Forecasting effects of congestion charges

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Abstract
This paper performs an ex-post evaluation of the transport model forecast of the effects of the Gothenburg congestion charges, implemented in 2013. We find that the predicted traffic reductions across the cordon and travel time gains were close to those observed in the peak. However, the reduction in traffic across the cordon was under-predicted in off-peak. The design of the charging system implies that the path disutility cannot be computed as a sum of link attributes. The route choice model is therefore implemented as a hierarchical algorithm, including a continuous value of travel time (VTT) distribution. The VTT distribution was estimated from stated choice (SC) data, but had to be adjusted to be consistent with observed outcome. One reason for the discrepancy may be that VTT inferred from SC data does not reveal travellers' long-term preferences. Another reason may be that apart from distance, travel time and charge there are other factors that determine drivers' route choice.

1   INTRODUCTION

Transport model predictions are a cornerstone of transport appraisal, forming the fundament of welfare calculations. For congestion pricing they are crucial for the design and prediction of revenues. Still, there are only a few systematic ex-post evaluations of transport model predictions (see Hartgen (2013), Nicolaisen and Driscoll (2014), and van Wee (2007)) for literature reviews on ex-post analysis). One reason for the lack of such is that the forecast is often conducted long before the implementation of the policy or project, with the result that model inputs are inaccurate. In many cases, even the design of the project or policy has changed since the forecast was made. Another reason is lack of data describing the traffic system before and after the implementation of the policy or project.

The present paper evaluates the forecasted effect of the Gothenburg congestion charges. The system is cordon-based and was implemented on 1 January, 2013. Introduction of this system provides an excellent opportunity for an ex-post evaluation, because travel times and traffic volumes were monitored in 2012 and 2013 (Börjesson and Kristoffersson 2014). It also provides a rare possibility of evaluating the values of time assigned in the route choice model, because drivers in many OD pairs have the choice of paying the charge or taking a detour to avoid being charged.

Detailed ex-post evaluations of transport model predictions, such as the present study, are important for understanding the strengths and limitations of transport model forecasts and for identifying needs for model development. Moreover, comparison of the prediction accuracy of the model between the Stockholm and the Gothenburg charges indicates the extent to which the accuracy of model predictions can be generalized and transferred between the cities. There exist a large number of studies predicting the effects of proposed congestion charging schemes (e.g. Eliasson and Mattsson 2006, Fridstrøm et al. 2000, Kickhöfer et al. 2010, Rich and Nielsen 2007 and Santos 2002). By drawing more general conclusions regarding which effects can be predicted with high accuracy and which effects are more difficult to model in different types of road networks, other model studies can be interpreted in a more informed way.

Flyvbjerg (2005) finds that forecasts of large rail infrastructure projects significantly over-predict demand, but that the main reason for this is strategic bias due to fiddling with the forecast assumptions. Pickrell (1989) finds the same for 10 urban transit projects in the United States. Flyvbjerg (2005) finds further that predictions for the road projects he analyses are slightly overestimated. Welde (2011), Welde and Odeck (2011) and Goodwin (1996), however, find that the demand forecasts for (toll-free) road projects tend to be underestimated.

Næss et al. (2006) and Li and Hensher (2010) find that traffic volume on toll roads was generally overestimated (the former analysing European and American projects and the latter Australian). Bain (2009 and 2011) also finds that forecasts tend to over-predict traffic volumes on toll-roads and suggests

that this pattern is due to optimism bias regarding revenues. Recent studies by Welde and Odeck (2011) and Welde (2011), using data on both tolled and toll-free roads, find that traffic volumes on tolled roads were fairly accurate, possibly because these forecasts have been scrutinized over the years, but that traffic volumes on toll-free roads were under-predicted. Leape (2006) shows that the predicted effect of the London congestion charges was also fairly accurate, just slightly under-predicting the traffic reduction.

The effects of the Gothenburg charges were predicted by the Swedish national transport model system Sampers (Beser Hugosson and Algers, 2002)[1]. Sampers has been in use for 10-15 years and has been carefully estimated, applying state-of-practice large-scale modelling techniques, but it lacks dynamic assignment, departure time choice and activity-based modelling techniques. Sampers was also applied to forecast the effects of the Stockholm congestion charges. Eliasson et al. (2013) find that the model predictions were accurate enough to facilitate the design of an efficient system design, but that travel time gains on links outside the toll cordon were substantially under-predicted, due to the inability of the static model to capture dynamic congestion and spillback queues[2]. Consequently, the model could not be applied to calculate the social benefit of the system.

The challenges facing the modellers forecasting the effect of the Gothenburg charges are slightly different from those that faced the modellers forecasting the effects of the Stockholm charge. On the one hand, dynamic congestion and spillback queues are a much smaller problem in Gothenburg. On the other hand, the topology of the transport network in Gothenburg implies a large number of OD relations where the driver has the choice between a faster charged route and an uncharged but slower route. In this respect, Gothenburg is more representative of other cities than Stockholm, where waterways effectively bar most unwanted route choice effects.

