Comparison of two dynamic transportation models: The case of Stockholm congestion charging

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Abstract

This paper reviews the transportation models used for predicting impacts of congestion charging in European cities and carries out in-depth comparison of two such models, METROPOLIS and SILVESTER. Both are mesoscopic dynamic models involving modal split and departure time choice calibrated 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 provide significant improvement in realism over static models. However results of cost benefit analysis differ substantially.

Keywords: Congestion charges, Congestion pricing, Road pricing, Transportation models, Dynamic assignment, Mesoscopic models, Departure time choice

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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 (Pigou, 1920; Vickrey, 1969; Small, 1983; Arnott et al., 1994; Glazer and Niskanen, 2000). The literature considering modeling of congestion charging 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 et al., 2003), Stockholm (Eliasson and Mattsson, 2006) and Copenhagen (Rich and Nielsen, 2007; Nielsen et al., 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 an important 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 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 we refer the reader to de Palma and Fosgerau (2011).

It is however 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 congestion charging. METROPOLIS (de Palma et al., 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 et al. (2005) analyze different congestion charging schemes using METROPOLIS and a stylized urban road network. Marchal and de Palma (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 (2011). 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 observed response 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 the models have been estimated and calibrated for Stockholm conditions. Section 4 discusses results of the model comparison and Section 5 concludes.

2. Brief description of METROPOLIS and SILVESTER

METROPOLIS is a traffic planning model which uses event based dynamic simulation. It was developed in Geneva by André de Palma, Fabrice Marchal and Yurii Nesterov (de Palma et al., 1997) and later on applied at the University of Cergy-Pontoise by de Palma and Marchal (de Palma and Marchal, 2002). METROPOLIS is based on a simple economic principle, explained originally in Vickrey (1969) and Arnott, de Palma and Lindsey (1993). SILVESTER is also a traffic planning model which uses dynamic simulation. SILVESTER has been developed at KTH Royal Institute of Technology in Stockholm by Leonid Engelson and Ida Kristoffersson (Kristoffersson and Engelson, 2009).

METROPOLIS describes the joint mode, departure time and route choice decisions of drivers. Each vehicle is described individually by the simulator. However, the modeling of congestion on links is carried out at the aggregate or macroscopic level. On the supply side a congestion function (bottleneck, BPR or DAVIS) describes the link travel delays. Demand is represented at microscopic level and each trip can be simulated. Users' characteristics which are necessary for modeling are: valuations of cost and travel time, early and late schedule delay parameters, distribution of preferred arrival times (PATs), and mode choice parameters like valuation of travel time for public transport (PT) and PT penalty or fee. In simulation, each trip is followed individually in its choices of mode, departure time and route. The user chooses the mode considering the average maximum expected utility (Logsum) offered by the car network in comparison with other modes. The choice of departure time for PT is not described by the model, since the PT travel times are external inputs to METROPOLIS. 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. 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. The decision will be based on the real time situation of the immediate link and memorized information about the rest of the network up to the destination. It should also be noted that one day corresponds to one iteration in METROPOLIS. The software uses a learning process where users acquire knowledge about their travel and use this information to modify their trip for the next day.

SILVESTER includes the same traveler choices as METROPOLIS: mode, departure time and route choice. However, unlike METROPOLIS, the model is built up of two parts: (1) a model for mode and departure time choice and (2) a model for route choice and calculation of route travel times and costs. SILVESTER iterates between these two parts to reach convergence between demand and supply. The mesoscopic dynamic assignment model CONTRAM (Taylor, 2003) calculates route choice and resulting travel times and monetary costs for trips in each OD-pair, given the demand for car trips departing in each fifteen minute interval. In CONTRAM, vehicles are grouped into packets that are routed through the network. Network supply is described in more detail in CONTRAM than in METROPOLIS, with signal plans coded explicitly as well as conflicting flows at intersections. Demand in the form of time sliced OD-matrices is produced by the model for mode and departure time choice and submitted to CONTRAM. However, preference heterogeneity is explicitly represented through a mixed logit model (Börjesson, 2008) for departure time and mode choice (car or public transport), which takes the travel times and costs from the assignment model and generates the demand for car trips departing in each fifteen minute interval. The time discretization into fifteen minute intervals is a difference compared to

