Stockholm congestion charging: an assessment with METROLIS and SILVESTER

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Abstract

This paper reviews and compares the performance of two dynamic transportation models METROPOLIS and SILVESTER that have been used to predict the impacts of congestion charging in European cities. These are mesoscopic dynamic models treating accumulation and dissipation of traffic queues, route choice, modal split, and departure time choice. We calibrated the models independently for the Stockholm baseline situation without charges and applied for modeling effects of congestion charging. The results obtained from the two models are mutually compared and validated against actual outcome of the Stockholm congestion charging scheme. Both models successfully represent result of the congestion charging trial on the aggregate level and provide significant improvement in realism over static models. Results of welfare analysis however differ substantially due to different model specification.

Keywords: Congestion charging, Transportation models, Dynamic assignment, Mesoscopic models, Departure time choice, METROPOLIS, SILVESTER.

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1. Introduction

There is a consensus that congestion charging in combination with other congestion mitigation measures is a proper instrument for reducing the adverse impacts of transportation on environment and improving citizens' quality of life. The interest towards design of effective congestion charging systems is growing in many countries and especially in large cities where congestion has become a burning issue. The transportation planning professionals agree that travel forecasts using a good quality regional transportation model is necessary for design of the charging system as well as for evaluation of a system in use.

There is a large scientific literature available on impacts of congestion charging (see, e.g. Pigou 1920; Vickrey 1969; Small 1983; Arnott, de Palma, and Lindsey 1993; Glazer and Niskanen 2000). The literature considering modeling of congestion charging for large networks is however more limited, e.g. Koh and Shepherd (2006). In practice, static assignment models integrated with travel demand models are often applied to forecast the impact in feasibility studies of congestion charging. This has been the case for example in Oslo (Odeck, Rekdal, and Hamre 2003), Stockholm (Eliasson and Mattsson 2006) and Copenhagen (Rich and Nielsen 2007; Nielsen, Daly, and Frederiksen 2002). It has however been agreed in the research community that the temporal aspects of congestion have a crucial role on system level. For example, the forecasts made with static models for Stockholm congestion charging system resulted in severe overestimation of impact on traffic flows during the peak hour and, at the same time, great underestimation of changes in travel times (Engelson and van Amelsfort 2011). Moreover, the most effective charges aim to redistribute trips in time in order to cut down the congestion peak. Therefore impact of time-varying charges on departure time choice is a crucial issue. A mesoscopic dynamic model (MDM) can capture the time-varying aspect of congestion and congestion charging. At the same time it is not as detailed as a microscopic model. A mesoscopic assignment model integrated with a travel demand model, including departure time modeling is therefore suitable for calibration of whole city networks and thus for modeling impacts of city-wide congestion charging schemes. For a recent survey of dynamic models incorporating time-dependent congestion and departure time decisions, we refer the reader to de Palma and Fosgerau (2011).

The impacts of congestion and road pricing in a fully dynamic model are complex and it is probably worthwhile to spend some time to explain it. Without congestion the drivers are assumed to select the shortest route in respect to the free flow travel time. However with congestion this route may not be optimal anymore, while a route with a longer free flow travel time may be better (faster). Typically, the dynamic shortest path depends on the time of the day. Consider time differentiated charges imposed for crossing a cordon around a CBD. Given origin and destination of the trip, the traveler may adjust the route in the first hand. A part of drivers having both origin and destination outside the cordon and using in the situation without charges a route that crossed the cordon twice will now avoid it by choosing a route around the cordon. This will reduce congestion on roads crossing the cordon in different grades. If the driver lives outside and works inside the cordon or vice versa there is no way to avoid paying the toll by just changing the route. However as a consequence of the above-mentioned changes in congestion levels her route choice may be affected. The choice of the dynamic shortest path in the presence of congestion and road user charges is a complex problem[5], which may have different solutions from two different models for the same case study due to different specifications. In practice, route choice can be represented by a deterministic or (more realistically) by a probabilistic model based on the random utility theory.

The second adjustment is the shift in departure time. The deterministic model of departure time choice is tricky. For any departure time, the travel cost is the weighted sum of travel time (calculated for the optimal route as discussed above), monetary cost and schedule delay, and there is no guarantee that the cost is a convex function of departure time. For example, if the travel time is quasi concave, the cost function may have several minima. This implies that the optimal departure time may change substantially when a toll (even small) is implemented. A probabilistic departure time choice mode produces more stable results. Note that in most applications, the travel cost is linear in travel time. However, this is not the case: travel cost, when estimated, are convex, and the convexity depends on the socio-economic characteristics (Picard, de Palma, and Dantan, 2013).

Finally, the mode choice decision is normally given by a probabilistic multinomial model. If both the route choice and the departure time choice are modeled by a logit approach the cost for the private transportation is a “double” logsum, since it integrates the departure time decisions as well as the route choice decisions. Mode choice is a key factor in the evaluation of road pricing, and care should be given to have a meaningful logsum formula[6].

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[5] de Palma et al. (1990) have shown that this problem is NP hard.

[6] A user may even change a destination of a discretionary trip or cancel it or, in a long term, change a work place or living place as a consequence of congestion charges. However these responses are not dealt with in the models considered in this paper.

It is not obvious which properties of the MDM that is most important for predicting impacts of congestion charging. The aim of this paper is therefore to compare the predictive capability of two MDMs in order to find properties important for correct prediction of impact of congestion charging. METROPOLIS (de Palma, Marchal, and Nesterov 1997) and SILVESTER (Kristoffersson and Engelson 2009) are two state-of-the-art MDMs developed in the last decade with specific focus on congestion charging applications. de Palma, Kilani, and Lindsey (2005) analyze different congestion charging schemes using METROPOLIS and a stylized urban road network. de Palma and Marchal (2001) apply METROPOLIS to Paris, and also give guidelines for model designers and planners who consider a shift to dynamic traffic simulation. Using METROPOLIS, de Palma and Lindsey (2006) assess phase implementation of charging in Paris. SILVESTER is applied to Stockholm in Kristoffersson (2013). Kristoffersson and Engelson (2011) use SILVESTER to evaluate efficiency and equity of alternative congestion charging schemes for Stockholm.

There are very few opportunities to validate transportation models by observing responses to charging. In Stockholm we have the unique possibility to use measurements from the field to validate transport models. Therefore both SILVESTER and METROPOLIS are in this paper calibrated to Stockholm conditions in the situation without charging. Model response to the charges are then compared both between the two transport models and to measurements; this in order to provide a benchmark for modeling of congestion charging and in order to find model properties that are important for correct prediction. A similar in-depth comparative study of transportation models suitable for predicting impacts of congestion charging has to our knowledge not been undertaken before. Given that METROPOLIS and SILVESTER share the same ambition to improve conventional static transportation modeling of impacts of congestion charging by using dynamic modeling, but approaches the task in different ways, there is a good opportunity to compare implications of different modeling strategies.

The structures of the two models are described in the next section, followed by a section on how these models have been estimated and calibrated for Stockholm conditions, on the bases line situation without congestion charging. Section 4 discusses the results as well as models comparison once the actual congestion charging has been implemented. .Section 5 concludes.

