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**Conference Paper**

## Modifications of the Stockholm congestion pricing scheme and effects on different user groups

50th Congress of the European Regional Science Association: "Sustainable Regional Growth and Development in the Creative Knowledge Economy", 19-23 August 2010, Jönköping, Sweden

**Provided in Cooperation with:**

European Regional Science Association (ERSA)

*Suggested Citation:* Kristoffersson, Ida (2010) : Modifications of the Stockholm congestion pricing scheme and effects on different user groups, 50th Congress of the European Regional Science Association: "Sustainable Regional Growth and Development in the Creative Knowledge Economy", 19-23 August 2010, Jönköping, Sweden, European Regional Science Association (ERSA), Louvain-la-Neuve

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# Modifications of the Stockholm Congestion Pricing Scheme and Effects on Different User Groups

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## **Abstract**

This paper uses a newly developed transport model to analyze effects of different congestion pricing schemes. The responses to congestion pricing included in the model are departure time, mode and route choice. Traffic analysis is performed on a large urban network of Stockholm using mesoscopic simulation. Through calculation of consumer surplus per geographical zone, effects of the congestion pricing schemes are also analyzed per socio-economic group in order to study equity effects. Model results suggest that both the current pricing scheme and a modification with differentiated toll depending on location have progressive effects.

## **1. Introduction**

The list of metropolitan areas considering congestion pricing becomes longer and longer, partly because of the success of the congestion pricing schemes implemented in London and Stockholm. Congestion pricing has for a long time been advocated by economists because of its possible efficiency gains (e.g. Vickrey, 1963). Furthermore, an advantage of congestion pricing is that the decision of which trips to change, so that they are no longer subject to pricing, stays with the user. It is travelers themselves that decide which trips are not worth the toll (Fosgerau and van Dender, 2010).

On the other hand, congestion pricing is still questioned regarding its equity effects. Opponents of congestion pricing argue that low-income groups are priced off the road and that those who can afford to pay the charge benefit from reduced travel times in the road network. Equity issues are often recognized as an important part of public resistance to implementation of congestion pricing (Oberholzer-Gee and Weck-Hannemann, 2002; Viegas, 2001).

A large number of theoretical studies have been made on equity effects of congestion pricing, for example a study of welfare effects for commuters along a congested urban traffic corridor by Arnott et al (1994). Small (1983) uses empirical data to analyze welfare effects for highway commuters and Eliasson and Mattsson (2006) extend the theoretical literature with a quantitative methodology for evaluating equity effects of real-world pricing schemes. In the mentioned paper, Eliasson and Mattsson (2006) conclude that analysis of equity effects have to be carried out for specific cities and specific congestion pricing and refund schemes to be able to draw any conclusions on the equity effects of congestion pricing. Furthermore, both Eliasson and Mattsson (2006) and Franklin (2005) find that for most people the total welfare levels are much larger than the size of the redistribution effects due to congestion pricing.

Equity can be analyzed along different dimensions commonly divided into horizontal, vertical and longitudinal equity. Horizontal equity studies opportunities for user groups who in other respects are equal, whereas vertical equity deals with effects on user groups that are unequal, especially effects for those in worst conditions before a pricing scheme is introduced. Longitudinal equity refers to the difference between the present and past situation. Vertical and longitudinal equity are likely to be the two most critical equity dimensions when it comes to congestion pricing. Viegas (2001) stress the importance of longitudinal equity in public resistance, since congestion pricing implies paying for something that until recently was completely free.

Regressive and progressive schemes are two other terms commonly used in this context. They are strongly related to the concept of vertical equity. With a regressive pricing scheme those who are already worse off receive the largest welfare loss, whereas with a progressive pricing scheme the privileged, e.g. users with high income, receive the largest welfare loss.

This paper analyzes how different user groups are affected by modifications to the present congestion pricing scheme in Stockholm. The Stockholm congestion pricing scheme has shown that pricing of transport systems can reduce congestion, increase accessibility and improve the environment in the city centre. However, considering the current scheme's relatively simple toll ring structure with equal charge at all toll locations

both inbound and outbound, it is likely that the scheme's ability to mitigate congestion can be improved.