Due to the many possible route choices, the predicted route choice proved to be highly sensitive to the value of travel time (VTT) assumed in traffic assignment. Moreover, a multi-passage rule was applied in Gothenburg (a driver is only charged once within an hour, even if making multiple passages across the cordon), implying that the path disutility cannot be computed as a sum of link attributes. The Gothenburg toll system thus resembles a zone-based congestion charging system such as the one in London. We demonstrate how this problem was solved, using a hierarchical route choice algorithm in combination with a continuous VTT distribution. Assumption of the VTT distribution in route choice has received surprisingly little attention in the literature. A likely reason is that very few congestion pricing systems inducing route choice effects have been

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[1] The model predictions evaluated in this paper are produced by an updated version of the model, where the land-use and transport network had been updated to the 2013 level. The volume delay functions have been replaced by new recently estimated volume delay functions for all regions in Sweden, increasing the prediction power of travel times.

[2] And this problem could thus not be avoided by adjusting parameters in the volume delay functions (Engelson and van Amelsfort 2011).

designed and evaluated in the world. Evaluation of the predicted route choice in Gothenburg is, therefore, of general interest for the modelling of route choice effects in response to congestion charging in many cities.

We find high accuracy in the predicted reduction of traffic volume across the cordon in the peak, 11% compared to the observed 12%. The reduction in the off-peak, however, was under-predicted, as it was in the Stockholm case. The lower accuracy of the off-peak predictions seems to be driven by the different and possibly more diversified adaptation strategies applied to discretionary trips, whereas virtually all commuters priced off the road switched to public transport. Due to limited congestion and the lack of spill-back queues and blocking of upstream intersections in Gothenburg, the travel times were predicted with high accuracy. The average travel time gains on selected links in the model were 14.0% compared to the observed 14.6%, implying high accuracy of a model-based cost-benefit analysis of the system (in contrast to the Stockholm case).

The paper is organized as follows. Section 2 describes the charging system and Section 3 the transport model. Section 4 describes the modifications that were made to the transport model to be able to predict effects of the congestion charge and the results are shown in section 5. Section 6 provides the conclusions of this study.

2   THE GOTHENBURG CONGESTION CHARGES

Gothenburg (Göteborg in Swedish) is the second largest city in Sweden with half a million inhabitants within the city borders and nearly a million in the metropolitan area. The city is traditionally a seaport and manufacturing city dominated by blue-collar jobs, the car manufacturing industry being one of the dominant sectors. These work places are mainly located north of the Göta river, while the central business district is located south of it. The region is further relatively sparsely populated and its planning does not support an efficient public transport system, implying a considerably lower share of public transport than Stockholm. For commuting trips in the OD pairs where the charges apply, the public transport market share was 26% in Gothenburg in 2012, while in Stockholm the corresponding market share was 77% before the congestion charges were introduced in 2006 (Börjesson and Kristoffersson 2014).

Gothenburg has begun its shift towards a more high-tech and service-oriented economy. The population was relatively stable during the second half of the 20th century, but since the beginning of the 21st century it has started to increase rapidly, prompting a denser and more transit-oriented society.

A cordon-based congestion charging scheme was introduced in Gothenburg in January 2013. The toll is time-of-the-day dependent, ranging from 0.8 euros to 1.8 euros during weekdays 6.00 – 18:30, while other time periods are free of

charge. The maximum daily charge is 6 euros[3]. Vehicles are charged when passing the cordon in either direction using automatic number plate recognition.

Relieving congestion was not the only, not even the main, objective of the charging system. The main objective was to raise yearly revenue of €100 million, co-financing a large infrastructure package, mainly in public transport. A third objective was to improve the local environment.

The topology of Stockholm is ideal for congestion charges. The bottlenecks are located on the arterials leading into the city centre, which is surrounded by water acting as a natural barrier, preventing rat-running. Gothenburg, however, has fewer natural barriers and the bottlenecks are mainly located on the highway hub northeast of the city centre, resulting in more rerouting in response to charges and more than twice as many checkpoints as the Stockholm system (38 compared to 18). The adopted design consists of a ring cordon with two antlers; see Figure 1.
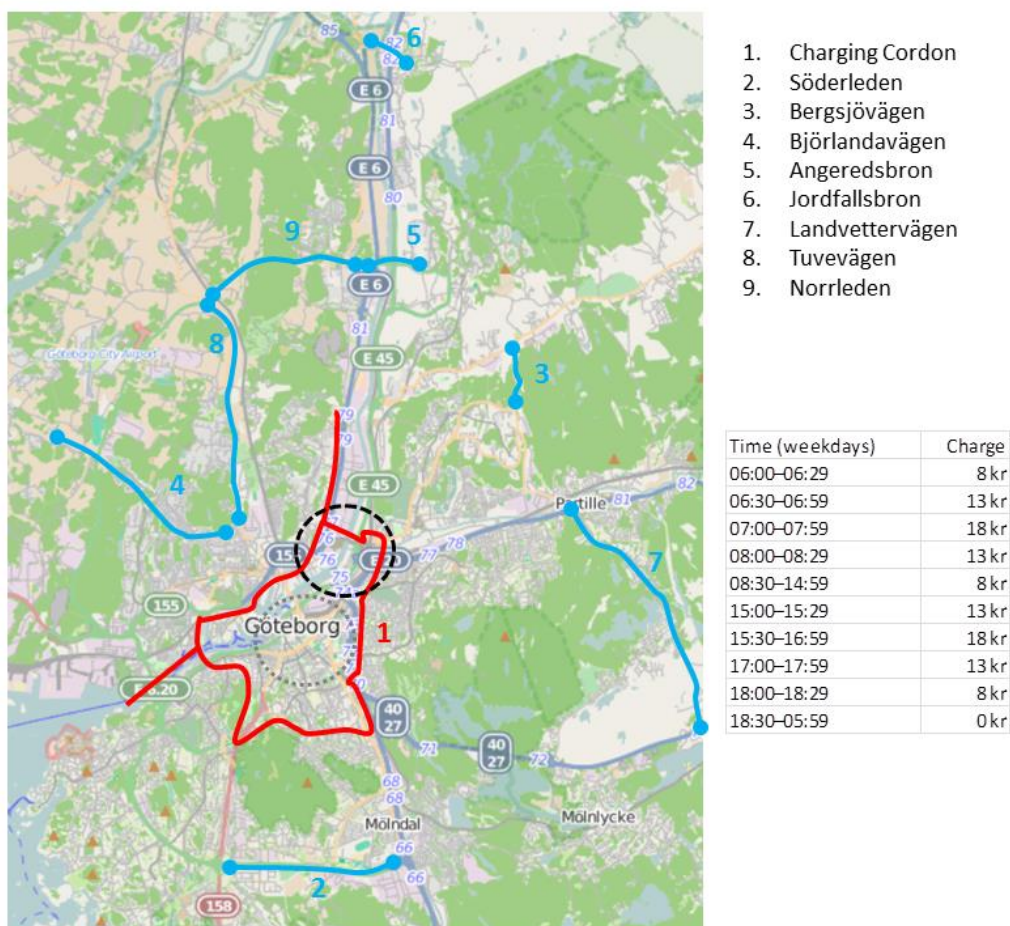