2. Model descriptions

2.1 METROPOLIS

METROPOLIS is a traffic planning model that uses event based dynamic simulation. It was developed in Geneva by André de Palma, Fabrice Marchal and Yurii Nesterov (de Palma, Marchal, and Nesterov 1997) and later on applied at the University of Cergy-Pontoise by de Palma and Marchal (de Palma and Marchal 2002). A preliminary version of this model, with toy networks, was initially developed by Ben-Akiva, de palm, and Kanaroglou (1986). Theses authors developed a first numerical implementation of a basic dynamic model, to a stochastic-discrete choice environment. METROPOLIS is based on a simple economic principle, explained originally in Vickrey (1969) and Arnott, de Palma and Lindsey (1993). This deterministic environment, was later–on extended by André de Palma, Yurii Nesterov, and Fabrice Marchal for large networks.

METROPOLIS describes the joint departure time and route choice, of drivers in a closed-loop setting. 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. On the supply side a congestion function describes the travel delays of the links. The traffic can be blocked at intersection, due to the presence of feedbacks. The demand is represented at microscopic level and each trip is modelled accordingly to its choices of mode, departure time and route of travel. The travelers are assumed to have a preferred arrival/departure time. The generalized cost of travel is calculated as a sum of the travel time cost and the early/late arrival penalty. The cost function is presented in Equation (1).

$$C(t) = \alpha . tt_c(t) + \beta . \left[\left(t^* - \Delta / 2 \right) - \left(t + tt_c(t) \right) \right]^+ + \gamma . \left[\left(t + tt_c(t) \right) - \left(t^* + \Delta / 2 \right) \right]^+ , \qquad (1)$$

[KI1]

where, $A^+ \equiv Max(0, A)$, C(t) is generalized cost for car user whose departure time is t from the origin, $tt_c(t)$ is travel time, α, β, γ are value of time, early and late arrival penalty respectively, t^* is the desired arrival time at destination and Δ is the flexible time period without penalty. The first term in the above equation represents the travel time cost; the second and third term represents early and late arrival penalty respectively. Typically, the user faces the following trade-off: either s/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. The departure time choice model for car is a continuous logit model, where the individual selects the departure time that minimizes the generalized cost function. The schedule delay parameters, have been estimated by many authors, of the basis of surveys (see, for example, Small, 1987, and de Palma and Rochat, 1999).

METROPOLIS uses a model of route choice that finds dynamic shortest path. The route choice decision is revised in each intersection based on the experience from the immediate link (connecting road between two intersections) and memorized information about rest of the network up to the destination. The approach is based on Bellman optimization principle, which guarantees optimization of the path chosen. It should also be noted that one day corresponds to one iteration in METROPOLIS. The approach used is based on a day-to-day learning process, where users acquire knowledge about their travel and use this information to modify their trip for the next day.

METROPOLIS features a two-stage nested logit model with a binary choice between auto and public transport in the outer nest, and a continuous choice of departure time for the auto mode in the inner nest so that trips are not allocated into pre-defined discrete time intervals such as peak and off-peak.

2.2 SILVESTER

SILVESTER is a traffic planning model which uses mesoscopic dynamic assignment. SILVESTER has been developed at KTH Royal Institute of Technology in Stockholm by Leonid Engelson and Ida Kristoffersson (Kristoffersson and Engelson 2009), continuing on work done by Maria Börjesson who estimated the demand model (Börjesson 2008).

The SILVESTER transport model extends the conventional four stage model by including departure time choice between short time periods of fifteen minutes and allowing shift in departure time which can lead to peak spreading. It also includes dynamic assignment which uses demand for each fifteen minute time period and is able to model both conflicting flows at intersections and blocking back of upstream links due to bottlenecks downstream. Furthermore, users are allowed to differ in their value of time and scheduling preferences not only between trip purposes, but also within trip purposes.

The modelling system consists of two main parts: a demand model and a supply model. The demand model calculates probabilities to start in each of the departure time periods or switch to public transport depending on travel costs, whereas the supply model calculates travel costs depending on departure time period. Public transport travel times (including waiting time etc.) are static and exogenous.

The demand model in SILVESTER is a mixed logit model (Börjesson 2008), which builds on the scheduling models of Small (1982) and Vickrey (1969), assuming that drivers trade-off travel costs (travel time, distance-based cost, charge etc.) against scheduling delay costs. There are three trip purposes in SILVESTER, with one demand model for each trip purpose: 1) commuting trips with fixed working hours and school trips, 2) business trips and 3) commuting trips with flexible working hours and other trips, where "other trips" includes e.g. shopping and leisure trips. Distribution traffic and other freight traffic is not modelled explicitly, but is assumed to have the same pattern as business trips. Equation (2) shows the utility functions used in the three models. Utility functions are similar, except that for business there is no public transport alternative.

$$\begin{aligned}
U_c^{k\omega ytd} &= SDE^{kd}E^{ty} + SDL^{kd}L^{ty} + COST^{kd}M^{\omega t} + TIME^{k}T^{\omega t} + TTU^{k}\sigma^{\omega t} + \varepsilon^{t}, \\
U_p^{k\omega} &= CPT^{\mathrm{k}} + TIMEP^{k}T_p^{\omega} + ST^{k}\delta^{k} + \varepsilon_p \\
SDE^{ty} &= \max(y-t,0) \\
SDL^{ty} &= \max(t-y,0)
\end{aligned} \tag{2}$$

In Equation (2), the index k denotes trip purpose, ω is origin-destination (OD)-pair, d is parameter distribution, y is preferred departure time period and t is actual departure time period[7]. SDE and SDL are schedule delay early and late respectively. M is monetary cost which includes both a distance-based cost and congestion charge (if applicable), T is travel time, σ is standard deviation of travel time, ε is a Gumbel distributed error term, C_p is an alternative specific constant for public transport and δ is the share of car users who also possess a public transport monthly card[8]. Since time is divided into 15 minute time intervals, SDE and SDL become multiples of 15 minutes.

SILVESTER is built up of two interacting submodels: (1) a submodel for mode and departure time choice and (2) a mesoscopic simulation model CONTRAM (Taylor 2003) for route choice and calculating OD travel times and costs. SILVESTER iterates between these two parts to reach consistence between demand and supply.

[MS2]CONTRAM is used as assignment model . This mesoscopic simulation model takes the travel demand in the form of time sliced OD-matrices, groups the trips into packets that are routed through the network and assigned sequentially in journey start time order. Each packet can influence others starting their journeys earlier as well as later, and knowledge of the network state develops as if through day to day experience.

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[7] Index $t = 0$ denotes departure times before 6.30 am, $t = 1, \ldots, 12$ denotes departure times in the twelve quarters from 6.30 to 9.30 am respectively and $t = 13$ departure times after 9:30 am

[8] In the estimation δ was a dummy variable equal to 1 if the driver had a public transport monthly card and 0 otherwise

Several iterations are performed in the assignment. Each packet follows its minimum cost route in each iteration, given the 'current' network state. If the assignment converges, no packet can switch unilaterally to a route of lower time or cost. CONTRAM uses deterministic assignment such that results are always the same given the same input and scenario settings.