The modification scenario, compared in this paper to the current toll ring in Stockholm, emanates from an objective to improve efficiency. From an efficiency point of view it is preferable to relate the charged amount to level of congestion. Ekström et al (2009b) find that changing the Stockholm congestion pricing scheme to have differentiated toll levels that are dependent on toll location and driving direction can improve net social surplus<sup>1</sup> with 35-39%. Typically Ekström et al (2009b) find that from an efficiency point of view the charge is too low on inbound links and too high on outbound links in the morning, because during this part of the day there is more traffic going into the central business district than going out.

It is however important to investigate the equity effects of having differentiated toll levels depending on toll location and driving direction. One needs to consider the socio-economic differences in geographical living areas, for example differences between the inner city (inside the toll ring) and the suburbs. Given that households in the inner city of Stockholm have a relatively high income, raising the inbound charge and lowering the outbound could put a high burden on car-users who are already worse off. The main question of this paper thus concerns vertical equity – investigating effects for groups who are initially unequal.

Effects of modifications to the current Stockholm congestion pricing scheme are in this paper studied using a recently developed dynamic transport model for Stockholm called SILVESTER (Kristoffersson and Engelson, 2009a). Choice of departure time is modeled in SILVESTER, which is very important (but often omitted) since both congestion and the charge one has to pay is time-dependent. Car travel times and time spent in queues are calculated using mesoscopic traffic simulation. SILVESTER models car users, but they can switch to public transport, which makes it possible to evaluate the mode switch effect induced by a specific congestion pricing scheme. Modifications suitable to analyze with SILVESTER include changes to charged amounts, timetable and locations where the charge is levied.

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<sup>1</sup> Net social surplus is here equal to the social surplus (consumer surplus + revenues) minus the cost of collecting the charges.

The aim of this paper is to investigate the effects of differentiated toll amounts depending on location and compare these results to a simulation of the current congestion pricing scheme in Stockholm, as well as a simulation of the situation without congestion pricing. Effects concern traffic flows, travel time and queuing time in the road network, as well as mode, route and departure time choices and welfare effects for different income groups.

The paper continues in the next section with a description of the transport model set up for Stockholm, the basic features of the analyzed scenarios and the method for calculating welfare changes for each user group. Section 3 reports and analyzes the results of each scenario and Section 4 concludes.

## **2. Model Description, Scenario Settings and User Groups**

### *2.1 Model Description*

The SILVESTER transport model simulates car traffic in Stockholm from 6:30 to 9:30. SILVESTER consists of two parts: 1) a mixed logit departure time and mode switch model in which car users choose which fifteen minute time interval to depart in, alternatively choose to switch to public transport, and 2) a mesoscopic traffic simulation model (CONTRAM) which calculates travel costs for each fifteen minute interval including travel times, distance costs and charging costs. Iteration is performed between the two parts to reach a general equilibrium. The combined model has been calibrated using reverse engineering (Kristoffersson and Engelson, 2010), such that it produces travel costs for the No-toll scenario that are in accordance with traffic flow measurements made before the toll ring was introduced in Stockholm.

SILVESTER aims at describing the full mix of traffic during the morning, not only commuting to work. On the demand side the model is therefore divided into three trip purposes (Table 1). Trips with these different trip purposes are likely to respond in very different ways to congestion pricing. The evaluations of the Stockholm Trial showed that commuting trips to work mainly changed mode and (to a smaller extent) route, whereas trips with other purposes showed a variety of different ways to adapt including

changing destination, shop on your way home from work and cancelling the trip (Eliasson et al, 2009).

Saleh and Farrell (2005) stress the importance of work schedule flexibility for citizen’s possibility to respond to congestion pricing through retiming of their trips. This supports the segmentation made in SILVESTER where commuting trips are divided into different trip purposes depending on work schedule flexibility. However, Saleh and Farrell (2005) also points out that citizens with flexible work schedules can still have inflexible non-work commitments just before or after the work trip, which puts limitations on their retiming possibilities. The SILVESTER demand model is estimated on both stated and revealed preference data. It is likely that some users with flexible working hours may disregard inflexible non-work commitments in their hypothetical choice, which would lead to an overestimation of the extent to which car users change departure time to avoid congestion pricing in the model.

