DEPARTURE TIME CHOICE EFFECTS OF CONGESTION CHARGES WITH AND WITHOUT TIME DIFFERENTIATION

Ida Kristoffersson; Centre for Traffic Research, Royal Institute of Technology in Stockholm (KTH); idak@kth.se (corresponding author)

ABSTRACT

This paper uses a simulation model to compare traffic and welfare effects of modifications in the charging schedule currently in use in Stockholm. In particular, a step toll is compared to its flat counterpart at two charging levels. The increments between steps are also increased in a peaked step toll scenario. In the model, car users have the possibility to respond to congestion charging by changing departure time, route or switch to public transport. Travel times are calculated using mesoscopic traffic simulation. The current step toll reaches the highest social surplus estimate in model predictions, but differences in traffic effects between the current step toll and its flat counterpart are rather small. Furthermore, results show that demand changes occur in the model to a considerably greater extent for trips with low value of time. The differences in welfare effects is for that reason large for different trip purposes, indicating the importance of accounting for heterogeneous trips when modelling effects of congestion charges.

Keywords: Congestion Charging, Departure Time Choice, Time Differentiation, Schedule Flexibility, Traffic Simulation

INTRODUCTION

In the last decade, congestion charging has been successfully introduced both in Stockholm (Eliasson et al., 2009) and in London (Litman, 2004) and several other cities are now considering charging as a means of reducing congestion. The main objections have for a long time concerned the practicability and public acceptability of congestion charging (May, 1992). The design of the congestion charging scheme, i.e. how much, when, where and whom to charge, must therefore be done with care.

This paper considers questions about how much and when to charge, that is the design of the charging schedule. In the paper, a simulation model of the Stockholm road network including route choice, departure time choice and switch to public transport is used to test changes in the charging schedule for the cordon in use in Stockholm today. In particular, the effects of flat tolls are compared to the effects of time differentiated tolls.

Earlier work on the temporal structure of charges mainly considered a bottleneck (Braid, 1989; Arnott, 1993) or a single urban highway (Chu, 1999), an exception being de Palma et al. (2005) who use the dynamic simulator METROPOLIS to compare different congestion charging schemes on a laboratory road network. These earlier studies all discuss and compare optimal toll levels that maximize social surplus. This is a difference compared to this paper, which starts out from the congestion charging scheme actually implemented in Stockholm and alter that schedule in order to investigate effects of modifications in the already implemented charging scheme.

Research on where to charge, i.e. on toll locations and cordon design, can be found for example in Ekström et al. (2009) and May et al. (2002). Research on charging beyond point or cordon charging can be found for example in May and Milne (2000), who compares cordon charging to time-based, time-in-congestion-based and distance-based charging.

The simulation model is described in the next section, followed by a section describing the different tolling scenarios compared in the paper. Section *scenario results* show and comment on the model predictions for each scenario. A concluding section ends the paper.

MODEL DESCRIPTION

This paper uses a quasi-dynamic simulation model called SILVESTER in order to compare effects of different congestion charging schedules. SILVESTER has been developed especially with analysis of congestion charging in mind (Kristoffersson and Engelson, 2009a). It models congestion in a more realistic way than conventional transportation models by dividing time into 15 minute time intervals and using mesoscopic rather than macroscopic traffic simulation so that traffic signals and queues at intersections are explicitly taken into account. SILVESTER also includes route and departure time choice as well as a possibility to switch to public transport, which are all common traveller responses to congestion charges (Transportation Research Board, 2003).

SILVESTER is calibrated for Stockholm and models car trips during the morning from 06:30 to 09:30. Route choice, travel time and monetary cost of the trip are calculated by the quasi-dynamic mesoscopic assignment model CONTRAM (Taylor, 2003). 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).

Table 1 – Description of trip purposes

Trip purpose	**Short**	**Percent of trips**
Commuting trips with fixed working hours and school trips	fixed	29
Business trips	business	11
Commuting trips with flexible working hours and other trips[1]	flexible	60

For each trip purpose a mixed logit departure time choice and mode switch model is used which has been estimated on revealed and stated preference data from car drivers travelling towards the inner city of Stockholm in 2005 (Börjesson, 2008). Departure time choice is modelled by including schedule delay parameters in the utility function similar to how

---

[1] “other trips” include for example shopping and leisure trips

schedule delay parameters was first introduced by Small (1982). Mode switch is modelled by including an alternative for the car users to switch to public transport. Equations 1 and 2 show the utility function used in the SILVESTER departure time choice and mode switch models[2].

$$
\begin{aligned}
U_{CAR,t} &= \beta_1 SDE_t + \beta_2 SDL_t + \beta_3 M_t + b_1 T_t + b_2 \sigma_t + \varepsilon_t, \quad t = 0,\ldots,13 \\
U_{PT} &= C_{PT} + b_3 T_{PT} + b_4 \delta_{card} + \varepsilon_{PT}
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
SDE &= \max(PDT - ADT, 0) \\
SDL &= \max(ADT - PDT, 0)
\end{aligned}
\tag{2}
$$

where *t* is index of time period[3], *SDE* and *SDL* are schedule deviation early and late respectively, *M* is monetary cost which includes both cost of toll and a distance-based cost, *T* is travel time, *σ* is standard deviation of travel time, *ε* is a Gumbel distributed error term, *CPT* is an alternative specific constant for public transport, *δcard* is the share of the car users who also have a public transport monthly card[4], *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. *ADT* is possible to observe from field measurements, but user *PDT* is not. In SILVESTER, the *PDT*-flows have been estimated using a method called reverse engineering (Kristoffersson and Engelson, 2009b). In reverse engineering, the *PDT*-flows are adjusted such that they reproduce the OD-matrix in the No-Toll-situation, given the departure time and mode switch model under consideration. The PDT-flows are then assumed to stay the same when evaluating the different tolling scenarios.

In the utility function, parameters labelled *β* 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. Heterogeneous parameters are simulated using random numbers 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.

Table 2 – Parameter values for the departure time choice and mode switch models. Mean and standard deviation of random parameters correspond to the underlying normal distributions.