2.3 Comparison of METROPPLIS and SILVESTER

Although METROPOLIS and SILVESTER both are mesoscopic simulation model, they differs from various aspects. SILVESTER has a detail supply model than METROPOLIS with signal plans coded explicitly and well defined conflicting flows at intersections. METROPOLIS does not include signals. Instead of modelling individual drivers as in METROPOLIS, the demand in SILVERPOLIS is divided up into a stream of small packets that contains a group of drivers who have same user characteristics, OD's and departure time period. Therefore, the route choice and departure time choice for drivers belong to a packet will be same, whereas it is likely to differ in METROPOLIS.

The time discretization into fifteen minute intervals is a difference compared to METROPOLIS in which time is continuous. Based on the resulting route flows, times and monetary costs, the OD matrices for times and monetary costs are skimmed for each 15 minutes interval of departure time and serve as input to the travel demand submodel. The preference heterogeneity is explicitly represented through a mixed logit specification (Börjesson 2008) for departure time and mode choice (car or public transport).

The user characteristics are similar in both models: cost and time valuations, early and late schedule delay parameters, and mode choice parameters such as travel time valuation and alternative specific constant for PT. However, some differences exist between the demand model specifications. The mixed logit model in SILVESTER includes also travel time uncertainty as described by the standard deviation of travel time and the PT alternative includes a dummy for season ticket. Furthermore, desired time of travel is given in SILVESTER as a distribution of preferred departure times (PDTs) unlike of PATs in METROPOLIS.

Table 1 compares the utility functions for mode and departure time choice in METROPOLIS and SILVESTER. In the utility functions *T* is car travel time, *M* is monetary cost, *E* is early schedule delay, *L* is late schedule delay, *and* σ is standard deviation of travel time, with index *t* referring to the departure time. Furthermore, T_p is time with public transport, δ is a dummy for PT season ticket, CPT is a public transport constant and ε is an error term. *TIME, COST, SDE, SDL, TTU, TIMEP* and *ST* are corresponding parameters. Parameter values for the Stockholm application will be given in the next section. Similarly to METROPOLIS, PT travel times do not depend on time-of-day and are external inputs to the SILVESTER model. Route choice in SILVESTER/CONTRAM is performed by assigning packets to the network in the order of departure time and finding their dynamic shortest paths. Several iterations of the assignment are carried out because each packet can influence others starting their journeys earlier as well as later. Just as in METROPOLIS, these iterations can be seen as corresponding to a learning process.

Table 1: Comparison of utility functions in METROPOLIS and SILVESTER

METROPOLIS (nested logit for mode choice, continuous logit for departure time choice)	SILVESTER (mixed logit for mode choice and for departure time choice)	
$U_{ct} = TIME * T_t + COST * M_t + SDE * E_t + SDL * L_t + \varepsilon_t$ $U_p = TIMEP * T_p + CPT + \varepsilon_p$	$U_{ct} = TIME * T_t + COST * M_t + SDE * E_t + SDL * L_t + TTU * \sigma_t + \varepsilon_t$ $U_p = TIMEP * T_p + ST * \delta + CPT + \varepsilon_p$	[KI3]

The output from METROPOLIS and SILVESTER can be both aggregate and disaggregate. Aggregate data includes network measures of efficiency such as average travel time, average speed, collected revenues, average consumer surplus, congestion and mileage. These variables are important, in particular, in CBA. Disaggregate data includes time-dependent traffic flow and travel time on all links, all users' data (including behavioral parameters and departure and arrival time) and also temporal distribution of some variables like flow and travel time on selected road stretches, zones or regions.

3. Application of the two models for Stockholm, baseline situation

Stockholm is the capital and the largest city of Sweden. At present Stockholm county has a population of about 2 million inhabitants (February 2012) while 3 million live within a daily commuting distance. The city of Stockholm is extremely mono-centric (Armelius and Hultkrantz, 2006). Within the inner city there is a compact central business district with numerous workplaces within one kilometer 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.

This section describes how SILVESTER and METROPOLIS have been estimated and calibrated to Stockholm conditions in the baseline situation without congestion charging. By estimation we mean finding the behavioral parameters on the demand side, i.e. parameters of the departure time and mode choice models based on adapted survey data. This includes estimation of scheduling, time, and cost parameters. Calibration refers to the adjustment of the complete transportation model (both demand and supply side) to match field measurements in the base line situation, which is the situation without congestion charging.

3.1 Estimation and implementation of demand models

The same data is used for estimating the behavioral parameters of both SILVESTER and METROPOLIS. This data consists of stated and revealed preference data from car drivers crossing the bridge "Tranebergsbron" (which lies just outside the city core of Stockholm, in west direction) driving into the CBD on a work day morning between 6 and 10 am (Börjesson 2006). Data was collected before introduction of charging in Stockholm, but the stated preference data contains responses to a hypothetical extra monetary cost (toll) on driving behavior. Demand models for both SILVESTER and METROPOLIS are estimated using the software Biogeme (Bierlaire 2003). Three demand models are estimated for SILVESTER/METROPOLIS: (1) *business* trips, (2) work trips with *fixed* schedule and school trips and (3) work trips with *flexible* schedule and other trips.

The estimation of the mixed logit (ML) model for SILVESTER is described in more detail in Börjesson (2008). For implementation in SILVESTER the mixed logit model has been re-estimated because the extra scheduling penalty for early departure time periods did not work well in implementation. The model for mode and departure time choice estimated for METROPOLIS differs from the model implemented in SILVESTER in two relations: First, instead of mixed logit a nested logit (NL) model has been estimated for METROPOLIS. Second, scheduling constraints are on the departure side in the SILVESTER model, whereas they are on the arrival side in the METROPOLIS model. See also the previous section for description of similarities and differences between the two models. Table 2, Table 3 and Table 4 compare the parameters of the demand models for each trip purpose in METROPOLIS and SILVESTER using the specifications of the utility functions described in Table 1. Mode choice is not available for business trips and the PT parameters are therefore not present in the demand model for business trips.

Table 2: Parameters for *business* trips in METROPOLIS and SILVESTER

Parameter	METROPOLIS	SILVESTER
TIME	-0.0688	-0.1924
COST	-0.0262	-0.1157 (0.1886)[9]
SDE	-0.0339	-0.1426 (0.1280)
SDL	-0.0428	-0.2825 (0.2557)
TTU	-	-0.1083

[9]The values given are mean and standard deviation of the draws of the mixed logit model used in simulation

Table 3: Parameters for *fixed* trips in METROPOLIS and SILVESTER

Parameter	METROPOLIS	SILVESTER
TIME	-0.0124	-0.1862
COST	-0.0145	-0.2160 (0.2319)
SDE	-0.0152[10]	-0.1662 (0.1261)
SDL	-0.0189	-0.2478 (0.1318)
TIMEP	-0.0465	-0.2214
CPT	-1.6404	-0.05
TTU	-	-0.064
ST	-	13.4886
Logsum parameter	4.77	-

Table 4: Parameters for *flexible* trips in METROPOLIS and SILVESTER

Parameter	METROPOLIS	SILVESTER
TIME	-0.0494	-0.2439
COST	-0.0372	-0.1921 (0.1558)
SDE	-0.0200	-0.1958 (0.1929)
SDL	-0.0190	-0.2020 (0.1675)
TIMEP	-0.0687	-0.1838
CPT	-4.9416	-1.3500
TTU	-	-0.0629
ST	-	10.8959
Logsum parameter	3.9796	-

The estimation results differ between the two techniques showing no specific trends. For business trip (Table 2) higher value of time (TIME/COST) for car travel is estimated in NL model then ML model. Similar value for early arrival penalty (SDE/COST) is estimated in both models; however, late arrival penalty (SDL/COST) was higher in ML model than NL model. Similar VOT estimation is found for both fixed and flexible trips (Table 3 and 4 respectively). VOT for PT travel also differs between the two estimation techniques reporting higher values in NL model. Higher value for early and late penalty is also estimated by NL model for fixed trips but the opposite is observed for flexible trips.

