Table 6: Network performance after calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation without congestion charge</td>
</tr>
<tr>
<td>Num. of users</td>
</tr>
<tr>
<td>Num. of vehicles</td>
</tr>
<tr>
<td>Travel time (min)</td>
</tr>
<tr>
<td>Travel cost (SEK)</td>
</tr>
<tr>
<td>Schedule delay cost (SEK)</td>
</tr>
<tr>
<td>Free flow cost (SEK)</td>
</tr>
<tr>
<td>Collected revenues (SEK)</td>
</tr>
<tr>
<td>Period (h)</td>
</tr>
<tr>
<td>Congestion (%)</td>
</tr>
<tr>
<td>Mileage (10^6 km)</td>
</tr>
<tr>
<td>Speed (km/h)</td>
</tr>
</tbody>
</table>

A rough calculation of yearly revenue collection from METROPOLIS result is presented below:

Revenue collected per day during morning peak = 1.23 MSEK\(^9\)
Revenue collected per day = 1.23 * 2.5\(^{10}\)MSEK
Working days per year = 230 days
Revenue collected per year = 1.23*2.5*230
= 707 MSEK

The final report of Stockholm Trial (Stockholmsförsöket (Stockholm trial), 2006) published by Stockholm Municipality shows that road-users pay around 760 million Swedish kroner per year.

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\(^7\)Period is defined as the period between the time by which 10% of the users have reached their destination and the time by which 90% of the users have reached their destination

\(^8\)Congestion (C) is defined as the ratio of the actual travel time (TT) to the free-flow travel time (TT\(_0\)): \(C = (TT - TT_0)/TT_0\).

\(^9\)M SEK stands for million Swedish kroner.

\(^{10}\)A multiplication factor 2.5 has been used to convert the morning revenue collection to whole day.
**Travel times**

Field travel time has been recorded in 100 sections. But eleven of them were selected to validate travel time. The positions of these sections are shown in **Figure 15**. From simulation result the total travel time of these eleven sections before introducing congestion charging was found to be 65 min but after the charge it reduces to 58.5 min. A 10.1% reduction in total travel time was observed from simulation, the actual reduction in travel time from filed was found to be 13.4%. METROPOLIS thus underestimates travel time reduction somewhat. To understand the correlation among the simulated and field travel time in each of the eleven sections, two scatter plots have been made and are presented in **Figure 16**.

![Figure 15: Position of sections for recording travel time](Courtesy: Ida Kristoffersson)

![Field Vs Simulated travel time (without charging)](y = 0.978x + 0.51 \quad R^2 = 0.521)

![Field Vs Simulated travel time (with charging)](y = 1.099x + 0.06 \quad R^2 = 0.588)

**Figure 16: Field Vs Simulated travel time in 11 sections with (left) and without (right) charging**
Both the scatter plots in Figure 16 suggest that the simulated data do not perfectly matches with the field data. A close observation may reveal that only 2 or 3 sections out of 11 sections shows large deviation from field travel time, other values are very close to the actual observation. The scatter plot after the charge gives better correlation than the one before charging.

5.2. Comparison with Results of SILVESTER

5.2.1. Aggregate network results

A comparison of SILVESTER and METROPOLIS aggregate results for both with and without congestion charging are presented in Table 7. Aggregate results are total or average values for 6.30 - 9.30 am.

<table>
<thead>
<tr>
<th></th>
<th>Simulation without congestion charge</th>
<th>Simulation with congestion charge</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SILVESTER</td>
<td>METROPOLIS</td>
<td>SILVESTER</td>
</tr>
<tr>
<td>Num. of trips</td>
<td>281758</td>
<td>473426</td>
<td>281758</td>
</tr>
<tr>
<td>Num. of cars</td>
<td>277370</td>
<td>271382</td>
<td>266598</td>
</tr>
<tr>
<td>Flow over cordon (veh/h)</td>
<td>36042</td>
<td>35560</td>
<td>29067</td>
</tr>
<tr>
<td>Mean OD Travel time (min)</td>
<td>19.6</td>
<td>25.9</td>
<td>18.4</td>
</tr>
<tr>
<td>Congestion %</td>
<td>42</td>
<td>57</td>
<td>36</td>
</tr>
<tr>
<td>Mileage (10^6veh-km)</td>
<td>3.7</td>
<td>4.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Speed (km/h)</td>
<td>39.1</td>
<td>37.2</td>
<td>40.9</td>
</tr>
</tbody>
</table>

From Table 7 we see that both models show almost similar improvement after introducing congestion charging in the model. For the same network and for same car demand METROPOLIS shows higher congestion. METROPOLIS uses scheduling preferences in terms of preferred arrival at work, whereas SILVESTER uses preferred departure time. The observed higher congestion in METROPOLIS can be explained from the finding of De Palma & Lindsey, (2001) i.e. the morning model may show higher congestion than the evening model.