METROPOLIS in which time is continuous. The SILVESTER mixed logit model for departure time and mode choice needs user characteristics similar to METROPOLIS: 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 as a distribution of preferred departure times (PDTs) instead of PATs. Table 1 compares the utility functions for mode and departure time choice in METROPOLIS and SILVESTER. In the utility functions *T* is 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, δ is a dummy for PT season ticket and ε is an error term. 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 is performed by assigning packets to the network in the order of departure time and finding their shortest paths. That later packets can affect the route choice of earlier packets is accounted for by iterations, starting the assignment process over again after going through all packets. 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 and departure time choice)
$U_{ct} = TIME * T_t + COST * M_t +$ $SDE * E_t + SDL * L_t + \varepsilon_t$	$U_{ct} = TIME * T_t + COST * M_t + SDE * E_t +$ $SDL * L_t + TTU * \sigma_t + \varepsilon_t$
$U_p = TIMEP * T_p + CPT + \varepsilon_p$	$U_p = TIMEP * T_p + ST * \delta + CPT + \varepsilon_p$

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, consumer surplus, congestion and mileage. Disaggregate data includes traffic flow on some selected links, temporal distribution of flow on selected links and travel time on some road sections.

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

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. 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 inner city of Stockholm, in north-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 an extra monetary cost on driving. 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 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 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. Tables 2-4 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)[1]
SDE	-0.0339	-0.1426 (0.1280)
SDL	-0.0428	-0.2825 (0.2557)
TTU	-	-0.1083

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[2]	-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	-

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

[2] In METROPOLIS early arrival penalty should be lower than value of time i.e.SDE<TIME, in order to obtain convergence in terms of expected and observed travel time. Only SDE for fixed trips does not follow the criteria and therefore, has been modified to 0.012. Standard error of the estimation(0.0087) allows us to do so.

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	-

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. Travelers who choose their departure time outside this period are recorded but do not affect the travel costs in the next iteration of the demand model. In METROPOLIS, each traveler's experience is used to modify their departure time on next day. The learning module collects travel information's inside the simulation period. Therefore the simulation period needs to be extended in METROPOLIS beyond the concerned 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

SILVESTER is based on 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 CONTRAM 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.

Calibration of SILVESTER and METROPOLIS was performed using field measurements from the situation *without* charging. Field data contained flow measurements for 59 validation links in twelve time periods between 6:30-9:30 am. Furthermore, we use field measurements of average travel time between 7:00-9:00 am on 11 road sections. For validation of travel times the travel time data has been collected using a video technique with automatic license plate matching. Figure 1 shows the location of the links with flow counts and the road sections with travel time measurements used for the calibration.