	Flexible		**Fixed**		**Business**	
Parameter	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev
β_1	-2.19	1.14	-1.93	-1.01	-2.45	-1.09
β_2	-1.83	0.75	-1.25	0.87	-1.74	0.03
β_3	-1.77	-1.20	-2.08	2.04	-3.35	2.03
b_1	-0.24		-0.19		-0.19	

---

[2] For business trips the public transport alternative is not available, since in the collected stated choice data almost no business traveller chose public transport.

[3] 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.

[4] In the estimation δ_{card} was a dummy variable equal to 1 if the driver had a public transport monthly card and 0 otherwise.

b_2	-0.06	-0.06	-0.11
b_3	-0.18	-0.22	NA
b_4	10.90	13.49	NA
C_{PT}	-5.65	-7.10	NA

Since the monetary cost parameter is heterogeneous in the population this means that car users in SILVESTER are modelled to have continuously distributed values of time (VOT's). VOT thus differs both within and across trip purposes. When trips are assigned to the network continuously distributed VOT's result in too long computation run times. Some of the heterogeneity in VOT is however kept by mixing trip purposes in assignment and dividing trips into three value-of-time-classes plus one class for vehicles that are exempted from congestion charging. Mayet and Hansen (2000) show the importance of accounting for heterogeneity in VOT when evaluating congestion charging. Specifically they point out that when VOT is no longer seen as constant then there is no longer a unique socially optimal charge and that introducing congestion charging in this case may increase consumer surplus as well as social surplus.

Consumer surplus is calculated in SILVESTER 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.

The Stockholm Trial in 2006 and the measurements and evaluations performed during this period served as a unique opportunity to validate the SILVESTER model. The Stockholm Trial congestion charging scheme was coded in SILVESTER and flow and travel time reductions compared (Kristoffersson and Engelson, 2009c). The validation showed similar model reductions in flow over the cordon compared to measurements from reality (approximately -18%). One should bear in mind though that some quite common traveller responses in reality, such as trip chaining, cancelling the trip and changing destination, are not included in SILVESTER.

TOLLING SCENARIOS

As described above, this paper compares different charging schedules, where the amount charged during the day are in some scenarios constant and in some scenarios changing in steps (Table 3). Smoothly varying tolls are not considered due to the time resolution of the simulation model, which is quasi-dynamic using time intervals of 15 minutes, and since smoothly varying tolls are unlikely to be implemented in Stockholm in the near future. Toll locations are the same in all scenarios since focus is on differences in time and not space. Figure 1 shows the toll cordon common to the scenarios compared in this paper.

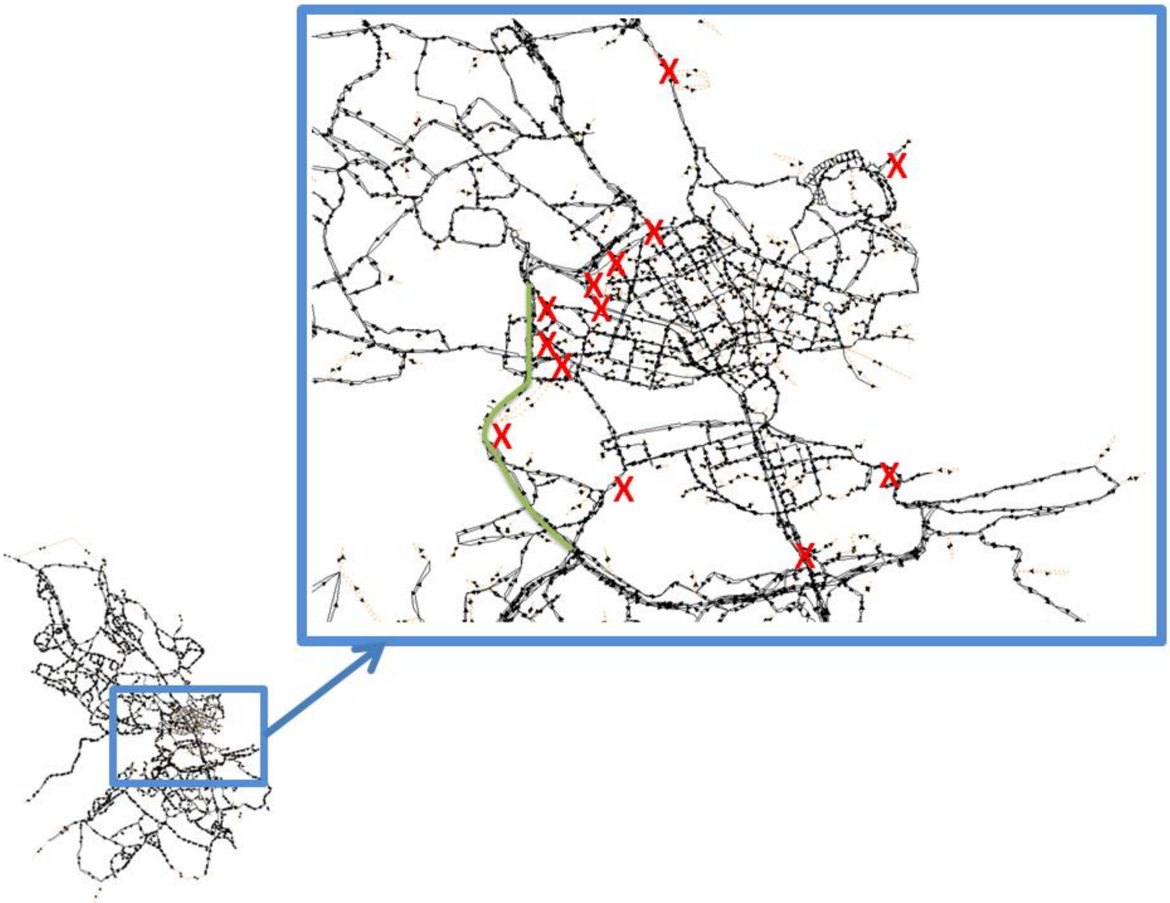

Figure 1 – The toll cordon in the Stockholm CONTRAM Network (The red x-marks represent toll locations and the green line shows the motorway "Essingeleden" which is free of charge)

The following list describes, together with Table 3, the scenarios in more detail:

1. **No Toll**: This is the base scenario. The flows in the preferred departure time intervals have been calibrated such that the resulting dynamic OD-matrix produces flows that resemble the 2005 traffic situation in Stockholm before any congestion charges were introduced.