Another observation is that for about 1.2 km/h speed difference between SILVESTER and METROPOLIS (with charging scenario) congestion difference is about 12%. It seems confusing but it should be noted that speed is measured for entire journeys while congestion is measured on a link basis. For example, if two models shows exactly same O-D travel time performances but the actual queues are placed in different locations on the network, we would obtain same speed for the two models but the congestion index could be different for each of them. But the most important finding is that both models predict similar reduction of congestion due to charging.
Although number of car users decreased due to charging, vehicle-kilometres travelled remains the same for METROPOLIS, while it reduced significantly for SILVESTER. It gives an indication that some drivers may have adjusted their routes due to congestion charging in METROPOLIS case.

SILVESTER model showed only 1.6% Public transport (PT) users for without charging situation. The model was based on data from car users only; public transport share was not the concern. But PT mode was introduced in the model to enable mode switching possibility due to charging. METROPOLIS takes PT share during modelling, therefore, behavioural parameters for PT should be correct for perfect modelling. The PT parameters in this model were modified from their original estimation. Finally the model showed about 57% share of car alternative. A travel habit survey report (ResvanorìStockholmslän 2004, Trivector report 2005:25) finds that 33% of commuters to and from the present charging zone currently use car. 58% use public transport and the remaining 9% use other modes (Armelius & Hultkrantz, 2006).

Based on the survey result it is true that the model overestimated the actual share of car users. The estimated parameter for mode choice was based on survey results of car travel data only. We have calibrated the PT constant (decreased the value) to make PT more attractive, and in the process we have succeeded to decrease car share from 71% (base situation with estimated parameters) to 57%. Instead of car share, more important parameter for this study was the change of car share after introducing toll. The survey results showed that about 18% car flow has been reduced over the cordon links due to congestion charge. METROPOLIS model shows about 15.1% car flow reduction over the cordon links, whereas SILVESTER model showed about 19.4% reduction of car flows over the cordon.

5.2.2. Link Flow

Average traffic flow over 59 validation links from 6:30AM to 9:30 AM has been recorded for both METROPOLIS and SILVESTER model. Both the flows i.e. before and after the congestion charge has been recorded. These flows are plotted against observed field flow in a scatter plot and presented in the following two figures:

![Figure 17: Observed Vs Simulated flow without charge from SILVESTER (to the left) & from METROPOLIS (to the right)](image-url)
It is observed from Figure 17 and Figure 18 that both the models can represent the actual situation precisely with respect to vehicle flow on the validation links. In the above figures the total flow between 6:30-9:30 is shown. But we also need to check the distribution of flow to have a better idea about calibration and these are presented in the next section.

5.2.3. Distribution of flow

The distribution of flow obtained from simulation result of METROPOLIS and SILVESTER along with the field observation has been plotted in Figure 19 and Figure 20. In these figures the total flow for all the 59 validation links has been calculated for each 15 minutes period from 6:30AM – 9:30 AM.
It is observed from the above two figures that SILVESTER represents the flow distribution closer to the field distribution than METROPOLIS for both the cases with and without congestion charging. It should be noted here that demand matrix in SILVESTER was basically produced from PDT matrix. The process would be clear from SILVESTER data flow diagram as shown in Figure 3.

Moreover this PDT matrix was estimated using reverse-engineering process with the help of a departure time model and actual departure time (ADT). The base year O-D matrix which helped to form the PDT matrix was taken from a regional static model for Stockholm, which is a part of the SAMPERS system (Algers & Beser, 2002). It was initially an O-D matrix of the peak hour between 7:00AM-8:00AM. Due to the quasi-dynamic nature of SILVESTER, the matrix was divided to 15 min intervals and extended to 6:30AM-9:30AM. This new O-D matrix was then calibrated against spring 2005 traffic counts i.e. traffic flow in the situation without charging.

Since SILVESTER was used in reverse-engineering process; estimated PDT matrices are influenced by the behavioural parameters used in SILVESTER. Therefore, it is likely that calibrated model of SILVESTER based on this PDT should give similar flow distribution as observed in the field.