1. Charging Cordon
2. Söderleden
3. Bergsjövägen
4. Björlandavägen
5. Angeredsbron
6. Jordfallsbron
7. Landvettervägen
8. Tuvevägen
9. Norrleden

Time (weekdays)	Charge
06:00–06:29	8 kr
06:30–06:59	13 kr
07:00–07:59	18 kr
08:00–08:29	13 kr
08:30–14:59	8 kr
15:00–15:29	13 kr
15:30–16:59	18 kr
17:00–17:59	13 kr
18:00–18:29	8 kr
18:30–05:59	0 kr

Fig. 1 The congestion charging scheme of Gothenburg. The red line depicts the ring and the antlers while the blue lines show alternative routes.

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[3] Here and in the rest of this paper we use the conversion rate 10SEK=€1.

Since many workplaces are located outside the city centre and the shape of the cordon is highly irregular, work trips may easily pass two or more checkpoints. To avoid penalizing these drivers more than others, a multi-passage rule was implemented. The rule states that if passing the cordon more than once within 60 minutes, only the highest charge has to be paid. Hence, the Gothenburg congestion charges are link-based but not additive, posing an extra difficulty in modelling the route choice (see section 4.1).

Changes in the public transport network and lane priority were introduced two weeks prior to the introduction of the congestion charges. We cannot distinguish the effect of these measures from the impact of the congestion charges. However, evidence from Stockholm, where a substantial improvement in the public transport system was implemented six months prior to the congestion charges, suggests that improvement in the public transport system has a negligible impact on the road traffic compared to the effect of congestion charges (Kottenhoff and Brundell-Freij 2009).

Travel times were observed for the arterial routes (depicted in Figure 2), relevant bypasses and for selected links inside the toll cordon in the morning peak (07:00 – 08:00) and averaged over all weekdays within five weeks in September and October for 2012 and 2013. Traffic counts were available for October and April for selected links and for December for the rest of the toll stations. A travel survey was undertaken in March – April 2012 and March – April 2013 with 3,000 respondents, which provided information on mode choice effects (City of Gothenburg 2013).
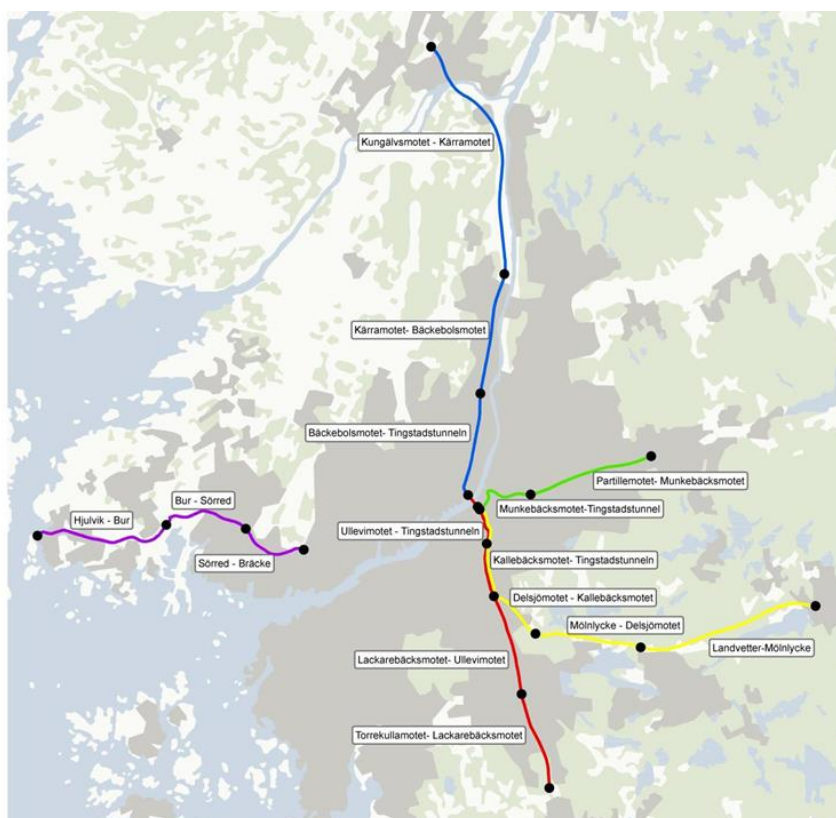