2. **Step Toll 10-15-20 SEK**: This is the charging scheme design that was introduced in Stockholm 2006.

3. **Flat Toll 15 SEK**: In this scenario the charge is 15 SEK during the whole morning. The amount is chosen such that the revenues are approximately equal to the revenues in scenario 2.

4. **Peaked Step Toll 5-15-25 SEK**: This is a variant of scenario 2 in which the differences between charges in adjacent time periods have been increased in order to further promote road user departure time changes.

5. **Flat Toll 5 SEK**: This scenario and the following (scenario 6) was chosen in order to be able to compare a flat and a time differentiated toll at a lower charge level and thus at a higher level of congestion.

6. **Step Toll 2,50-5-7,50 SEK**: This is the time differentiated scenario corresponding to scenario 5. The revenues collected in this scenario approximately equal the revenues collected in scenario 5.

Table 3 gives an overview of the tolling scenarios compared in the paper. Scenario 2, 4 and 6 are differentiated in time, whereas a flat charge is used in scenario 3 and 5.

Table 3 – Amounts charged in the different time periods

Tolling Scenario	**06:30-07:00**	**07:00-07:30**	**07:30-08:30**	**08:30-09:00**	**09:00-15:30**
1. No Toll	-	-	-	-	-
2. Step Toll 10-15-20 SEK	10	15	20	15	10
3. Flat Toll 15 SEK	15	15	15	15	15
4. Peaked Tolls 5-15-25 SEK	5	15	25	15	5
5. Flat Toll 5 SEK	5	5	5	5	5
6. Step Toll 2,50-5-7,50 SEK	2,50	5	7,50	5	2,50

SCENARIO RESULTS

Overall Network Results

Table 4 summarizes the findings regarding a number of network characteristics for the six tolling scenarios, but let us first describe the starting point, i.e. the No-Toll-scenario: In this scenario 211 out of 5116 links exceed capacity at some point during the modelled morning peak period and the average congestion index in the network lies between 1.02 in the last time interval and 1.41 in the time interval 8:00-8:15, with an average of 1.32 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.

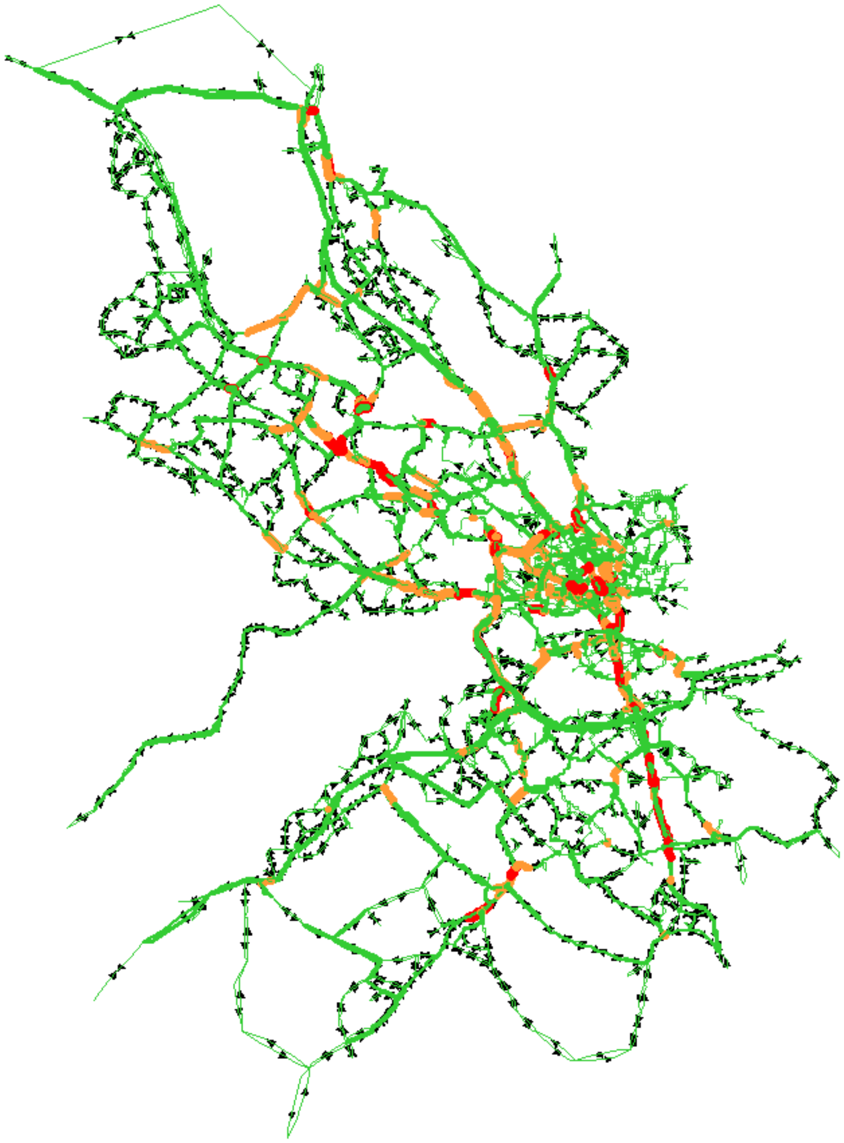

Figure 2 – Volume over capacity in the No-Toll-scenario for the time interval 8:00-8:15 (red links have a V/C ratio over 1, orange link a V/C ratio between 0.8 and 1, and green links a V/C ratio less than 0.8)

Moving on to the results of the tolling scenarios, we notice that all scenarios manage to increase average speed in the network and on the cordon links, and to reduce flow on the cordon, total distance travelled in the network and the measure we use for congestion in the nework, which is number of links that exceed capacity times number of time intervals capacity is exceeded (Table 4).

Flow on cordon is on average reduced most in scenario 3, which is the flat toll of 15 SEK. Average flow reduction for the peak hour is highest in scenario 4, which one would expect considering that this is the scenario with peaked tolls. Congestion is reduced most in scenario 4, even though this scenario does not manage to reduce total distance travelled as much as scenario 2 and 3. The difference in congestion reduction between the flat and the time differentiated toll on the 15 SEK level is only 0.4%. On the 5 SEK level the difference is 1%. This result indicates that the difference between the flat and the time differentiated toll in ability to reduce congestion increases with level of congestion still present in the road network subject to charging. The overall picture is however that the differences between the results of the flat and the time differentiated toll are small. This rather similar performance of the flat and the time differentiated toll will be investigated further in the remainder of the paper.