METROPOLIS does not take 15 min demand segments, rather it takes the total demand for each O-D pair and creates the demand based on PAT and traffic condition. Each day the departure time is modified to match the traffic condition observed from previous days and arrive on time. Moreover the travellers’ behavioural parameters are changed from the SILVESTER estimation as described in section 4.4. Also bucket rounding of the demand matrices changed the original demand distribution among the different O-D pairs. Since the PAT used in METROPOLIS has been created from the same PDT used for SILVESTER, the distribution of flow should be at least similar to SILVESTER. But flow distribution is largely affected by the behavioural parameters which help to decide when to travel and the O-D demand. Both these elements are changed in METROPOLIS which may be a reason behind the difference in flow distribution compared to SILVESTER and to the field measurements. We could change the PAT to make the distribution similar to the field but due to time constraint we had
5.2.4. Travel times

Travel time is a good indication of model performance. Travel times on 11 different sections of road are calculated for both SILVESTER and METROPOLIS model and are compared with field travel time on those sections. These sections are showed in the Figure 15. The travel time on those links are collected for both before and after congestion charge and presented in Table 8 below:

<table>
<thead>
<tr>
<th></th>
<th>FIELD</th>
<th>SILVESTER</th>
<th>METROPOLIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travel time on 11 stretches without charging (min)</td>
<td>60.73</td>
<td>59</td>
<td>65</td>
</tr>
<tr>
<td>Total travel time on 11 stretches with charging (min)</td>
<td>52.58</td>
<td>55</td>
<td>58.46</td>
</tr>
<tr>
<td>Change %</td>
<td>13.4</td>
<td>6.8</td>
<td>10.1</td>
</tr>
</tbody>
</table>

The travel time in 11 different sections are summed up in Table 8. The percentage change in travel time indicated that SILVESTER underestimate travel time reduction due to congestion charging while METROPOLIS shows travel time reduction closer to the reality. Higher travel time is observed in METROPOLIS which can be explained from the fact that the congestion is higher in this model than SILVESTER. Travel times in SILVESTER are closer to field values which may also be an indication that congestion percentage shown by this model represents the real situation. But without further information no conclusion should be drawn based on only aggregate data. Scatter plot may give some more information about correlation of travel time between observed and simulated. The scatter plots are shown in the following four plots, where simulated travel times in each of the eleven sections are plotted against actual field observation.

Figure 21: Field Vs Simulated travel time without charging for SILVESTER (to the left) and for METROPOLIS (to the right)
From the four scatter plots presented in Figure 21 & Figure 22 it is difficult to see which model gives better representation of reality. The $R^2$ value and the equation of the fitted line show that, METROPOLIS gives better result than SILVESTER for both the situations with or without charging. Out of 11 sections only 3 or 4 sections give large deviation from field result for METROPOLIS because of higher congestion in those roads others are close to the field. But SILVESTER result suggests that most of sections show small deviations from field.
6. Conclusion

This thesis deals with calibration of a dynamic network simulator METROPOLIS, for Stockholm road network. Later Stockholm congestion charging scheme has been analysed with this software. The calibration results suggest that METROPOLIS can simulate the real situation quite accurately; except that the flow distribution shows some deviation from field for both the cases with and without charging. In spite of that, the results give us good indication about the software’s capability in predicting the effects of congestion charging.

Comparison with SILVESTER result indicates that METROPOLIS shows higher congestion and this is also the reason behind longer travel times and lower speed. But more importantly both models showed similar changes after introducing congestion charging. Therefore, both of them could be useful in predicting the effects of congestion charging.

The scope of this study was to evaluate METROPOLIS for predicting the impact of congestion charging for Stockholm and compare the results with SILVESTER. Both models take into account route choice and departure time choice. The theoretical basis and structure of the two models are different which has been explained in different parts of this report. Despite all these differences, METROPOLIS gives similar prediction like SILVESTER, about the impacts of congestion charging in Stockholm. The results are in some cases even better than SILVESTER. Thus a conclusion could be made that dynamic models give good prediction about the effects of congestion charging.

From this study it is understood that, the important factors for modelling congestion charging could be the demand distribution for preferred time of travel, the route choice and the departure time choice, each with its own behavioural parameters.

7. Further Research

It is mentioned in the beginning that this research is a part of a European project named SILVERPOLIS which will review the transportation models used for predicting impacts of road user charging. The present work has focused only the modelling of Stockholm congestion charging in METROPOLIS and comparing the results with the existing model SILVESTER. In future, more detail study could be done on these two models to discover/analyse important properties of dynamic models for perfect prediction of congestion charging effect.

The distribution of flow has shown some deviation from the field. The calibration of preferred arrival time (which was out of scope of this thesis) could fix this problem. The continuation of this work will involve the calibration of PAT for perfect fit of flow distribution.

Some people were exempted from congestion charging in SILVESTER model, but it could not be done for METROPOLIS. Therefore, the effect of exemption will remain a question for future study.

Only morning peak period was simulated in both the models. It is unknown whether the models are capable to replicate a whole day flow fluctuations and to predict the congestion charging effect for that. It will take larger computation power and longer simulation time to run a whole day simulation. Hence this task is left for future research.
8. REFERENCES