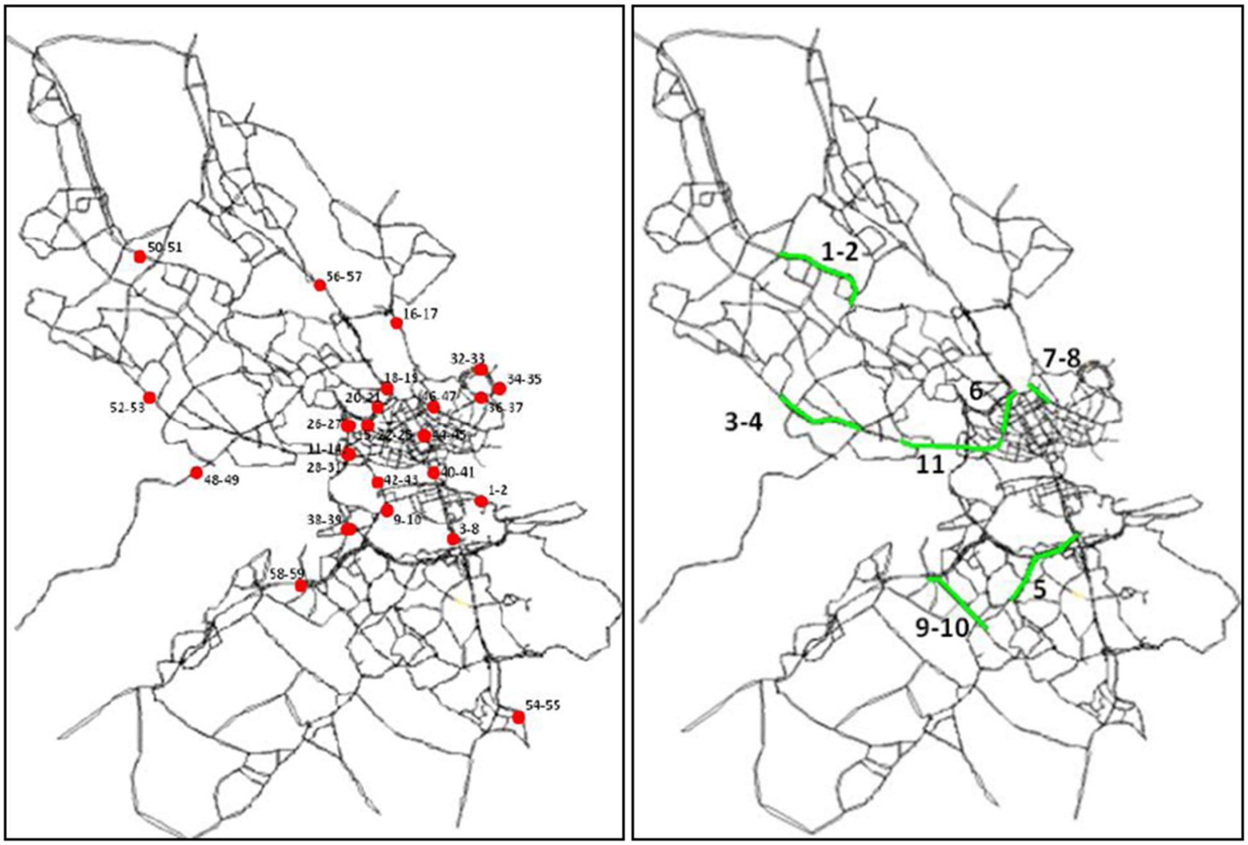


Figure 1: Position of links (to the left) for flow measurement and road sections (to the right) for travel time measurement

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 the time-sliced demand matrices are not directly available. Instead, the SILVESTER PDT-distributions shifted forward by the free-flow travel times were taken as an initial guess for the PAT-distributions in the METROPOLIS model. These initial PAT-distributions were then calibrated by changing the level of demand and shifting the distributions later. It was done in order to achieve a good fit of simulated link flows to field measurements in the baseline situation. The spillback effect was not considered and simple bottleneck function was used as the congestion function in METROPOLIS.