Table 4– Network characteristics for the different tolling scenarios

Tolling Scenario	**Average network speed**	**Average speed on cordon**	**Average flow on cordon, peak hour in brackets**	**Total distance travelled in network**	**# links that exceed capacity * # time intervals capacity is exceeded**	**Change in # links that exceed capacity * # time intervals capacity is exceeded**
1. No Toll	41.6 km/h	43.9 km/h	35604 (38948) veh/h	3421878 veh-km	211*664 = 140104	-
2. Step Toll 10-15-20 SEK	+4.1%	+9.1%	-18.4% (-21.2%)	-3.4%	156*471 = 73476	-47.6%
3. Flat Toll 15 SEK	+4.1%	+9.1%	-19.3% (-15.8%)	-3.8%	158*468 = 73944	-47.2%
4. Peaked Tolls 5-15-25 SEK	+3.8%	+8.0%	-15.9% (-24.4%)	-2.4%	154*472 = 72688	-48.1%
5. Flat Toll 5 SEK	+1.7%	+4.6%	-9.4% (-7.1%)	-1.4%	193*584 = 112712	-19.6%
6. Step Toll 2,50-5-7,50 SEK	+1.7%	+4.8%	-8.4% (-12.3%)	-1.1%	187*595 = 111265	-20.6%

Time Spent in Queue

Figure 3 shows total time spent queuing on all links in the network for each time interval. In most of the scenarios queuing time peaks in the time interval 8:00-8:15. The time differentiated tolls show a somewhat flatter queuing peak than the flat tolls. The peaked toll result in high queue levels in the beginning of the morning, when at the same time the peak is not much lower than in scenario 2.

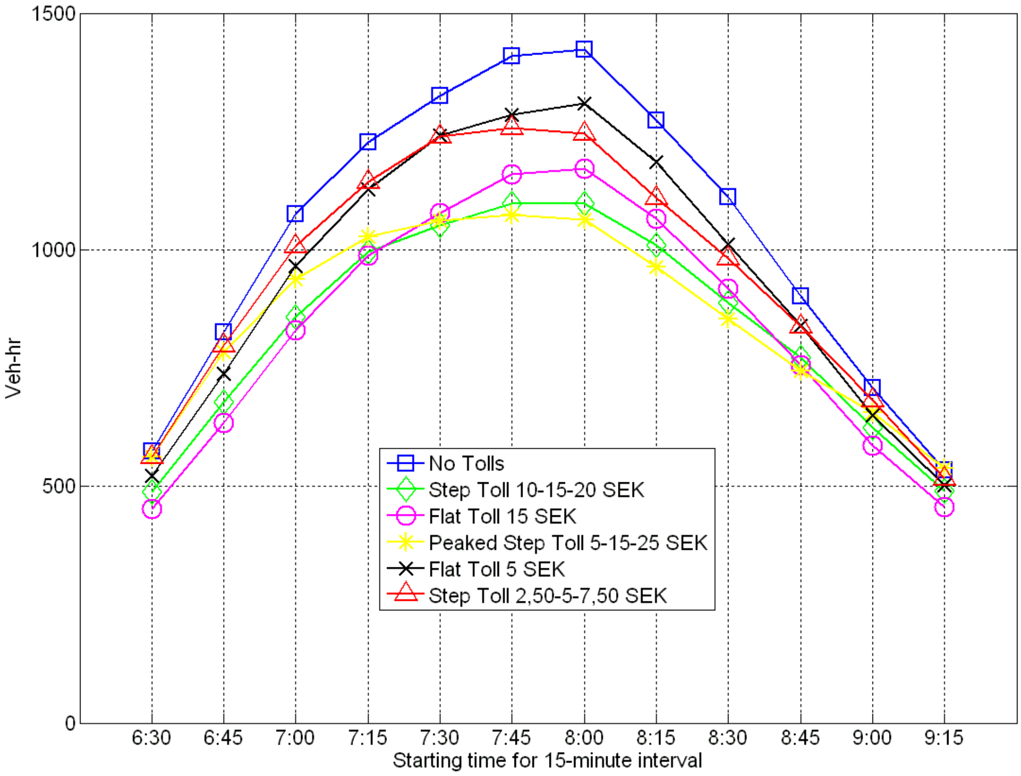

Figure 3 – Total queue time on all links in the network

Figure 4 shows total time spend queuing on cordon links. Both the flat and the time differentiated toll at the 15 SEK level succeed in eliminating most of the queuing peak. Scenario 4 with peaked tolls has no possibility to improve much upon scenario 2 and 3 due to the fact that already the flat toll managed to cut most of the peak. In fact, scenario 4 performs worse than scenario 2, giving rise to a small peak in early time intervals due to the low charge levied there (5 SEK). At the lower charging level the differences between the flat and the time differentiated toll are more pronounced. The flat toll of 5 SEK does not manage to eliminate most of the queuing peak and there is a possibility for the time differentiated charge to flatten out the peak. This occurs however only to some extent, and is combined with another effect – the peak is shifted towards earlier time intervals.