Fig. 2 Measured travel time sections for arterials

3   MODEL DESCRIPTION

The national transport forecasting model Sampers consists of five regional models, where Gothenburg is covered by the western Sweden sub-model. The demand model consists of nested logit models for six trip purposes (work, school, business, recreation, social and others) covering trip generation, destination choice and mode choice, and are estimated on national travel survey data 1994-2001. The demand models are linked to the software package Emme/3, assigning demand by mode to the transport network. For cars, travel times and cost from the assignment are fed back to the demand level in an iterative loop until convergence is reached, usually after the fourth iteration. Travel time and cost for public transport, walking and biking are assumed to be independent of transport volumes.

OD matrices for freight and professional traffic are generated by an external model and kept constant in the forecast. The route choice is still modelled in the assignment model, implying that this traffic affects the congestion level facing the private car traffic.

The transport model is static and departure time choice is not modelled. Instead, the mode-specific OD matrixes produced by the demand models are split into three time periods (morning peak, afternoon peak and off-peak) according to fixed factors specific to each trip purpose. The OD matrixes for each time period are then assigned to the network. The congestion charge must therefore be approximated by a constant charge within each time period, although it varies in reality. The charging level is approximated by a weighted average of the actual congestion charge within the given time period. The weights are equal to the observed traffic volume sampled at 15-minute intervals. The approximation errors are highest for the off-peak period, including both midday where the charge ranges from 0.8 to 1.3 euros and night time which is free of charge.

4   MODELING THE ROUTE CHOICE EFFECTS

The static and deterministic assignment model EMME/3 distributes drivers by routes according to Wardrop user equilibrium. Route disutility U is assumed to be a linear function of travel time (T), travel distance (D) and congestion charge (C)

$$U = \alpha T + \beta D + C, \qquad\qquad (4.1)$$

with α being the VTT and β the distance cost. If there are no charges levied in a network, route choices are usually quite insensitive to the relative weights of these variables, due to high correlation between travel time and distance. When congestion charges are introduced, however, a travel cost, uncorrelated with travel time or distance, enters the path disutility, implying that the relative weights have a larger impact on the simulated route choice.

There is not much evidence in earlier literature regarding the relative weights of travel time, travel distance and congestion charge in route choice models. Route choice observations from Stockholm provide some but no conclusive evidence

regarding these weights since there are only a few OD pairs where route choices are influenced by these weights.

In the Gothenburg transport system, however, there are plenty of OD pairs where the route choice is influenced by the weights. In this section, we will describe how the route choice was modelled and how the weighs were determined. The route choice modelling approach was designed such that the multi-passage rule could be implemented, requiring adjustments to the standard method because path disutility cannot be computed as a sum of link attributes.

Section 4.1 describes the implementation of the multi-passage rule, which takes advantage of a continuous VTT distribution. In the process of designing and predicting the effects of the Gothenburg system, a study was undertaken to assign values to the parameters α and β in the path disutility function. This work is described in 4.2.

4.1   Modelling the multi-passage rule

In an assignment, the path disutility (such as the one defined by 4.1) of a route is normally the sum of the disutilities of all links within the route. This is, however, not the case in the Gothenburg network when the multi-passage rule applies. Then a driver only has to pay one charge even if he or she uses more than one charged link.

To implement the multi-passage rule, a hierarchical route choice algorithm with two levels was applied in the assignment. In the upper level, the drivers are split into two classes, paying and non-paying drivers. In the lower level, the drivers are assigned to the network; the paying drivers have access to the full road network while the non-paying drivers can use only the links without charges.

The assignment is run iteratively in three steps. In the first step (the lower level of the hierarchical route choice algorithm), the travel time and travel distance between each OD pair, for paying drivers and for non-paying drivers respectively, are calculated under the assumption that the drivers minimize the path disutility defined by

$$U = \alpha_L T + \beta D. \tag{4.2}$$

The route choice differs between paying and non-paying drivers because the former may use the whole road network while the latter have access to uncharged links only. The charge C is set to zero in the lower level since the upper level of the route algorithm determines the share of drivers that pay the charge. Hence, only the relative weights of T and D, i.e. the ratio α_L/β, determines the route choice. In this step, α_L and β are assumed constant across the population in order to produce unique travel time and travel distance for each OD pair. The travel time and travel distance matrices for the paying drivers obtained by network skimming after the assignment are denoted T_P and D_P. For non-paying drivers, the corresponding matrices are denoted T_N and D_N.