In SILVESTER, the preferred departure times are distributed on the interval 6:30-9:30 AM and the simulation is performed for the same period. The departure rates are considered constant for each 15 minutes interval. In METROPOLIS, the trips are assigned individually on the network at departure time modeled in a continuous scale. Each traveler's experience is used to modify her departure time on next day. The learning

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[10] Theoretically, as shown in Arnott, de Palma and Lindsey (1993) the existence of equilibrium in the case of homogenous users is conditioned on having the early schedule delay penalty lower than value of time. Only SDE for fixed trips does not follow the criteria and therefore, in order to obtain convergence in terms of expected and observed travel time, it has been modified to 0.012. This value is within the Average plus/minus standard error of estimation (0.0087).

module collects travel information inside the simulation period. Therefore a simulation period in METROPOLIS has to be longer than the evaluation period. A simulation period of 5:00-11:00AM was selected and the demand matrix was extended for this period by putting some extra demand on both ends.

3.2 Calibration

For dynamic network assignment SILVESTER uses CONTRAM model for Stockholm that has been used and calibrated for decades. The signal plans and saturation flows were adapted to correctly represent the actual traffic situation in Stockholm. The link capacities for the before-charges situation in the network model are consistent with saturation flows and conflicting flows at each intersection. These capacities were imported to METROPOLIS and used in the simple bottleneck congestion functions. The spillback effect was not considered in METROPOLIS.

Calibration of SILVESTER and METROPOLIS was performed using field measurements from the situation *without* charging. Field data contained flow measurements for 59 calibration links in twelve time periods between 6:30-9:30 am. Figure 1 shows the location of the links with flow counts used for the calibration

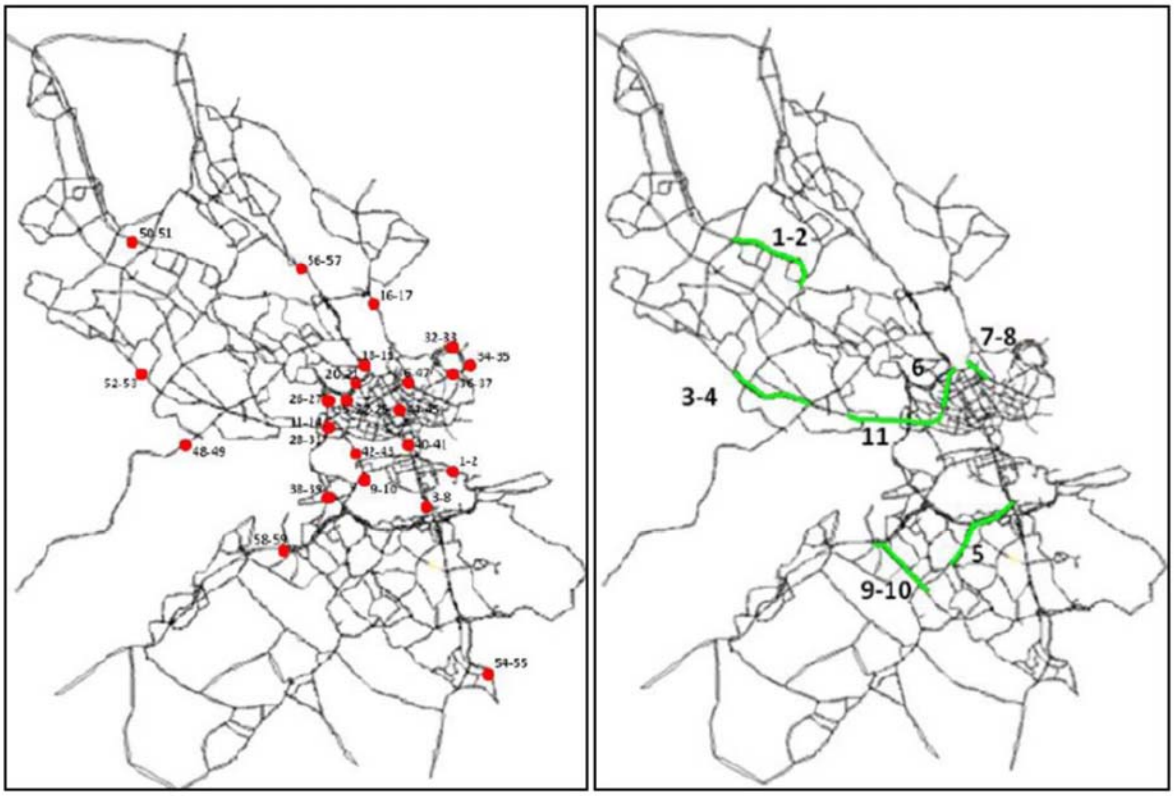


Figure 1: Position of links for flow measurement and road stretches for travel time measurement

and the road stretches with travel time measurements used for the validation (see next section).

The SILVESTER preferred departure times were calibrated using reverse engineering (Kristoffersson and Engelson 2008). This method takes as input (1) an OD-matrix (calibrated against link flow field measurements) with number of vehicles starting in each actual departure time (ADT) interval and (2) probabilities from the estimated departure time choice model. The demand in each preferred departure time (PDT) interval is then adjusted such that ADT flow rates are reproduced keeping demand and supply consistent.

The reverse engineering approach is not suitable for METROPOLIS, since instead of time-sliced demand matrices it applies a continuous departure time choice model to a global demand matrix. Therefore, the PDT-distributions from SILVESTER shifted forward by the free-flow travel times were taken as an initial guess for the PAT-distributions in the METROPOLIS model. Since the demand in METROPOLIS is spread over a larger (and eventually variable) period than in SILVESTER, with the same demand as SILVESTER METROPOLIS showed too low flows on the counted links. Therefore, the demand in METROPOLIS was further increased. Thus was done in order to achieve a good fit of simulated link flows to field measurements in the baseline situation. The changes of PAT-distributions and the level of demand were applied uniformly for all OD pairs.