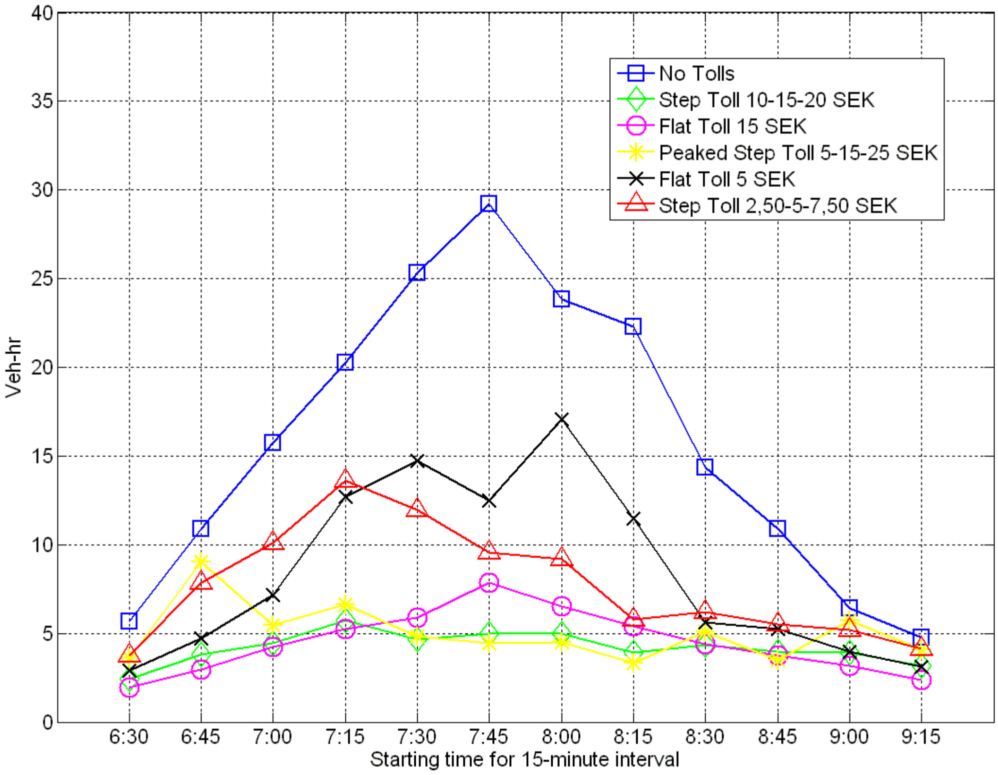

Figure 4 – Total queue time on cordon links

Changes in Trip Demand Compared to the No Toll Scenario

As described in the model description section, demand in SILVESTER is elastic with respect to route, departure time and partially mode choice. Mode choice is partially modelled in the sense that car users can switch to public transport, but there are no public transport users in the model that can switch to car. The model thus assumes that shifting from public transport to car because of congestion charges on car driving (possibly due to shorter car travel times) is a negligible effect.

Figure 5 shows changes in demand compared to the No-Toll-scenario for trips crossing the cordon (except through trips). Compared to the No-Toll-scenario, scenario 2 results in about 19600 fewer vehicle counts (-18.4%) on cordon links in the modelled time period (Table 4). About 5600 of these counts correspond to vehicles changing departure time to a time interval before the charging period starts and about 3100 counts correspond to car users switching to public transport (Figure 5). Through trips changing route answer for the rest of the reduction in vehicle counts over the cordon. Taking into account that each trough trip crosses the cordon twice, this means that about 5450 out of 36500 through trips changed route in scenario 2.

The result in scenario 2 is an overestimate of changes in departure time to a time interval before charging starts compared to measurements from the Stockholm Trial. Also route choice effects for through trips are somewhat overestimated. However, the overall reduction of trips in the modelled period corresponds well in magnitude to the combined effect of changes in mode, route, departure time, trip chaining, destination and cancellation of trips observed in reality. In fact, since trips in SILVESTER that change to a time interval before 6:30 are no longer included in assignment they could be seen as corresponding to cancelled trips. A problem here is of course that one would assume cancellation of trips not to be concentrated mainly towards the beginning of the morning.

The likely cause of the overestimated departure time choice effect, with traffic moving to a time interval before charging starts, is that the schedule delay parameter distributions do not vary with time interval in SILVESTER. Thus, the schedule delay early cost of departing for example 30 minutes before PDT is the same at 6:30 as at 9:30, which could be questioned. The limitations of the conventional time-independent formulation of schedule delay are shown in Tseng and Verhoef (2008), whose results also suggest that value of schedule delay do vary over the morning peak. Further research will discuss the implications on the performance of flat and time differentiated tolls, when reducing departure time choice effects through an extra penalty in SILVESTER on schedule delay for early time periods.

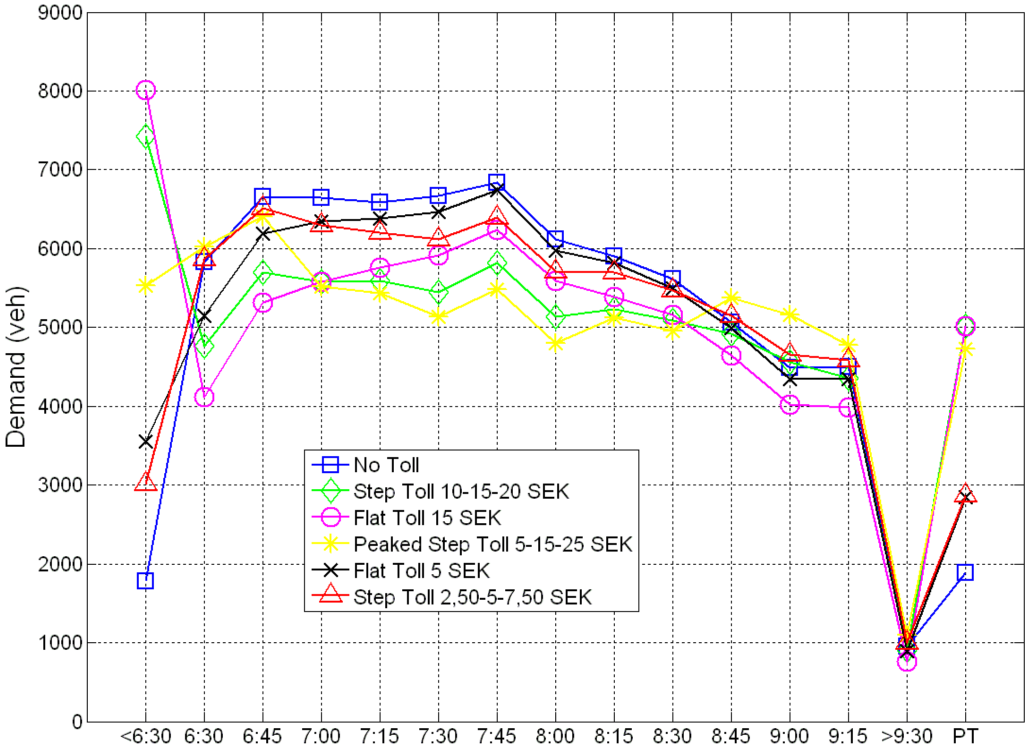

Figure 5 – Changes in demand for trips to or from the inner city for each starting interval and public transport

In scenario 3 about 6200 vehicles change departure time to a time interval before 6:30 compared to the No-Toll-scenario. That this number is somewhat higher than in scenario 2 is reasonable, since the flat charge is higher than the time differentiated charge in the early time intervals (15 compared to 10 SEK). The number of trips switching to public transport is similar to scenario 2 for scenario 3 and 4. Scenario 5 and 6, that operate on a lower charge level, result in about 1000 trips switching to public transport compared to the No-Toll-scenario. In scenario 5 and 6 demand for travel before 6:30 increases about as much as demand for public transport, i.e. with about 1000 trips. Scenario 4 reduces demand for trips in the peak hour most (-5000 trips), as one would expect due to the peaked tolling schedule in this scenario, and scenario 5 reduces demand for trips in the peak hour least (-500 trips), which is also expected since this scenario has the smallest flat charge. None of the tolling scenarios yields any differences in demand for trips departing after the modelled time period, i.e. after 9:30.