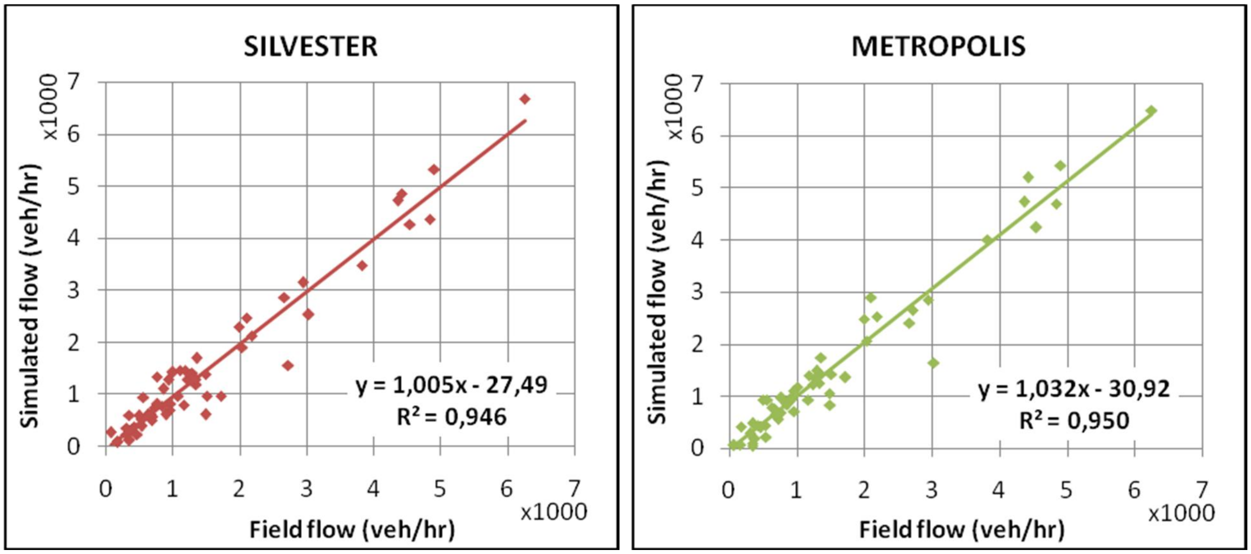


Figure 2: Field vs. Simulated flow in 59 calibration links for before charging situation