<i>Trip purpose</i>	<i>Short</i>	<i>Percent of trips</i>
Commuting trips with fixed working hours and school trips	fixed	29
Business trips	business	11
Commuting trips with flexible working hours and other trips <sup>2</sup>	flexible	60

Table 1: Description of trip purposes

The main idea behind the departure time and mode switch model builds on the tradition of Small (1982) in that it calculates the cost to the user for changing departure time as a schedule delay cost which increases the more the user deviates from her preferred departure time. The choice of departure time then becomes a trade-off between the schedule delay cost and the generalized travel costs in the different time intervals. The departure time and mode switch model used in SILVESTER was estimated based on both revealed and stated preference data from car users in Stockholm (Börjesson, 2008). Equation 1 shows the utility function used in the demand models.

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<sup>2</sup> “other trips” include for example shopping and leisure trips

$$\begin{aligned}
U_{CAR,t} &= (\beta_1 + b_{early})SDE_t + \beta_2SDL_t + \beta_3M_t + b_1T_t + b_2\sigma_t + \varepsilon_t, \quad t = 0, \dots, 13 \\
U_{PT} &= C_{PT} + b_3T_{PT} + b_4\delta_{card} + \varepsilon_{PT} \\
SDE &= \max(PDT - ADT, 0) \\
SDL &= \max(ADT - PDT, 0)
\end{aligned} \tag{1}$$

where  $t$  is index of time period<sup>3</sup>,  $SDE$  and  $SDL$  are schedule deviation early and late respectively,  $bearly$  is an extra penalty for changing to an earlier time interval if the target interval is in the early morning<sup>4</sup>,  $M$  is monetary cost which includes both cost of toll and a distance-based cost,  $T$  is travel time,  $\sigma$  is standard deviation of travel time,  $\varepsilon$  is a Gumbel distributed error term,  $CPT$  is an alternative specific constant for public transport,  $\delta_{card}$  is the share of car users who also possess a public transport monthly card<sup>5</sup>,  $PDT$  is the preferred departure time interval and  $ADT$  is the actual departure time interval chosen. Since time is divided into 15 minute time intervals,  $SDE$  and  $SDL$  become multiples of 15 minutes.

In the utility function, parameters labelled  $\beta$  are heterogeneous in the population following a Johnson's SB distribution bounded between  $[-1,0]$ , whereas parameters labelled  $b$  are assumed to be constant in the population. Since the parameters for monetary cost, schedule delay early and late have been estimated as distributions, this means that there is continuous heterogeneity in the value of time (VOT) and the value of schedule delay (VSD) in the demand model population. Van den Berg and Verhoef (2010) stress the importance of including heterogeneity in drivers VOT and VSD when modelling effects of congestion pricing, especially for estimation of welfare gains.

Heterogeneous parameters are in SILVESTER simulated using 50 random draws and the probability to choose an alternative is calculated by averaging over the probabilities corresponding to each random number as described in Train (2003). Parameter values for the different trip purposes are reported in Table 2.

<sup>3</sup> The time period index  $t=0$  denotes departure times before 06:30,  $t=1-12$  denotes departure times in the twelve quarters from 06:30-09:30 respectively and  $t=13$  departure times after 09:30.

<sup>4</sup> For flexible and business trips the extra penalty applies to time intervals before 07:30 and for fixed trips it applies to time intervals before 07:00.

<sup>5</sup> In the estimation  $\delta_{card}$  was a dummy variable equal to 1 if the driver had a public transport monthly card and 0 otherwise.

<i>Parameters</i>	<i>Flexible</i>	<i>Fixed</i>	<i>Business</i>
$\beta 1$	-0.26 (0.30)	-0.16 (0.16)	-0.17 (0.26)
$\beta 2$	-0.32 (0.22)	-0.36 (0.22)	-0.27 (0.26)
$\beta 3$	-0.30 (0.21)	-0.26 (0.21)	-0.12 (0.16)
<i>bearly</i>	-0.05	-0.02	-0.07
<i>b1</i>	-0.23	-0.08	-0.19
<i>b2</i>	-0.09	-0.09	-0.13
<i>b3</i>	-0.19	-0.24	-
<i>b4</i>	18.33	16.74	-
<i>CPT</i>	-37.2	-24	-

Table 2: Parameter values for the departure time choice and mode switch models. For random parameters the reported value corresponds to the mean of the draws used in simulation. The standard deviation of the draws is given inside brackets.