Consumer Surplus and Revenues

Total Consumer Surplus and Revenues for the Scenarios

Figure 6 shows total revenues and total consumer surplus for the different tolling scenarios compared to the No-Toll-scenario. As mentioned earlier, the flat and the time differentiated tolls are on purpose chosen such that their total revenues approximately equal each other for the schemes to be comparable.

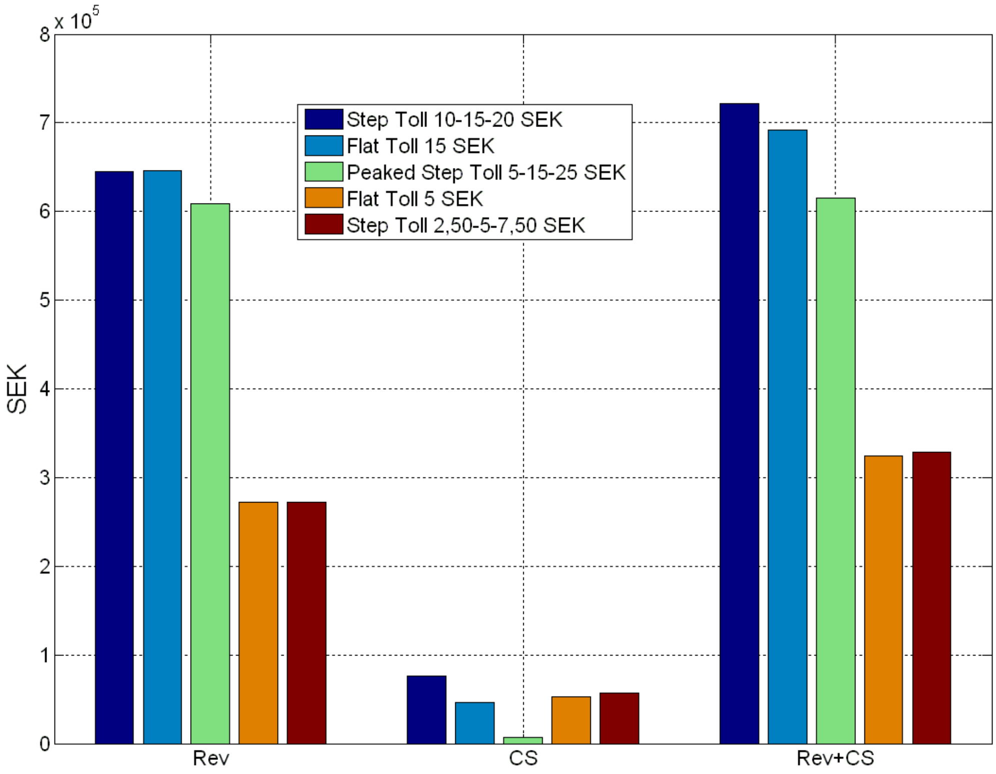

Figure 6 – Comparison of consumer surplus and revenues for the different tolling scenarios

Total consumer surplus is positive in all scenarios even before revenues are redistributed to the users. A positive consumer surplus is uncommon in static macroscopic models, but appear here since the supply model used in SILVESTER is a quasi-dynamic, mesoscopic model in which drivers not crossing the cordon can benefit from reduced congestion on links other than the tolled links. Furthermore car users in the model have heterogeneous VOT's, which also affect consumer surplus.

The differences in the static and dynamic analysis of tolling effects are described for example in Fosgerau and Van Dender (2010). They show how the optimal time-varying toll removes all congestion at a bottleneck, whereas queuing is still present after applying the optimal static toll. The same paper also describes how allowing for travellers to have different VOT's will in general lead to increased welfare effects, i.e. a higher consumer surplus, than in the case of homogeneous travellers. The reason here is that trips that no longer occur on the charged links (because the traveller changed mode, departure time, route, cancelled the trip etc.) are likely to have a lower VOT, than trips still performed after tolling is implemented. Thus the average VOT increases for charged trips, which leads to higher welfare benefit estimates of the charging policy.

This pattern is found also in the scenario results of SILVESTER. Table 5 shows the reduction in vehicle-kilometres travelled 6:30-9:30 per user class. In all scenarios the reduction in vehicle-kilometres is considerably higher for trips with low VOT than in the other classes. This implies that the majority of trips that change departure time or switch to public transport are trips with low VOT. The effect on route choice cannot be assessed from Table 5.

Table 5 – Reduction in vehicle-kilometres travelled per user class in assignment

Change in vehicle-kilometres travelled 06:30-09:30	**Class 1: Low VOT (36 SEK/h)**	**Class 2: Medium VOT (102 SEK/h)**	**Class 3: High VOT (405 SEK/h)**	**Class 4: Exempted vehicles (109 SEK/h)**
2. Step Toll 10-15-20 SEK	-14.9%	-1.4%	-0.5%	-0.2%
3. Flat Toll 15 SEK	-15.7%	-1.6%	-0.6%	-0.2%
4. Peaked Tolls 5-15-25 SEK	-11.3%	-0.9%	-0.5%	-0.2%
5. Flat Toll 5 SEK	-5.4%	-0.1%	-0.6%	-0.2%
6. Step Toll 2,50-5-7,50 SEK	-4.8%	-0.1%	-0.5%	-0.1%

Furthermore, Figure 6 shows that social surplus (consumer surplus and revenues) is greatest for scenario 2. This is in line with earlier work showing the superiority of time differentiation over a flat toll (e.g. Chu, 1999). It is however worth noticing that social surplus of the peaked step toll is lower than that of the flat toll, probably due to the fact that the peaked step toll does not manage to remove as much traffic from the modelled time period as the flat toll.