The second step (the upper level of the hierarchical route choice) determines the share of paying drivers in each OD pair. It is based on the general formulation of travel disutility (4.1). In this step, the VTT α (of the population of

drivers in each OD pair) is assumed to follow a cumulative distribution Φ (Section 4.2 describes how this was determined). The random distribution of α implies that some drivers in the OD pair will think it is worth paying a charge to save time, while others do not. For a driver with VTT α, it is worth paying the charge C only if $\alpha T_P + \beta D_P + C < \alpha T_N + \beta D_N$. The driver with the trade-off $\hat{\alpha}$, computed as

$$\hat{\alpha} = \frac{C + \beta D_P - \beta D_N}{T_N - T_P}, \tag{4.3}$$

will be indifferent towards paying or not paying. Due to the multi-passage rule, the charge C is constant and equal for all OD pairs.

In the third step, the drivers are assigned to the two classes, paying and non-paying, by multiplying the total number of trips in the OD pair by $1 - \Phi(\hat{\alpha})$ and $\Phi(\hat{\alpha})$ respectively. The drivers in the paying and in the non-paying group are assigned to the network simultaneously, and the procedure is repeated from the first step until convergence is reached.

The VTT distribution Φ is assumed to be the same for all OD pairs and β is still assumed constant across the population of drivers[4]. Note that both a discrete and a continuous probability function would be sufficient for avoiding the same choice of all drivers in an OD pair. However, applying a continuous, rather than a discrete, VTT distribution has three advantages: it is more realistic, it prevents thresholds effect on the share of drivers assigned to the paying and non-paying groups (Leurent 1993), and it is easier to implement.

The assumption of the lower level, that α_L/β is constant, is not consistent with the assumption of the upper level, where α is assumed to be a random variable and β is fixed. The only way of avoiding this inconsistency would be to assume that the distributions of α and β are perfectly correlated such that α/β remains constant. In practice, however, this approach produced unrealistically large shares of non-paying drivers and was therefore discarded.

When the initial situation, before the charges apply, is modelled, the second step in the iteration procedure (the upper level of the hierarchical route choice) vanishes.

In the situation with charges, the model predicts that approximately 30% of the checkpoint passages are free of charge due to the multi-passage rule, whereas it turned out to be on average 45% in 2013. This under-prediction is mainly due to the significant number of round trips for which the multi-passage rule applies, i.e. for tours where the cordon of both trip legs is passed, back and forth, within one hour. This way of using the multi-passage rule is not implemented in the model. This under-estimation of the share of drivers utilizing the multi-passage rule means that the average charge assumed in the

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[4] In the upper level, different VTT distributions are actually implemented for the five trip classes: commuters, employer business trips, other regional trips, freight, and long-distance private trips. The sixth class consists of vehicles exempted from the charge. The model uses higher distance cost for freight than for other trip classes.

model is higher than the actual average charge. To account for this, the charge implemented in the model was adjusted downward to match the actual average charge per passage in 2013.

4.2   Weighs on travel time versus distance

In the lower level of the hierarchical route choice, only the relative weight, α_L/β, influences the choice of route. In the initial situation before charges, the model-computed traffic volumes matched the observed traffic fairly well, both on the links across the cordon and on the surrounding highways, when the ratio α_L/β was taken to be 100 km/h. Hence, the ratio α_L/β = 100 km/h was used in the lower level of the route choice algorithm.

In the upper level of the algorithm (remember that this level of the algorithm vanishes when charges do not apply), VTT is taken to be randomly distributed in the population. The VTT distribution was estimated based on the Stated Choice (SC) data from the national VTT study, for drivers in Stockholm and Gothenburg only.[5] The hypothesis that this distribution is lognormal could not be rejected (using the test developed by Bierlaire and Fosgerau (2007)). The mean of the distribution for commuters is 11.3 €/h, but since the distribution is positively skewed, with a long right tail, the median VTT is substantially lower, 5.0 €/h. In order to minimize the aggregation error in the route choice, the median VTT has been assigned to α_L. The mean VTT would be a relevant choice for calculation of the economic effect.

The ratio α_L/β = 100 km/h and the median α_L = 5.0 €/h in the upper level imply the marginal distance cost β = 0.05 €/km. Although the marginal distance cost varies substantially between vehicles[6] (depending on factors such as age and brand, etc.), 0.05 €/km barely covers the fuel cost for most vehicles, and was considered unreasonably low. Moreover, the result of assignment with this combination of parameters in the situation with charges was that most drivers in the OD pairs where both charged and un-charged route existed were forecasted to take a detour to avoid paying the charge. This was also considered unlikely, partially based on the experiences from Stockholm.

A remedy to this problem was to stretch the lognormal VTT distribution to the right (by shifting the corresponding normal distribution to the right). The size of this stretch was guided by a route choice SC survey conducted in the spring of 2010. This survey was conducted from a random sample of 1,000 inhabitants of the municipality of Gothenburg aged 18-75 in 2010. The respondents were presented with 13 binary choices of routes between well-known landmarks (see Figure 3 for an example). No information about travel time or distance was presented. In the first five binary choices, no congestion charge applied. In the following eight binary choices, a congestion charge was levied on one of the routes.