The early penalty parameter has been adjusted in calibration in order to get reasonable<sup>6</sup> results from reverse engineering, which did not work well with a sudden discontinuity in the utility function. Our first approach was to re-estimate the demand models without the early penalty and try reverse engineering again. This resulted in reasonable PDT profiles from reverse engineering, but validation of SILVESTER showed that it overestimated the number of trips changing to a time interval before 6:30 because of the congestion pricing scheme that start at that time (Kristoffersson and Engelson, 2009b). Thus, some form of early penalty for SDE was needed. The early penalty has therefore been manually adjusted such that it is largest before 06:30 and then decreases in each time interval until 07:30 (for *fixed* trips it decreases until 07:00). This “smoothing” of the early penalty resulted in reasonable PDT profiles using reverse engineering. In ongoing work the model is re-estimated with a separate early penalty in each of the early time intervals.

That the schedule delay early parameter is not constant over the morning is reasonable since the value of being at home decreases with time. Schedule delay parameters that vary over the morning have been estimated for example in Tseng and

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<sup>6</sup> A reasonable PDT profile here refers to a profile without a sudden dip in the number of preferred trips that want to travel in a time interval during the morning.



Verhoef (2007). In the paper, Tseng and Verhoef summarizes the main drawback of the conventional model, which uses VSD that does not vary by time of day: “*the conventional model is implausible particularly in that it implicitly assumes that the willingness to pay for spending a minute at home instead of being in the vehicle does not vary by time of day, even not for very early departures*”. The validation of SILVESTER supports the importance of accounting for variation in VSD by time of day and, as discussed above, one penalty for early time intervals was not a sufficiently good approximation of reality in our case.

Consumer surplus is in SILVESTER calculated as a mixed logsum, which gives the expected utility from a choice in the mixed logit departure time choice and mode switch model. Since in the SILVESTER case the cost parameter is itself randomly distributed in the population, the logsum must be converted to monetary terms *before* averaging. De Jong et al. (2007) describe the superiority of the (mixed) logsum over the “rule-of-a-half” as a measure of welfare changes.

Regarding the traffic simulation part of SILVESTER, the ideal would have been to have one user class for each draw in the demand models. In that case we would have had a VOT associated with each draw. Since there are three trip purposes and 50 draws, this would correspond to 150 user classes in assignment. CONTRAM allows for 32 user classes, but given the size of the Stockholm network only about 4 user classes are feasible in order to have a run time of SILVESTER which is no longer than 24 hours.

Route choice under congestion pricing depends to a large extent on car users VOT. Demand is therefore divided into four user classes in assignment depending on VOT: 1) low VOT (<43 SEK<sup>7</sup>/h), 2) medium VOT (43-200 SEK/h), 3) high VOT (>200 SEK/h) and 4) vehicles that are exempted from the toll. For each trip purpose the percent of vehicles in each class depends on the VOT distribution of that trip purpose, except that a fixed percentage (28%) of the vehicles are modelled to be exempted from toll independent of trip purpose. The generalized cost function in assignment is dependent on user class and contains distance and travel time according to Equation 2:

$$V_c = 0.79D_c + VOTmed_c T_c, \quad (2)$$

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<sup>7</sup> 10 SEK ≈ 1,05 EUR

where  $VOT_{medc}$  is the median VOT in user class  $c$ . Class dependent values are reported in Table 3.

<i>User class</i>	<i>VOT<sub>medc</sub></i>	<i>Percent of all users</i>	<i>Percent of flexible users</i>	<i>Percent of fixed users</i>	<i>Percent of business users</i>
1	23	30	25	44	16
2	82	30	36	20	24
3	387	12	11	8	32
4	55	28	28	28	28

Table 3: Characteristics of the user classes in assignment.

## 2.2 Scenario Settings

Three scenarios are compared in the paper:

1. **No toll** – A scenario without congestion pricing.
2. **Current toll ring** – The toll ring implemented in Stockholm today, which constitutes of tolling stations on bridges around the inner city (Figure 1). The charges are time-dependent and vary between 10, 15 and 20 SEK per crossing, with the highest charge during peak hour (in the morning this is 7:30-8:30).
3. **Differentiated toll ring** – In this scenario the current toll ring locations are fixed, but amounts are differentiated by location of the toll. The amounts have been optimized in Ekström et al (2009b) for the morning peak hour. A time profile similar to the current toll ring scheme is applied to the peak hour toll to get the amounts for the whole simulation period 6:30-9:30. Compared to the current scheme, tolls are generally higher inbound and lower outbound in this differentiated scenario. The inbound tolls vary between 18-43 SEK per crossing and the outbound between 8-21,5 SEK per crossing during peak hour depending on location.