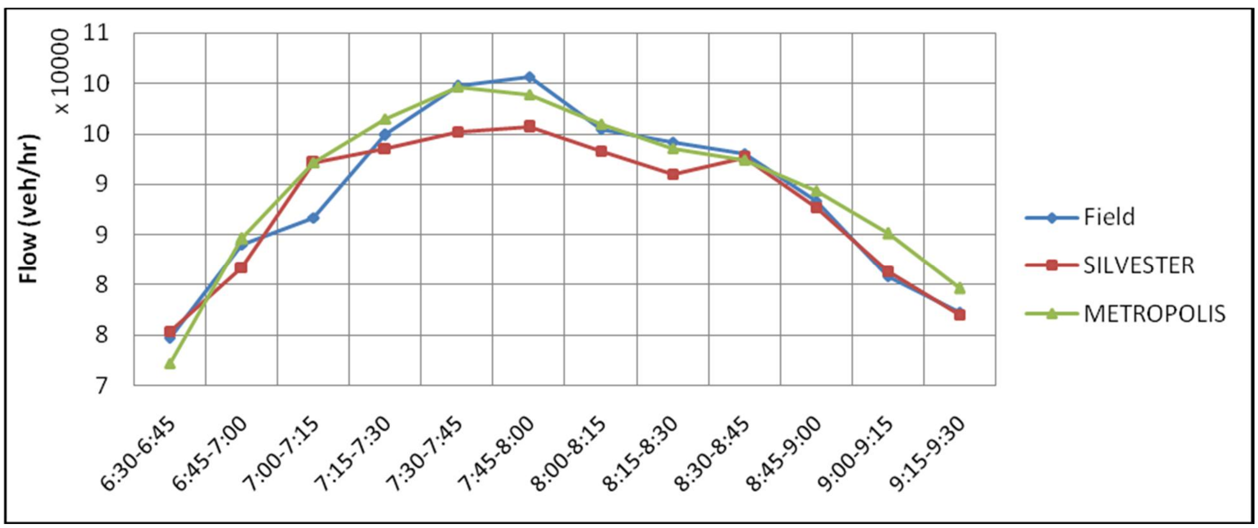


Figure 3: Distribution of total hourly flow in 59 calibration links

Figure 2 and 3 show that calibration results for both the models are good. The R^2 value suggest that the calibrated SILVESTER and METROPOLIS model can capture about 95% of the observed variability in link flows on the 59 calibration links. The observed and modelled distribution of flow by 15 minutes intervals indicates that the models are capable of 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 in the situation with congestion charging (the specification is given in Section 4.1). During calibration the demand was adjusted to have similar link flows on the selected links (shown in Figure 1). The calibration process is different for two models as described in previous section. With the same demand METROPOLIS showed much lower flow in the selected links than field observation with low congestion. To have the same flow over the selected links, the demand in METROPOLIS was increased. Hence, flow over the cordon remains close for two models but the number of car trips per hour is 19.5% larger in METROPOLIS

Both models show similar congestion percentage[3]. METROPOLIS shows lower network speed which is the reason behind higher travel time.

Table 5: Aggregate result for SILVESTER and METROPOLIS

	SILVESTER	METROPOLIS
Flow over the cordon (veh/hr)	35 611	35 651
Mean travel time (min)	19	20.8
Congestion (%)	41.1	41.3
Speed (km/hr)	39.3	34.9
Number of car trips starting between 6:30-9:30	280 801	335 337
Mileage (10^6veh-km)	3.49	4.08

For validation of the models the travel time in 11 selected road sections are calculated and compared with field result. Position of the road sections are shown in Figure 1. Two scatter plots for field and simulated travel times for SILVESTER and METROPOLIS model as 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 sections 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.