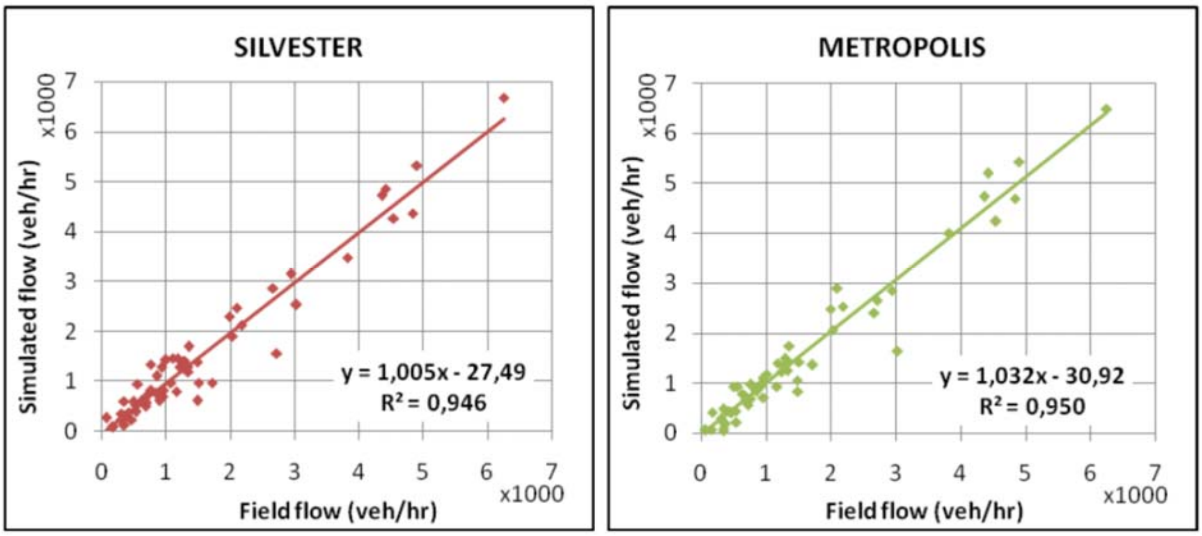


Figure 2: Field vs. Simulated flow in 59 calibration links for before charging situation

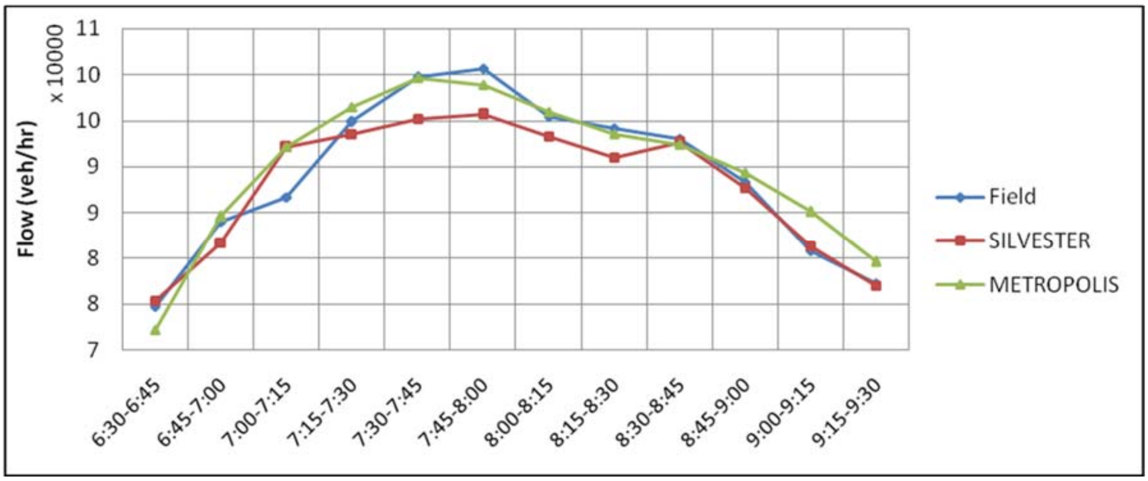


Figure 3: Distribution of total hourly flow in 59 calibration links

Figure 2 and Figure 3 show that calibration results for both the models are good. The R^2 value suggests that the calibrated SILVESTER and METROPOLIS models can capture about 95% of the observed variability in link flows on the 59 calibration count stations. The observed and modelled distributions of flow by 15 minutes intervals indicates that the models are capable of appropriately predicting the temporal distribution of flow.

3.3 Validation and comparison of model results in the baseline situation

The aggregate simulation results are presented in Table 5. The term ‘cordon’ refers to the screen line along which the charging gates are located (the specification is given in Section 4.1). The calibration process is different for two models as described in previous section. After the adjustments, flow over the cordon is similar for the two models but the number of car trips starting between 6:30 and 9:30 is 19.5% larger in METROPOLIS than in SILVESTER. This is a considerable discrepancy that can be partially explained by the uniform nature of the adjustments described in the previous section. Probably shifting and scaling by different amount in different OD-pairs would result in better concordance between the models. However, detailed analysis of the differences in demand between the calibrated models reveals that the largest differences are related to trips having both origin and destination outside the cordon. Most of such trips are not affected by the congestion charging system. Therefore conclusions of this paper related to modeling the effect of congestion charging probably would not be influenced by a more involved calibration.

Table 5: Aggregated result for SILVESTER and METROPOLIS

	SILVESTER	METROPOLIS	Relative difference (%)
Flow over the cordon (veh/hr)	35 611	35 651	0
Mean travel distance (km)	12.4	11.6	-7
Mean free flow travel time (min)	13.5	14.7	9
Mean travel time (min)	19.0	20.8	9
Congestion (%)	41.1	41.3	0
Speed (km/hr)	39.3	34.9	-11
Number of car trips starting between 6:30-9:30	280 801	335 337	19
Mileage (10^6veh-km)	3.49	3.88	11

METROPOLIS sends the cars to slightly shorter routes but the free flow travel times are longer than in SILVESTER, most probably due to different route choice criteria. The models show similar congestion percentage[11], hence the realized travel times in METROPOLIS are longer and the speeds are lower than in SILVESTER.

For validation of the models the average travel time between 7:00-9:00 am in 11 selected road stretches are calculated and compared with field result. Position of the road stretches are shown in Figure 1. The measurements of average travel time were performed using a video technique with automatic license plate matching. Two scatter plots for field and simulated travel times are presented in Figure 4. The validation result for METROPOLIS model is closer to the observed data than for SILVESTER model. The total travel time in these 11 stretches before charging was 51.17 min as obtained from field. METROPOLIS predicted the total travel time as 53.45 min, while SILVESTER predicted 47.71 min.

[11] Congestion percentage is the relative difference between the actual total travel time and the total free-flow travel time.