Figure 1 shows the CONTRAM Stockholm network. Locations of the current toll stations are marked with x. Figure 1 thus covers the locations of the tolls in scenario 2 and 3.

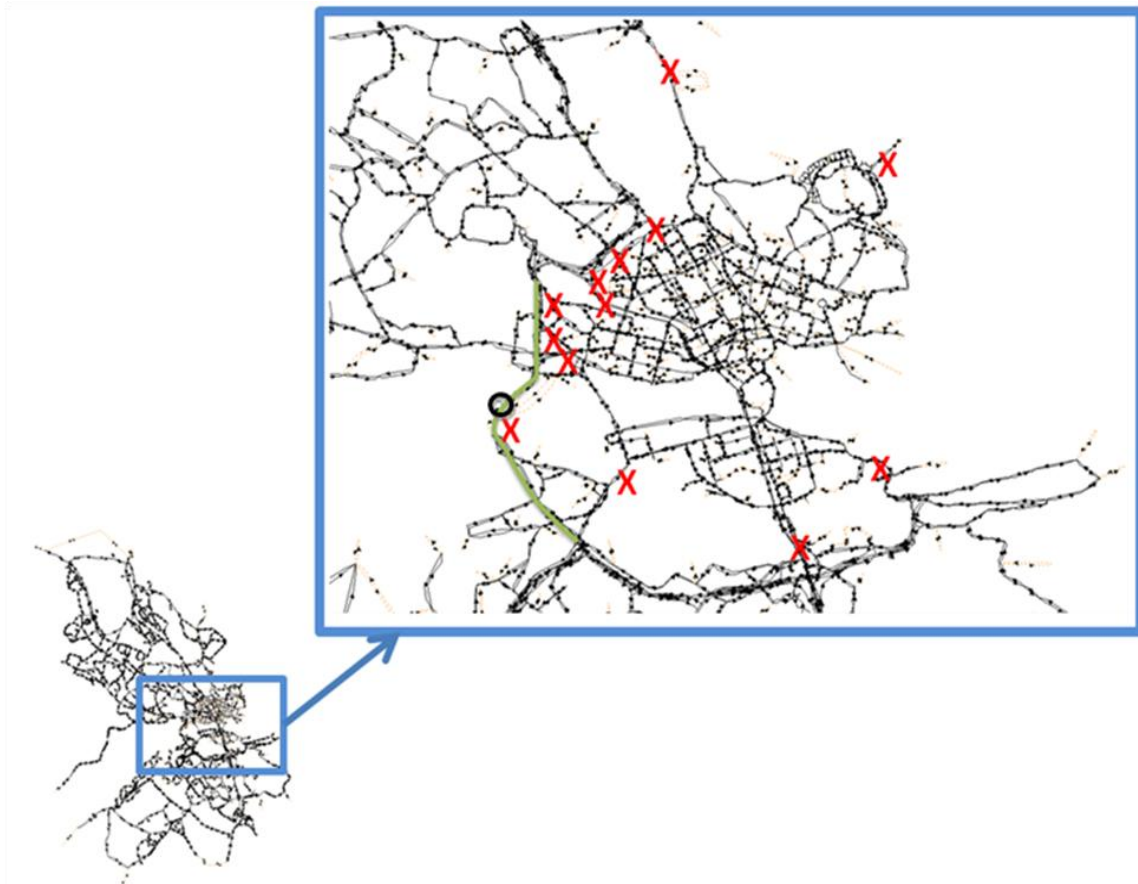


Figure 1: The Stockholm Contram network and locations of the tolling stations ( $x$  – location of gantries in the current toll ring)

### 2.3 User groups

In this paper, welfare effects will be evaluated according to income group, with three categories: low income (less than 195000 SEK/year), medium income (195000-375000 SEK/year) and high income (more than 375000 SEK/year). Income values correspond to income before taxes. Future research will investigate effects on more user groups such as household type and residential location.