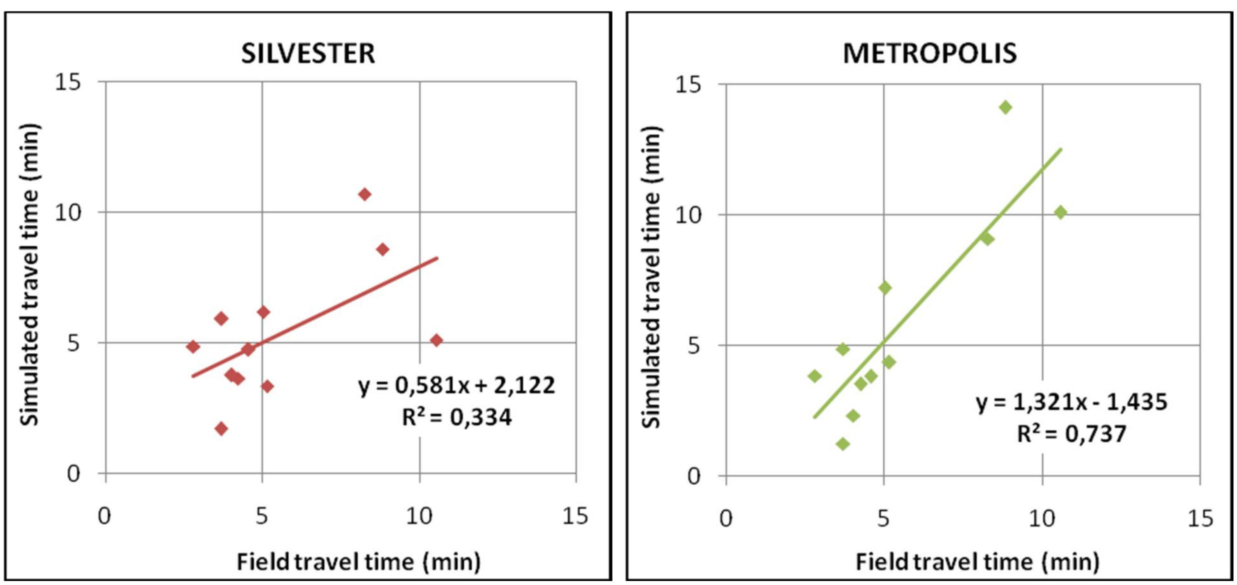


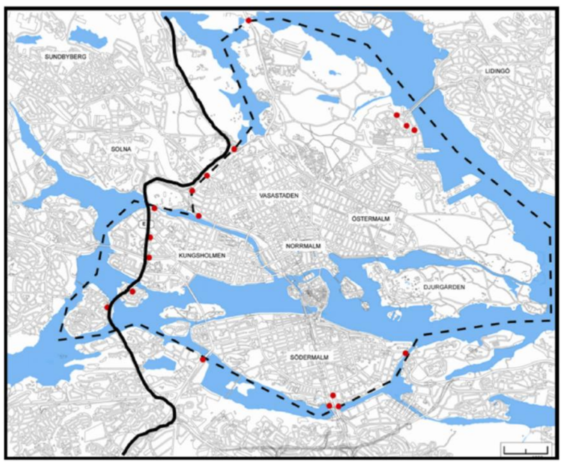
Figure 4: Field vs. Simulated travel time on 11 road sections before charging situation

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

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 315000 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).

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 models.

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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 logsum for the binary mode choice and 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 travel time savings (VTTS) (Ibid), or when they can adjust their departure time (Arnott et al., 1994). In METROPOLIS, all drivers with the same trip purpose (fixed, flexible or business) have the same VTTS while in SILVESTER the VTTS for each trip purpose is distributed on a long interval. Verhoef and Small (2004) showed that ignoring heterogeneity of VTTS 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 selected points 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 sections 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.

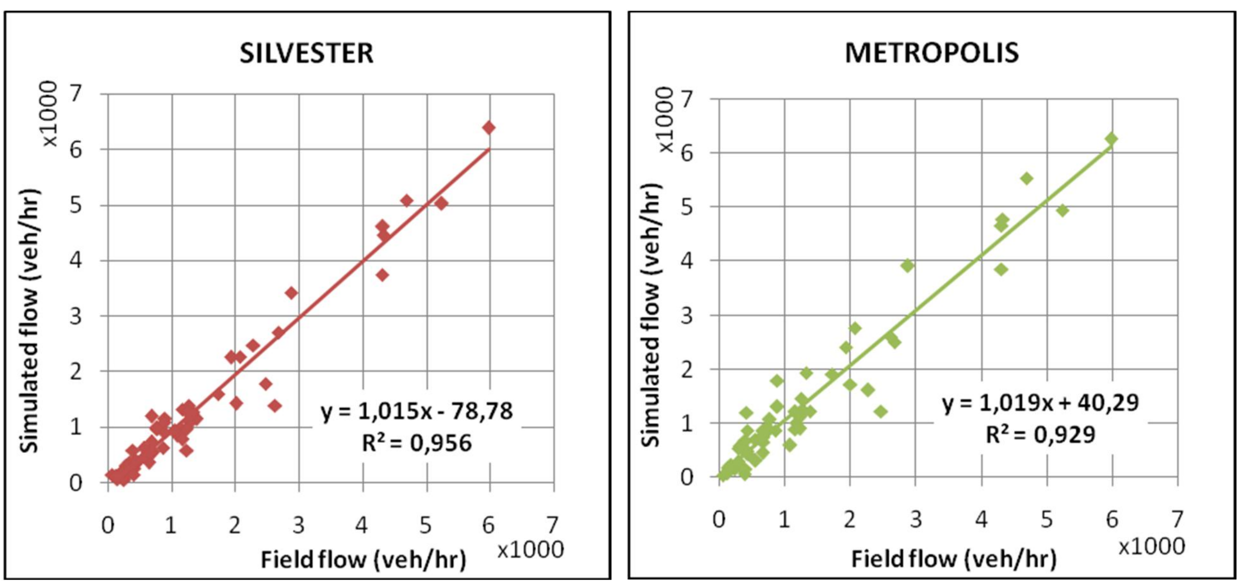

Figure 6: Field vs. Simulated flow in 59 calibration links after charging situation