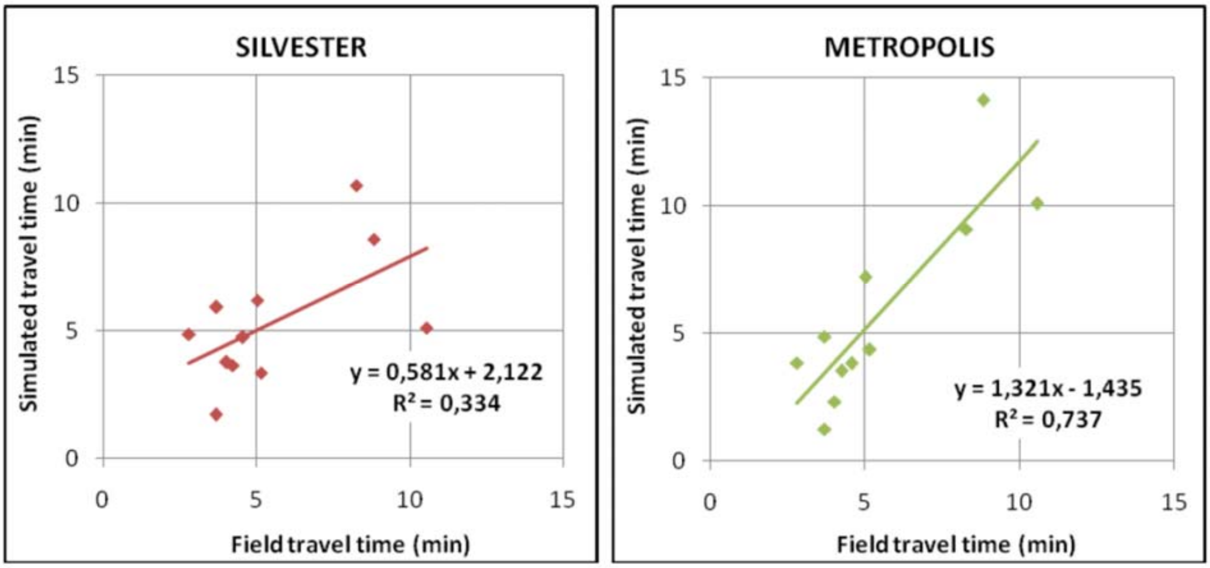
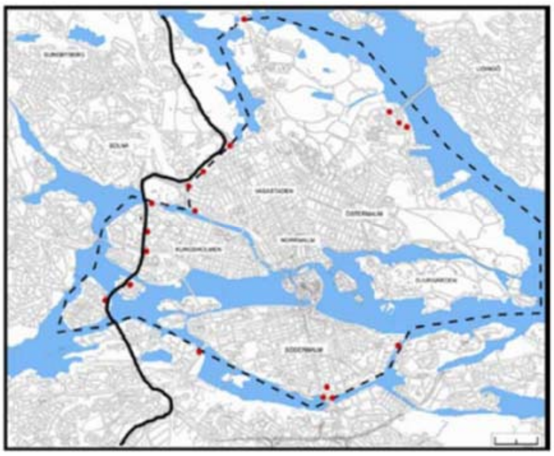


Figure 4: Field vs. Simulated travel time on 11 road stretches before charging situation

4. Application to Stockholm congestion charging

4.1 Stockholm congestion charging scheme

Stockholm is the capital and the largest city of Sweden. A large fraction of the morning rush hour traffic is directed towards the central areas and is concentrated on a few main roads. A time-dependent congestion charging system has been made permanent in Stockholm from August 1, 2007 after a full scale six months trial performed in 2006. The charging system is implemented as a cordon around the city. The cordon surrounds an area with a diameter of approximately 5 km and with about 315 000 people living inside. The position of the tolling stations is shown in Figure 5. The owners of all non-exempted cars driving through the cordon between 6.30 am to 6.30 pm are charged between 10 and 20 SEK depending on the time of day.



Time	Congestion charge (SEK)
06:30–06:59	10
07:00–07:29	15
07:30–08:29	20
08:30–08:59	15
09:00–15:29	10
15:30–15:59	15
16:00–17:29	20
17:30–17:59	15
18:00–18:29	10
18:30–06:29	0

Figure 5: The charging points (red dots) and the charging schedule (table to the right).

At the time of the study, one Euro was about 10 SEK.

4.2 Response to congestion charging

In this section the simulated demand and system response to congestion charges are compared for the two models. The aggregate results are presented in Table 6. SILVESTER shows stronger modal shift than METROPOLIS. Field observation shows 18.1% decrease in traffic flow over the cordon. SILVESTER overestimates the flow change while METROPOLIS underestimates it. Change in other parameters like travel time, congestion and speed are very similar for the two models.

Table 6: Change in aggregate results due to charging

	SILVESTER	**METROPOLIS**
Number of car	-5.0%	-2.6%
Flow over the cordon	-25.3%	-12.4%
Average travel time OD-par	-6.8%	-7.6%
Congestion	-20.7%	-22.9%
Speed	7.1%	7.6%
Mileage	-5.16%	-1.11%
Consumer surplus, MSEK	0.53	-0.61
Revenues, MSEK	0.91	1.27
Net benefit, MSEK	1.44	0.66

The change in consumer surplus shows how much the travelers gain or lose from the congestion charging system, before the revenues are returned to the population. In SILVESTER, the total surplus is calculated as logsum for each draw of the mixed logit simulation weighted by the number of travelers represented by the draw. In METROPOLIS, the surplus is computed as the logsum of the binary mode choice and continuous departure time choice then aggregated over all travelers. The consumer surplus and revenue values obtained from METROPOLIS were normalized to the time period between 6:30 and 9:30 AM in order to compare them to the corresponding results from SILVESTER. This was done by applying the share of travelers that have preferred departure time in this period. The resulting revenue collection is lower in SILVESTER due to lower flow through the cordon in the charging scenario and the fact that METROPOLIS model does not take into account that some vehicles are exempted from charging while SILVESTER does (Kristoffersson, 2011).

The surplus includes the tolls paid by the drivers. According to the standard textbook analysis (Walters, 1961), the drivers paying the congestion charge are not fully compensated by shorter travel times whereby the change in consumer surplus shall be negative. However the standard analysis considers one link connecting one origin-destination (OD) pair with static volume-delay function and homogeneous travelers. The benefit of congestion charging may be higher in a road network with multiple OD-pairs (Verhoef and Small, 2004), when the drivers have different values of time (VoT) (Ibid), or when they can adjust their departure time (Arnott, de Palma and Lindsey, 1994). In the version of METROPOLIS considered here, all drivers with the same trip purpose (fixed, flexible or business) have the same value of time (VoT) while in SILVESTER the VoT for each trip purpose is distributed on a large support. Verhoef and Small (2004) showed that ignoring heterogeneity of VoT in a system with a free parallel road leads to great *underestimation* of social benefits, by disregarding the efficiency gains due to separation of traffic. This may explain why the consumer surplus is higher in SILVESTER than in METROPOLIS.

Traffic flow in 59 count stations has been analyzed after the charge and it still shows good result for both models in comparison to field flow. The result is shown in Figure 6. Similarly travel time results after the charge for 11 selected road stretches are compared with field travel time as shown in Figure 7. SILVESTER shows better R^2 than before while METROPOLIS remains at the same level.