Basis for calculations of consumer surplus per user group is the consumer surplus per trip originating in each zone. The change in consumer surplus ( $\Delta CS$ ) due to introduction of congestion pricing is for user group  $j$  calculated as follows:

$$\Delta CS_j = \frac{\sum_i \Delta CS_i \cdot \Omega_{ij} \cdot N_j}{\sum_i \Omega_{ij}}, \quad (3)$$

where  $\Omega_{ij}$  is number of inhabitants in zone  $i$  that belong to group  $j$  and  $N_j$  is number of car trips produced on average by an individual in group  $j$ . The population in each zone segmented on income group is taken from the standard (static) transport model used in Sweden called SAMPERS (Algers and Beser, 2002).  $N_j$  is taken from a travel behavior survey conducted in Stockholm in 2004 (Ericson and Fried, 2006). Table 4 shows number of car trips assumed to be produced by each individual in the three income groups. As one would expect, the production of car trips per person is largest in the high income group and lowest in the low income group.

$N_j$	<i>Low income</i> ( $j=1$ )	<i>Medium income</i> ( $j=2$ )	<i>High income</i> ( $j=3$ )	<i>Average</i>
# Car trips undertaken during a work day 6:30-9:30 (per person)	0.088	0.188	0.249	0.156

Table 4: Car trip production depending on income group.

### 3. Results

Table 5 summarizes simulation results regarding a number of network characteristics for the four tolling scenarios, but let us first describe the starting point, i.e. the No-Toll-scenario: In this scenario 358 out of 5116 links exceed capacity at some point during the modelled morning peak period and the average congestion index (average travel time over free-flow time) in the network lies between 1.26 in the time interval 6:30-6:45 and 1.49 in the time interval 8:00-8:15, with an average of 1.38 seen over the whole morning. However on some exceptional links travel time is more than three times the free-flow time. Figure 2, which shows the volume over capacity ratio, confirms that congestion is minor in large parts of the network but severe in the city centre and on some of the approach roads towards the inner city, even at a fairly long distance from the city centre.

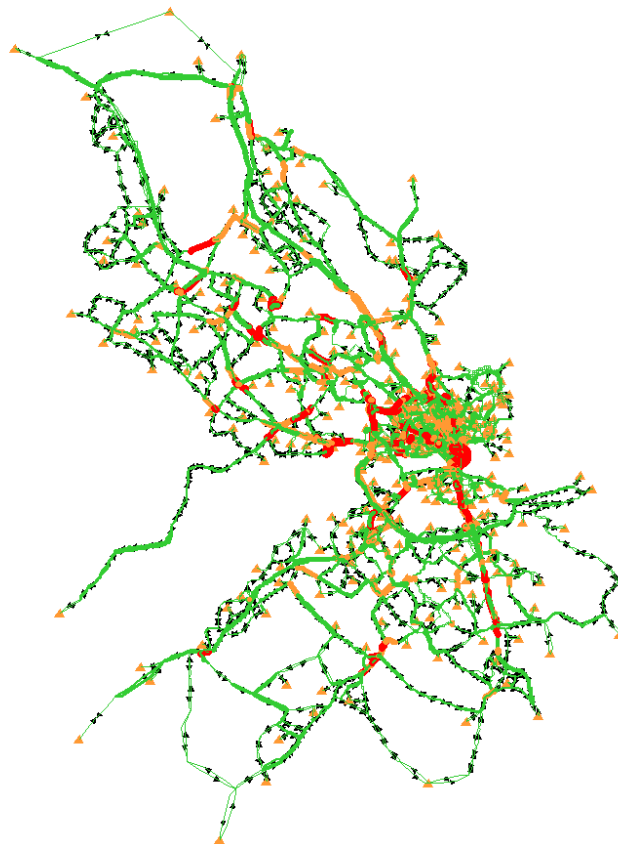


Figure 2: Volume over capacity in the No-Toll-scenario for the time interval 8:00-8:15 (red links have a V/C ratio over 1, orange link a V/C ratio between 0.8 and 1, and green links a V/C ratio less than 0.8)

Returning to Table 5, it shows that average network speed and especially the speed on the cordon links increases when the network is subject to congestion pricing, as expected. The total distance travelled in the network decreases, since some trips change departure time to a starting time outside of the modelled morning period (6:30-9:30) and some trips switch to public transport. The route choice counteracts this decrease in total distance travelled somewhat, since the congestion pricing scheme encourages car users to travel a longer route around the inner city on the motorway Essingeleden which is free of charge (The green road in Figure 1). This increase in distance due to the route choice is however minor and corresponds for scenario 2) approximately to 0.2% (the difference between the reduction in overall demand (-2%) and the reduction in total vehicle-kilometers (-1.8%)).