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[5] Drivers residing in these cities have significantly higher VTT than other Swedish drivers.
[6] And it is further uncertain what distance cost the drivers perceive and take into account when choosing route.
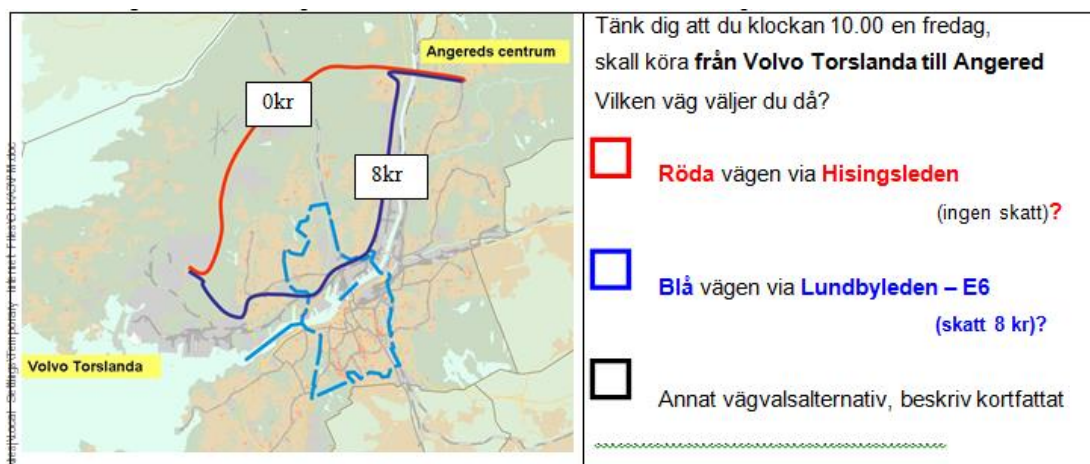
Fig. 3 Sample binary choice from the SC survey

The resulting choices from the survey were combined with route travel time and distance from the network model. Parameters α and β of a binary logit model were estimated with utility functions defined by (4.1) and constraining the ratio α/β to 100 km/h. The resulting estimate of α was 10.8 €/h, assumed to correspond to the median in the new stretched VTT distribution for commuters. The median VTT $\alpha_L = 10.8$ €/h and the ratio $\alpha_L/\beta = 100$ km/h imply the distance cost $\beta = 0.108$ €/km. This is still at the lower end of the distribution of driving cost including wear and tear but larger than the fuel cost for most cars.

The relatively low distance cost might be explained by another finding in the route choice SC survey: the respondents tended to prefer the larger arterials to streets, even in cases when the arterial route involves longer travel time and travel distance, and is also charged. This is not captured in the utility function 4.1, which may explain why the value of β that we derive is lower than the actual distance cost for most vehicles.

5   RESULTS

The model results were compared with traffic counts, observed travel time and travel survey results on modal split described in Section 2.

5.1 Traffic flow

Table 1 compares the observed and the predicted effect on traffic volume across the cordon. For the morning and afternoon peak, the model predictions are very close to the observed, while the predicted off-peak effect is slightly underestimated (predicted 7% compared to the measured 10%). This indicates that the effect of congestion charges on commuting trips is more accurately modelled than the effect on other trips.

Total traffic flow per day across the toll cordon was overestimated by 5% in the situation without charges and 7% in the situation with. On some of the main arterials, the discrepancy between prediction and outcome is even larger (see Figure 4). This correlates with an underestimation of travel times on these links (see section 5.2). The discrepancy between predicted and observed traffic flow

is larger in the morning and afternoon peak periods when there is congestion in the network and the bulk of the trips are commuting trips.

Table 1 Traffic flow across the toll cordon before and after introduction of congestion charges

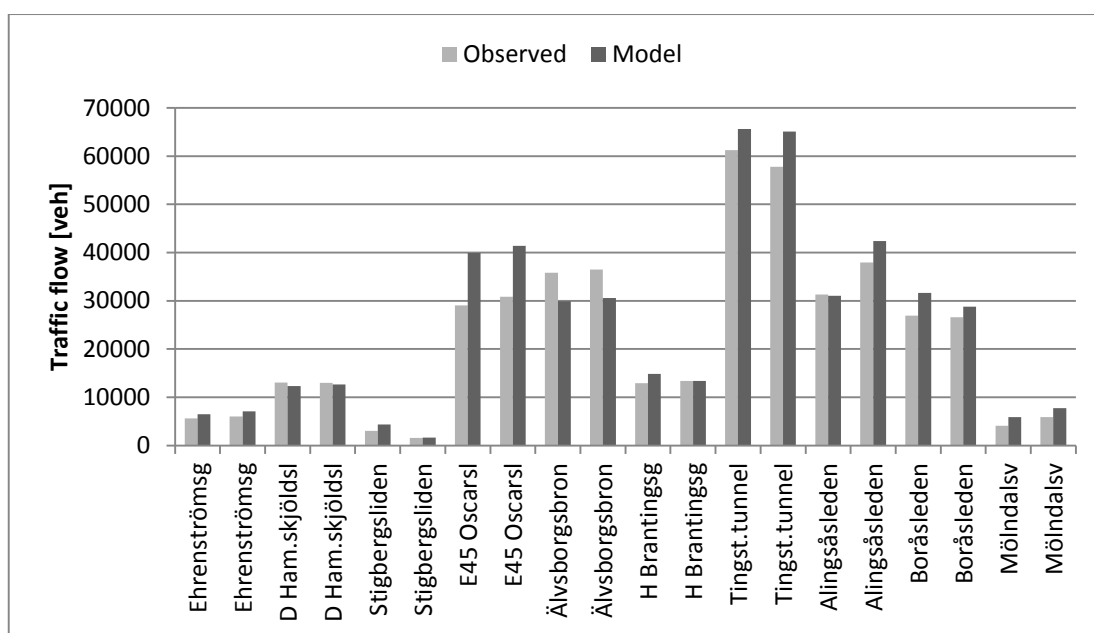|	Before		After		Change	
	Observed	Model	Observed	Model	Observed	Model
Morning	62067	69112	54557	61 728	-12%	-11%
Afternoon	67594	74000	59819	65 745	-12%	-11%
Off-peak	53548	54790	48407	50 786	-10%	-7%
Day	794801	834119	712821	762 807	-10%	-9%