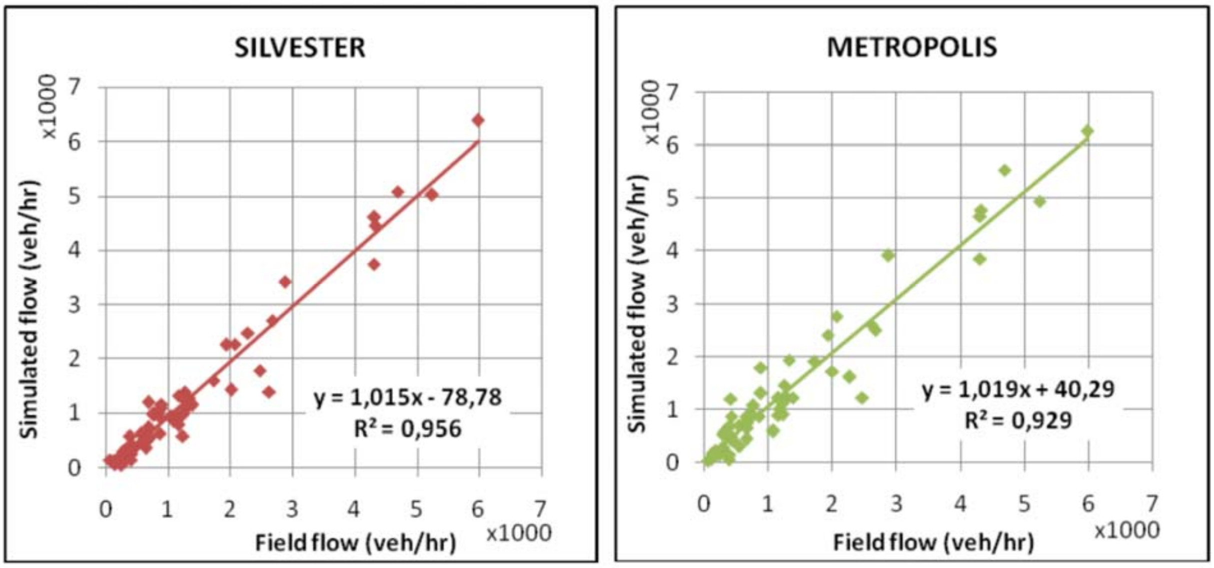


Figure 6: Field vs. Simulated flow in 59 calibration links after charging situation

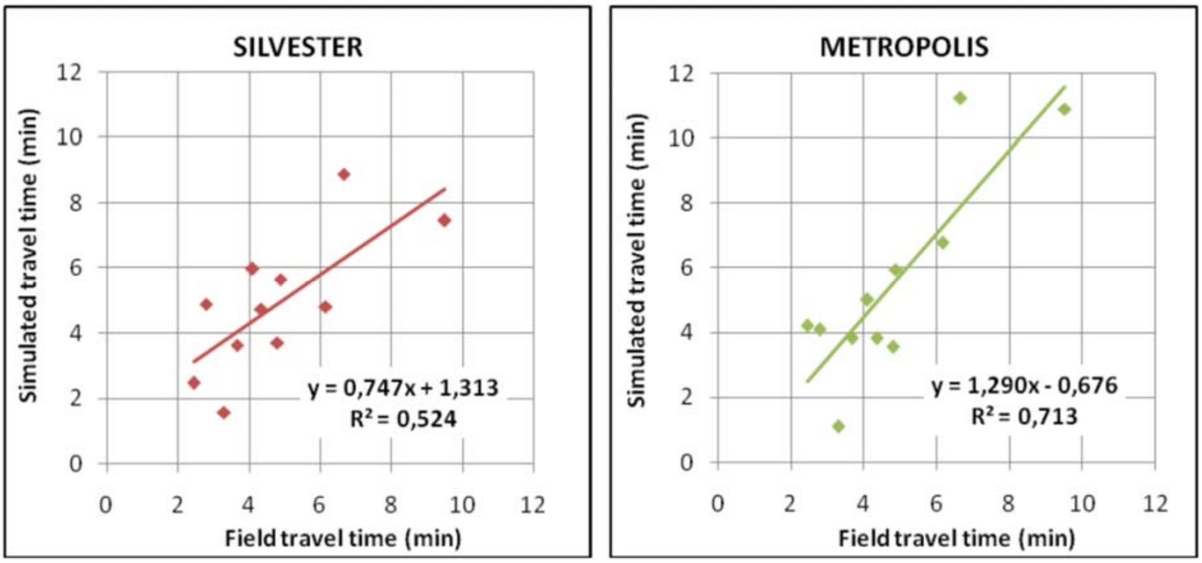


Figure 7: Field vs. Simulated travel time in 11 road stretches after charging situation

In order to observe the temporal change in traffic flow over the simulation period the flow data in every 15 min interval both before and after implementation of charging are compiled. Figure 8 shows the change in total flow for 59 calibration links for each time interval. The figure shows that SILVESTER predicts higher reduction of flow during peak period than field measurement. Flow reduction in METROPOLIS is lower than field but the reduction pattern is similar to the field.

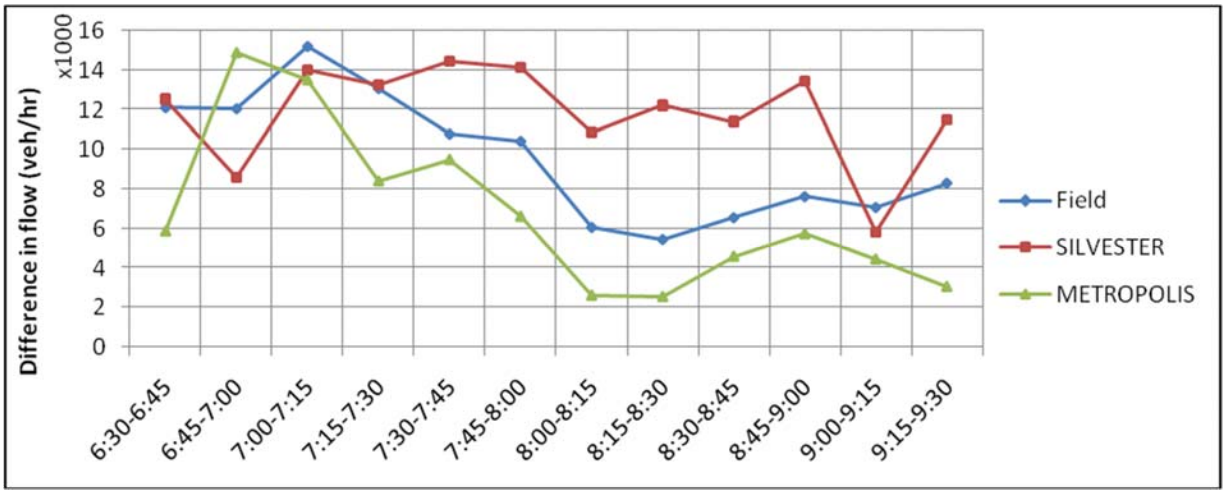


Figure 8: Temporal change in traffic flow for 59 calibration links

To observe the change in travel time due to charging in each of the 11 road stretches, a linear plot is made which is presented in Figure 9. It is observed from the figure that SILVESTER model shows better prediction of travel time change than METROPOLIS model. It is worth mentioning here that the total reduction of travel time in these 11 road stretches are 7.8 min as observed from field data. SILVESTER model predicted this decrease as 4.3 min whereas METROPOLIS predicted it as 2.8 min. The decrease in travel time is not so great for METROPOLIS due to two road stretches: St Eriksgatan and Stora Mossen. The link St Eriksgatan is a special one. This is the only link in the city where increase of the flow was observed as a result of congestion charging. This is because an alternative route for many trips going via this link from the city would be to cross the cordon trice. So they use this link and pay just for one crossing. In spite of the flow increase the travel time actually decreased because the conflicting flows on the intersections decreased. This is captured by SILVESTER but not by METROPOLIS and this example shows that this can be an important feature for local studies. Stora Mossen link is a continuation of St Eriksgatan and probably can be explained by the same reason.