<i>Characteristic</i>	<i>1) No toll</i>	<i>2) Current toll ring</i>	<i>3) Differentiated toll ring</i>
<i>Average network speed</i>	39.8 km/h	41.0 (+3.0%)	41.5 (+4.3%)
<i>Average speed on cordon links</i>	41.8 km/h	45.6 (+9.0%)	47.1 (+12.7%)
<i>Total distance travelled in network</i>	3645877 veh-km	3581864 (-1.8%)	3532984 (-3.1%)
<i>Total queuing time in network</i>	16776 veh-h	14771 (-12.0%)	14284 (-14.9%)
<i># links that exceed capacity * # time intervals capacity is exceeded</i>	358*1097 = 436606 links*tp	260*899 = 233740	261*796 = 207756

Table 5: Overall network results for the different scenarios.

Table 6 compares the welfare effects of the two tolling scenarios. Welfare effects are investigated at network level: total change in consumer surplus ( $\Delta CS$ ), revenues and total change in social surplus ( $\Delta SS$ ) compared to the situation without congestion pricing. Change in consumer surplus per income group and per trip purpose is also reported.

<i>Welfare measure</i>	<i>2) Current toll ring</i>	<i>3) Differentiated toll ring</i>
<i>Total <math>\Delta</math> CS</i>	-441096 SEK	-687450 SEK
<i>Total revenues</i>	716917 SEK	974013 SEK
<i>Total <math>\Delta</math> SS</i>	275821 SEK	286563 SEK
<i>Average <math>\Delta</math> CS per trip</i>	-1.55 SEK	-2.42 SEK
<i>Gainers no refund</i>	45.4 %	45.9 %
<i>Average <math>\Delta</math> CS flexible trips</i>	-1.85 SEK	-2.88 SEK
<i>Average <math>\Delta</math> CS fixed trips</i>	-1.81 SEK	-2.54 SEK
<i>Average <math>\Delta</math> CS business trips</i>	+0.87 SEK	+0.52
<i>Average <math>\Delta</math> CS low income users</i>	-0.15 SEK	-0.20 SEK
<i>Average <math>\Delta</math> CS medium income users</i>	-0.33 SEK	-0.43 SEK
<i>Average <math>\Delta</math> CS high income users</i>	-0.46 SEK	-0.53 SEK

Table 6: Comparison of welfare effects for different user groups

#### 4. Conclusions

For the current toll ring and the modification with differentiated toll depending on location, the model results show that the change in consumer surplus is least negative for low income car users and most negative for high income users. This suggests that the both congestion pricing scenarios are progressive rather than regressive.

Looking at the results of this paper one should bear in mind that the responses possible in the model are to change route, mode or departure time. The users can thus not respond by for example changing destination or cancelling the trip. The reductions in flow over the cordon are thus smaller than what measurements from reality have shown (Eliasson et al, 2009). However they are only slightly smaller, which indicates an overestimation of especially departure time adaptations. The reason behind this could be that in reality there are inflexible non-work commitments also for those with flexible working hours which were not captured in the stated preference study, as discussed in section 2.1. It is also likely that the penalties for changing departure time in the early morning are not satisfactory. The parameter values of these early penalties will be

determined in future work through re-estimation of the departure time and mode choice model with separate dummy variables for each early time interval. Furthermore, the results indicate that departure time changes occur for most OD-pairs, whereas mode switch increases almost only for trips passing the cordon.

One very important question not dealt with in this paper is the question of revenue use. Future work will investigate the effects of different refund schemes on equity effects of modifications to the current congestion pricing scheme in Stockholm. Furthermore, we will also study equity effects based on other segmentations of the population, e.g. type of household (single, two or more adults without children in household, one adult with children, two or more adults with children). Also, the number of congestion pricing scenarios will be extended in future work, comparing for example toll locations other than the current toll ring.

## **Acknowledgement**

This paper is part of the project “Alternative road user charging and individuals’ travel choices” (AVENIR), which is founded by the Swedish Transport Administration and the Swedish Governmental Agency for Innovation Systems (VINNOVA). Thanks to my supervisor Leonid Engelson and co-supervisor Staffan Algers for fruitful discussions.

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