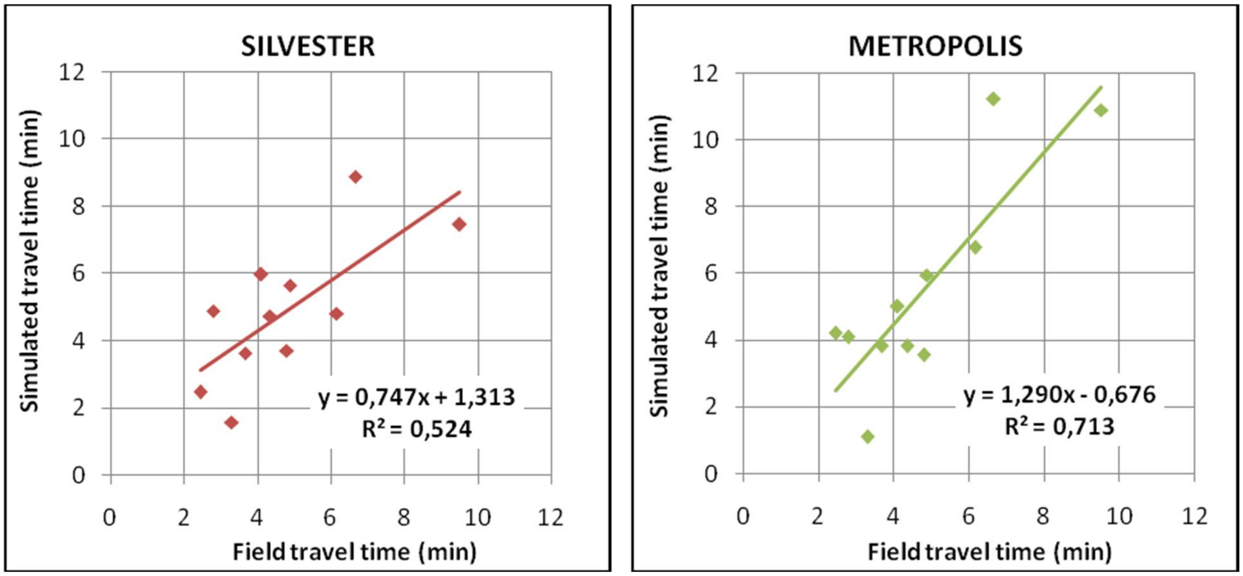

Figure 7: Field vs. Simulated travel time in 11 road sections after charging situation

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 7 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.