At the lower charging level the flat and the time differentiated tolls result in approximately the same social surplus.

Average Consumer Surplus per Preferred Departure Time Interval

Figure 7 shows average consumer surplus per PDT-interval. All scenarios result in negative consumer surplus for users with a PDT-interval in the late morning. Since there is a charge also after 9:30 these user can not gain anything by switching later. Scenario 2, 3 and 5 result in highest average consumer surplus for users with early PDT's, whereas in scenario 4 and 6 consumer surplus is highest for users that have their PDT in the peak hour.

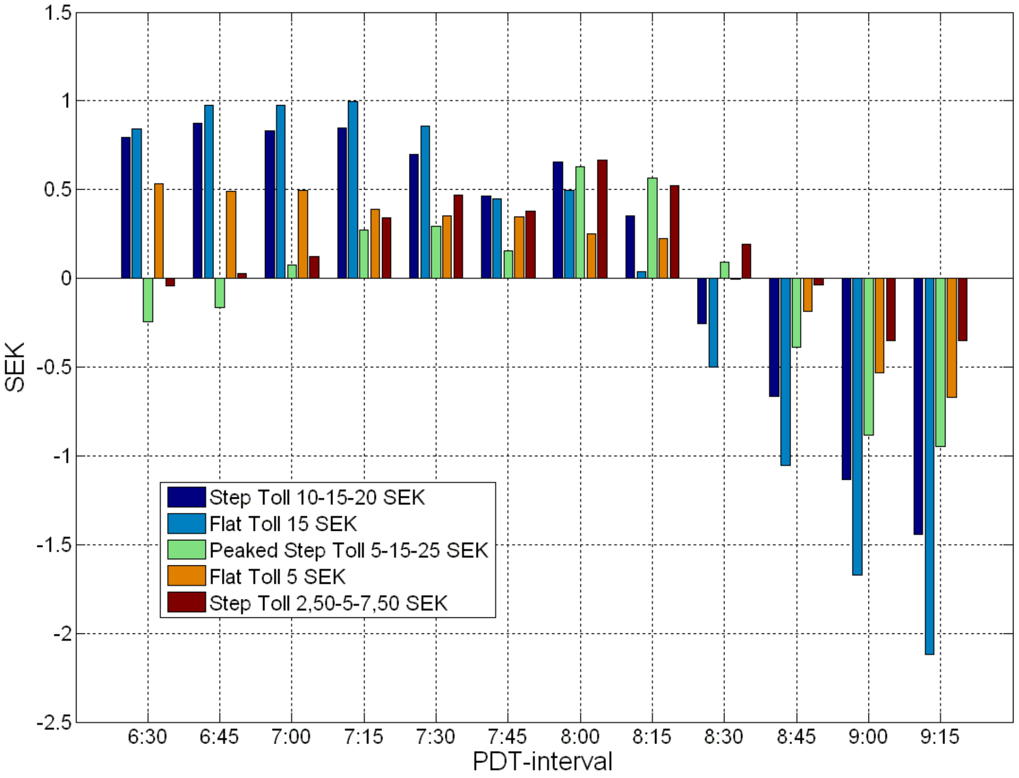

Figure 7 – Comparison of consumer surplus per preferred departure time interval for the different tolling scenarios

Average Consumer Surplus per Trip Purpose

When consumer surplus is analyzed per trip purpose large differences between the purposes become apparent. The pattern is however consistent over the different scenarios. Figure 8 shows that consumer surplus is negative or approximately zero in all scenarios for flexible trips, whereas it is positive for both fixed and business trips. This result indicates that fixed and especially business trips benefit from reduced congestion due to adjustments made by flexible trips. From this one realizes that the overall effect of charging is to a large extent decided by the trip purpose mix in the model.

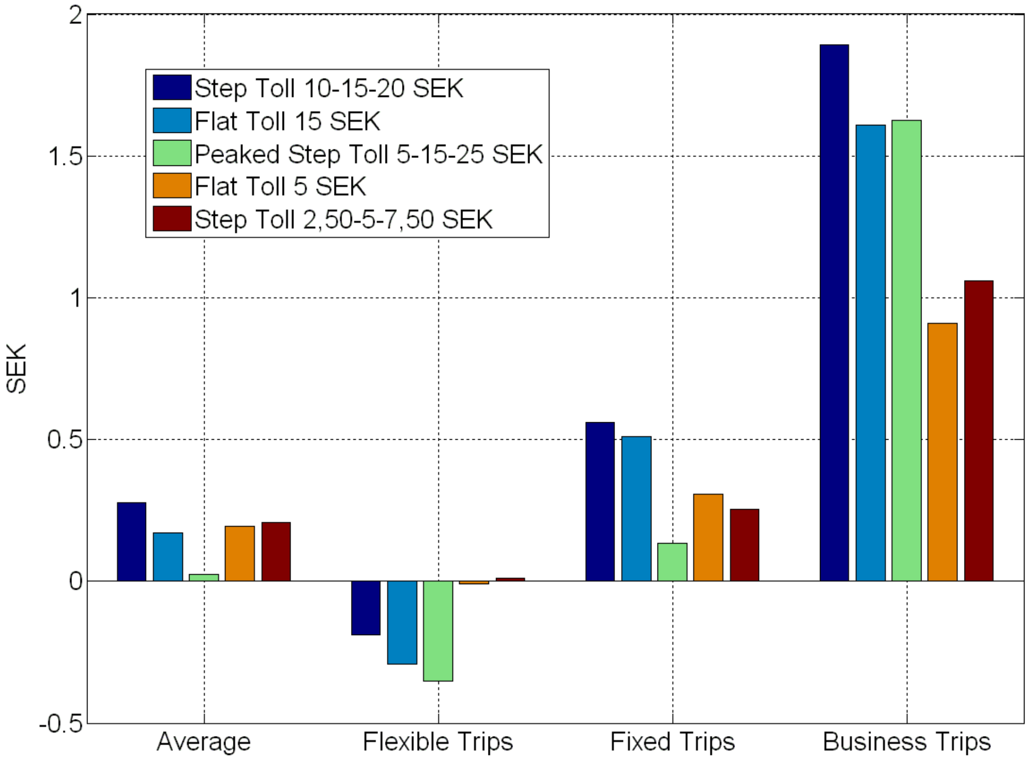

Figure 8 – Comparison of average consumer surplus per trip purpose

CONCLUSIONS

This paper compares different congestion charging schedules on the present toll cordon in the Stockholm network, using a newly developed modelling system that includes route choice, departure time choice and switch to public transport as well as mesoscopic simulation of traffic in the network. The paper aims at investigating differences between flat and time differentiated tolling schedules.