Fig. 4 Comparison between measured and modelled traffic flow for the whole day on main arterials across the toll cordon 2012

On large arterials across the cordon, traffic flow decrease was overestimated. However, as showed earlier, the total decrease prediction is relatively accurate. This implies that traffic flow decrease was considerably underestimated on the local streets passing the cordon. The volume delay functions are very sensitive to the coding of junctions and will need thorough manual coding to work properly. Overestimation of travel time gains on the local streets passing the cordon would explain the underestimation of traffic flow decrease across the cordon. This in turn might explain why traffic flow decrease was overestimated on the large arterials.

5.2 Travel time

Figure 5 and Figure 6 compare predicted and observed travel times in the situations with and without the charges. The travel time was underpredicted by 33% on the northern inner arterial (Bäckebol – Tingstad) and overpredicted by 33% on the eastern inner arterial (Munkebäck – Tingstad). However, the travel time *change* between before and after the introduction of congestion charges was generally neither underestimated nor overestimated (see Figure 4 and Figure 5).
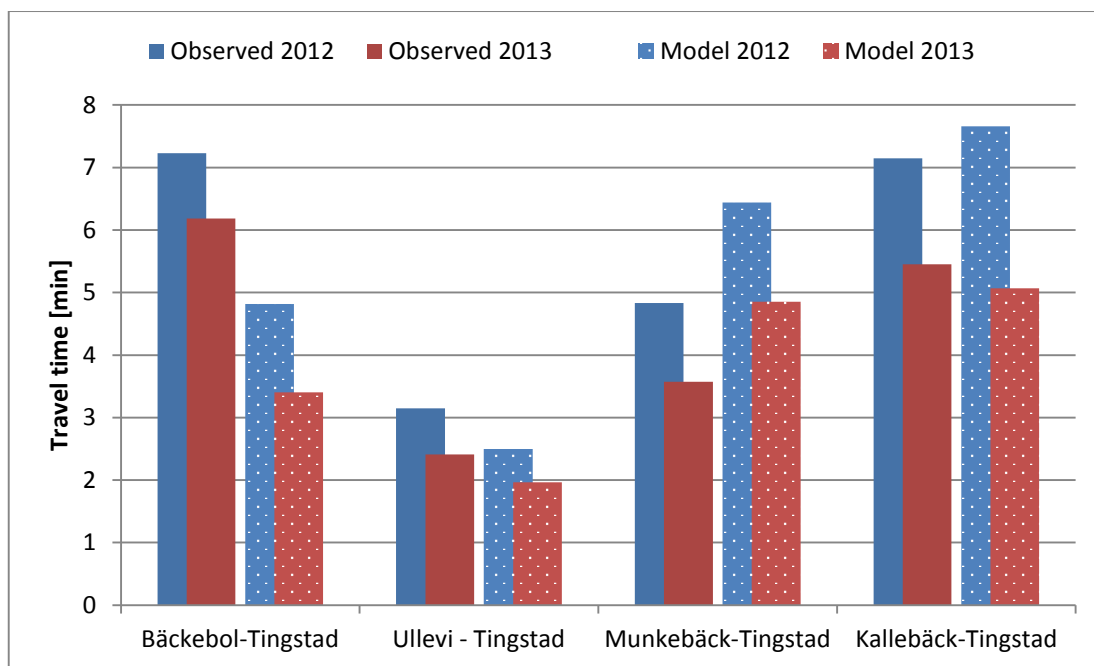
Fig. 5 Comparison between measured and modelled travel time on inner arterials during morning peak
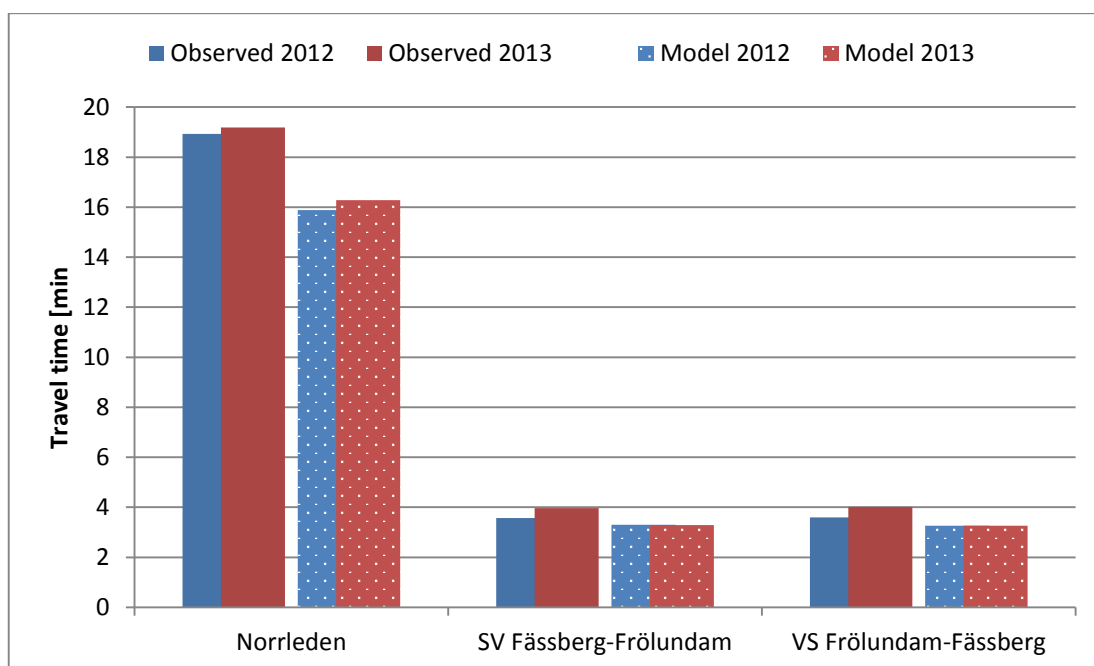