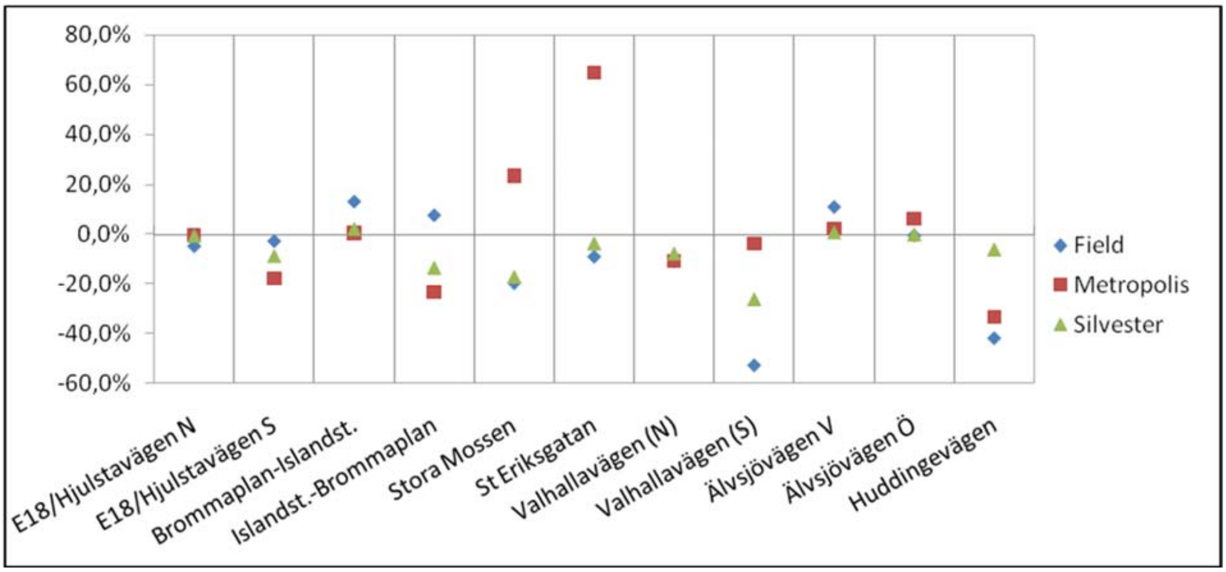


Figure 9: Change of travel time in different road stretches

5. Conclusions and recommendations

Road pricing is one of the most attractive solutions to the increasingly important problem of congestion in urban areas. However, there is a strong opposition to road pricing, and therefore a need to develop reliable models to assess the different impacts of road pricing. The assessment of road pricing is usually made by a cost benefit (CBA) analysis. We believe that such cost benefit analysis needs to be based on measures and indexes that are based on strong economic principles. Both aggregate ad disaggregate data are important to achieve such evaluation. In particular the number of trips, travel times and travel costs between all OD-pairs with and without the road pricing are necessary as input to CBA and have to be calculated by the model. This is the case of the two dynamic models, SILVESTER and METROPOLIS, which have been used to asses Stockholm congestion charging scheme.

Application of the models based on random utility maximization may result in overestimation of the behavioral response to road pricing since the users in a short term may be not completely rational but more conservative and stick to their original mode, route and departure time. On the other hand, models ignoring the time dependent variation in travel time flow and departure time choice by the travelers are likely to underestimate the impact of road pricing since it contains little margins of adjustments. Furthermore, the static assignment models underestimate the impact of road pricing on travel times due to absence of blocking back mechanism. This leads to overestimation of changes in total travel costs and changes in travel demand, since increasing travel costs due to the pricing are not appropriately compensated in the model by reduction of travel time due to reduced number of car trips. . For example the forecast carried out with the Swedish national model Sampers before the introduction of congestion charges in Stockholm gave 29% decrease in traffic flows through the gates and 5% decrease of travel time on selected routes during the morning period 7:30-9:00 (Engelson and van Amelsfort, 2011). In reality, both the flow and the travel time reduced by 13%.

The mere aggregate results are not enough for the assessment of congestion charges. In order to assess road pricing, one should also address its benefit (and cost) along the different dimensions (mainly congestion cost, flow, revenue, schedule delay cost, mode shift and speed). Moreover, disaggregation is needed at the user level. This is because with positive overall benefit road pricing can have a negative impact on some individuals. Often, the impacts are believed to be regressive, in the sense that poor commuters are worse off, while rich commuters (more flexible) are better off. It remains to analyze in more details, who are the winners and who are the loosers.

Validation and calibration of a dynamic model for a big city, although a large effort, is necessary in order to get a reasonably reliable assessment of the congestion charges. Not only the traffic flows on the charging locations but also on bypasses and the travel times on major highways and location of traffic queues have to be calibrated. After calibration of the two models for the situation without charging, we have managed to predict the impacts of Stockholm congestion charging scheme in a satisfactory manner at aggregate level. The aggregate reduction of travel times is similar in both models. However the computed reduction in flow passing the cordon is rather different between the two models, one overestimating and another underestimating the flow reductions provided by field data. Note that the fit of both flow change and travel time change is very difficult to achieve in a static model. The flexibility in the dynamic model appears sufficient to fit these two fundamental measures of traffic. In this respect, we have observed a significant improvement compared to the static model that was used for predicting the effect of congestion charges in Stockholm.

The major response of the drivers in the two models is the shift in departure time choices due to the dynamic congestion charge. This response is clearly impossible to observe in any static model and difficult to assess in a simple dynamic assignment model. Our result indicates that the dynamic traffic models used, SILVESTER and METROPOLIS, provide satisfactory fit and predictions.

Our results provide the benefit of road pricing. Basically the benefit are negative according to METROPOLIS when the user have to pay for tolls, however, after redistribution as a lump sum, the benefits are positive. The results are more optimistic with SYLVESTER, possibly because the latter model used wider distribution of VoT, so that the users can adjust to the changes in a more convenient and efficient manner.

Regarding differences between SILVESTER and METROPOLIS, the preliminary results indicate that the fully dynamic property of METROPOLIS with appropriate integration of scheduling and routing decisions is an advantage over the quasi-dynamic SILVESTER, since it provides flow profiles that are smoother, and therefore more in line with the smooth flow profiles of field measurements. Advantages of SILVESTER are that it has a more advanced demand model (mixed Logit compared to nested logit) and more detailed supply model (intersection interactions). This translates in the preliminary results mainly for the consumer surplus.

Only two models are selected in this study for a detail comparison about their modeling techniques and prediction power about the outcomes of congestion charging. Please note that the selection of the two models does not necessarily confirm their superiority over other available models that could be used for modeling congestion charging. The selection was primarily motivated by the authors' wide knowledge about the two models as most of them were directly involved in developing them. Comparison with other dynamic model will also be usefully be made in the future.

Finally, both models are based a solid micro-foundations. In particular, they can be used to compute the travelers' surplus. This is an essential input in Land Use Transport interaction (LUTI) models. Some interface has been built, in particular, between UrbanSim (developed by Paul Waddell), and METROPOLIS. The output of UrbanSim, the locations or households and firms, allow to compute the Origin-Destination matrices. On the contrary, the output of METROPOLIS, travel time and travelers choices, allows to compute the consumers surplus, which plays a key role in LUTI models (for example, to explain the price of land, or to explain the residential location decisions). The reader will see details in the book based on SustainCity, which uses UrbanSim, METROPOLIS and MaTSim for the Ile-de-France, Brussels and Zurich (see Waddell, et al. 2015).

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