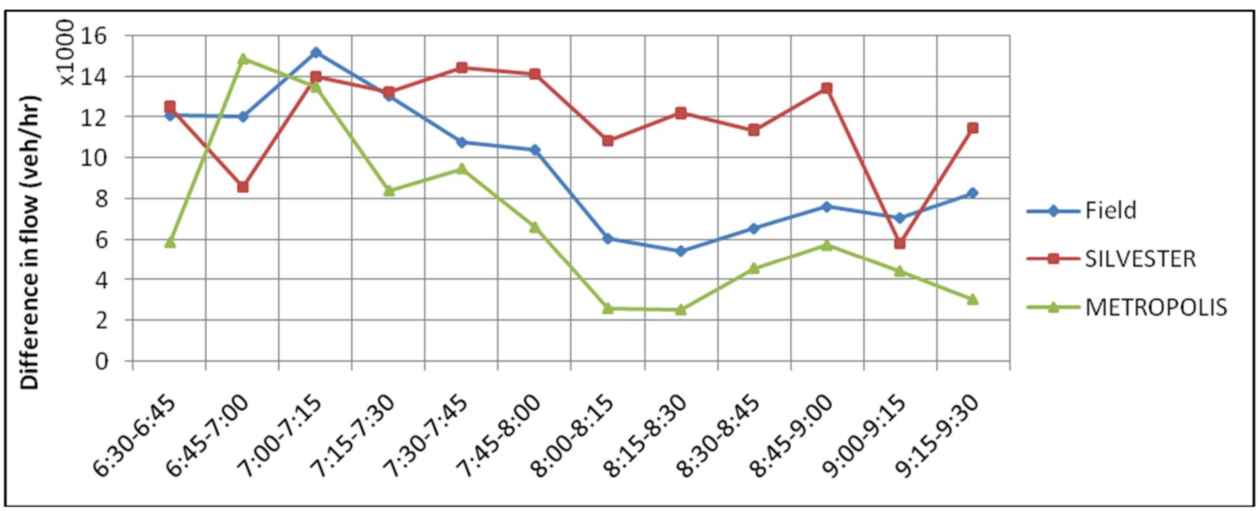

Figure 8: Temporal change in traffic flow for 59 calibration links

To observe the change in travel time due to charging in each of the 11 road sections, 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 sections 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 sections: 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 CONTRAM 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.

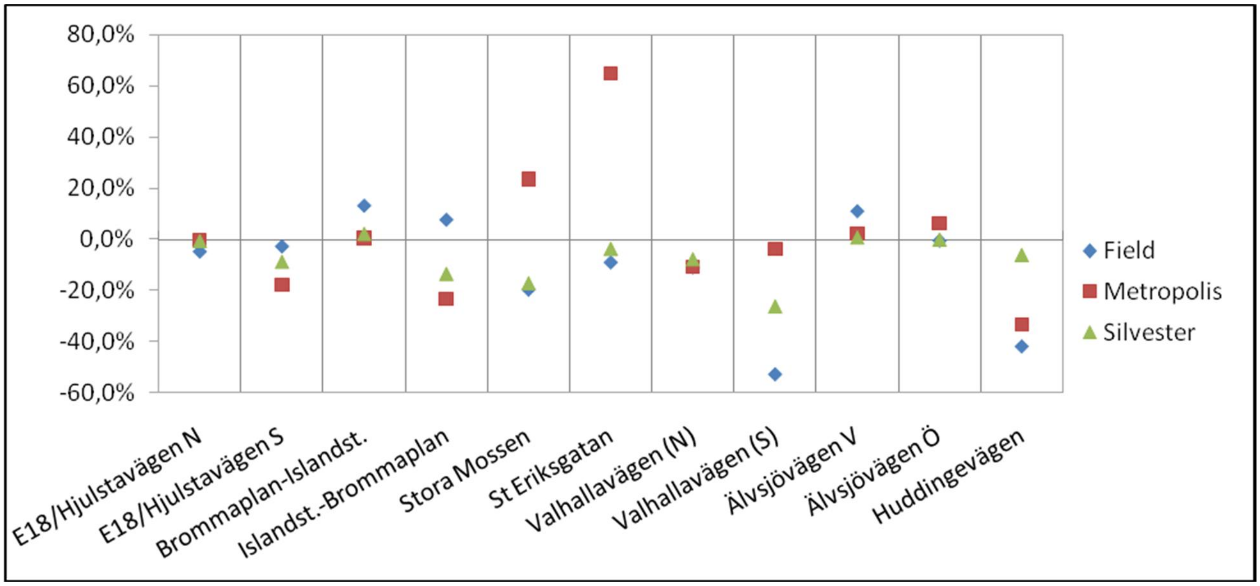

Figure 9: Change of travel time in different road sections

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 analysis. We believe that such cost benefit analysis needs to be based on measures and indexes that are based on strong economic principles. This is the case of the two dynamic models, SILVESTER and METROPOLIS, which have been used to asses Stockholm congestion charging scheme.

The mere aggregate results are not enough for the assessment. 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.

Validation and calibration of a dynamic models 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 mayor 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 between the models. However the computed reduction in flow over 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 (Engelson and van Amelsfort, 2011).

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 in any static model and difficult in a 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 VTTS, 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 (spillback and intersection interactions). This translates in the preliminary results mainly for the consumer surplus.

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