The results of model predictions indicate that social surplus is greatest with the present step toll, followed by its flat counterpart. Differences are however rather small and the average reduction in flow over the toll cordon is actually somewhat larger in the case of the flat toll. When the increments between steps are increased, as in the peaked step toll scenario, fewer trips have an incentive to change departure time to a time interval before the charging period starts due to the low toll in the early morning. This scenario therefore results in a smaller traffic flow reduction and lower social surplus than both the present step toll and the flat toll.

Scenario results will however be subject to a sensitivity analysis, which will investigate to what extent the results depend upon the (overestimated) change of departure time to a time interval before charging starts. This sensitivity analysis will be performed through implementation of an extra schedule delay cost for changes that take place early in the morning. Such an extra penalty can be motivated since it is likely that the marginal cost of departing early from home is higher earlier in the morning.

Furthermore, modelling results indicate that the trip purpose mix of traffic is very important for the effects of congestion charging and for the estimated welfare benefits. The reason for this is that there are large differences in schedule flexibility, VOT and preferred time of travel across the trip purposes. A trip purpose with many trips having a low VOT (e.g. leisure trips) tend to change mode, departure time and route to a greater extent than a trip purpose where most trips have a high VOT (e.g. business trips). Related to this is the question of the share of commercial traffic, which in general has a very high VOT. More research on the magnitude of commercial traffic and the travel pattern of these trips is needed. Results also differed a lot between commuting trips with flexible working hours and commuting trips with fixed working hours, indicating that large errors could be made if treating all commuting trips alike.

ACKNOWLEDGEMENTS

Thanks to the Swedish Road Administration and the Swedish Governmental Agency for Innovation Systems for providing necessary financial support. Thanks also to my supervisor Leonid Engelson for advice and critical reading of the paper. Furthermore, I am grateful for the constructive feedback received at a lunch seminar organized by Centre for Transport Studies at KTH.

REFERENCES

Arnott, R., de Palma, A. and Lindsey, R. (1993). A structural model of peak period congestion: A traffic bottleneck with elastic demand. American Economic Review, 83, 161-179.

Braid, R. M. (1989). Uniform versus peak-load pricing of a bottleneck with elastic demand. Journal of Urban Economics, 26, 320-327.

Börjesson, M. (2008). Joint RP-SP data in a mixed logit analysis of trip timing decisions. Transportation Research Part E, 44, 1025-1038.

Chu, X. (1999). Alternative congestion pricing schedules. Regional Science and Urban Economics, 29, 697-722.

De Jong, G., Daly, A., Pieters, M. and van der Hoorn, T. (2007). The logsum as an evaluation measure: Review of the literature and new results. Transportation Research Part A, 41, 874-889.

De Palma, A., Kilani, M. and Lindsey, R. (2005). Congestion pricing on a road network: A study using the dynamic equilibrium simulator METROPOLIS. Transportation Research Part A, 39, 588-611.

Ekström, J., Engelson, L. and Rydegren, C. (2009). Heuristic algorithms for a second-best congestion pricing problem. Netnomics, 10, 85-102.

Eliasson, J., Hultkrantz, L., Nerhagen, L. and Smidfelt Rosqvist, L. (2009). The Stockholm congestion charging trial 2006: Overview of effects. Transportation Research Part A, 43, 240-250.

Fosgerau, M. and Van Dender, K. (2010). Road pricing with complications. International Transport Forum Discussion Paper. Available from: http://www.internationaltransportforum.org/jtrc/DiscussionPapers/DP201002.pdf

May, A. D. (1992). Road Pricing: An international perspective. Transportation, 19, 313-333.

May, A. D. and Milne, D. S. (2000). Effects of alternative road pricing systems on network performance. Transportation Research Part A, 34, 407-436.

May, A. D., Liu, R., Shepherd, S. P. and Sumalee, A. (2002). The impact of cordon design on the performance of road pricing schemes. Transport Policy, 9, 209-220.

Mayet, J. and Hansen, M. (2000). Congestion pricing with continuously distributed values of time. Journal of Transport Economics and Policy, 34, 359-370.

Kristoffersson, I. and Engelson, L. (2009a). A dynamic transportation model for the Stockholm area: Implementation issues regarding departure time choice and OD-pair reduction. Networks and Spatial Economics, 9, 551-573.

Kristoffersson, I. and Engelson, L. (2009b). Estimating preferred departure times of road-users in a real-life network. Submitted.

Kristoffersson, I. And Engelson, L. (2009c). Valideringsrapport – Hur väl kan trafikmodellen SILVESTER återskapa Stockholmsförsökets effekter? Rapport, KTH, Stockholm. TRITA-TEC-RR 09-004. (In Swedish)

Litman, T. (2004). London congestion pricing: Implications for other cities. Victoria Transport Policy Institute. Available from: http://city-maut-muenchen.de/fileadmin/Dokumente/london_implications.pdf

Small, K. A. (1982). The scheduling of consumer activities: Work trips. The American Economic Review, 72, 467-479.

Taylor, N. B. (2003). The CONTRAM dynamic traffic assignment model. Networks and Spatial Economics, 2003:3, 297-322.

Train, K. (2003). Discrete choice methods with simulation. Cambridge University Press.

Transportation Research Board (2003). Road value pricing: traveller response to transport system changes. Transit Cooperative Research Program Report 95. Available from: http://www.trb.org/Publications/Blurbs/Road_Value_Pricing_Traveler_Response_to_Transporta_161219.aspx

Tseng, Y-Y. and Verhoef, E.T. (2008). Value of time by time of day: A stated preference study. Transportation Research Part B, 42, 607-618.