Fig. 6 Comparison between measured and modelled travel time on bypasses during morning peak

The deviation in travel time that occurs on some links indicates that the network needs to be better coded and presumably that the model needs to be calibrated.

5.3 Modal split

The modelled change in total number of car trips and public transport trips can be compared with panel survey data projected on the entire population. The comparison can provide insights on mode choice accuracy in the model. Figure 7 illustrates how the effect on work trips is more accurately predicted than the

effect on other trips by comparing the total number of trips generated per mode in the model with results from the travel survey.

The public transport results from the travel survey should be interpreted with caution as changes in public transport supply (the first survey was undertaken as early as in March – April 2012) and weather conditions are likely to have affected public transport ridership during the time period. These are most likely the reasons why ridership increased more than car travel decreased in the survey data. The sales of monthly public transport cards increased by 15 000 from 2012 to 2013, but part of this can be explained by long-term trends in the region. According to the panel survey, the increase was around 12 000. If this is correct, it means that virtually the whole decrease in car travel to work was due to a switch to public transport. This is not captured by the model, which predicted that the total number of motorized work trips would decrease. However, the model is supposed to capture long- term effects on travel demand which might not have been visible only one year after implementation.
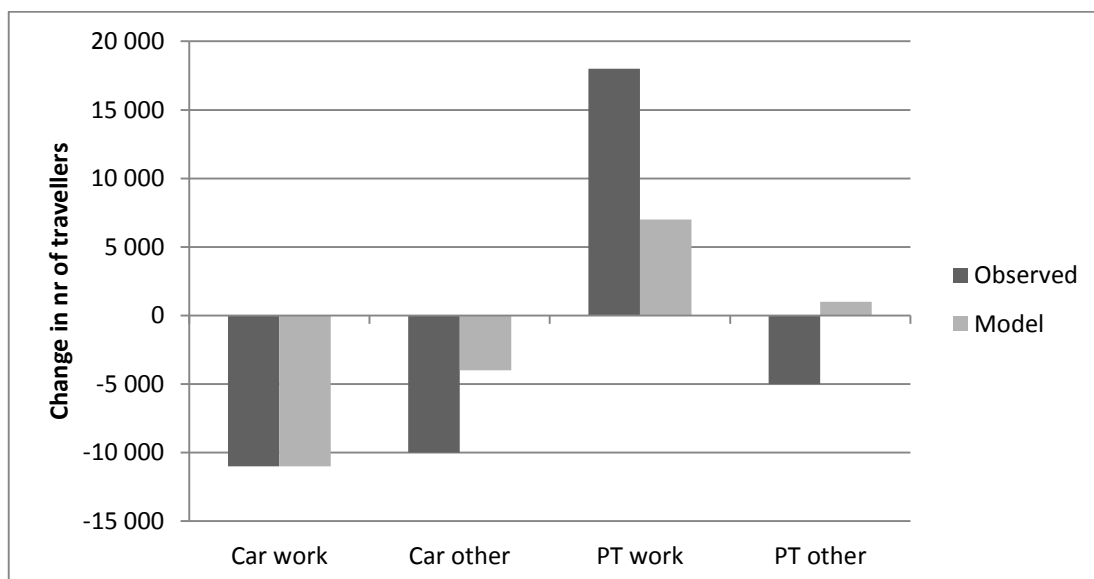

Fig. 7 Change in number of travellers between 2012 and 2013

5.4 Revenue

The multi-passage rule makes revenue predictions difficult. The average charge per passage that was adjusted in the model to correct for the incomplete modelling of the multi-passage rule led to a more realistic level of behaviour change (i.e., exaggeration of traffic flow decrease in the model was addressed) that was only possible to accomplish ex-post. This adjustment led to a realistic prediction of the revenue, when accounting for the error in total flows.

6 CONCLUSIONS

The aim of this study was to evaluate to what extent a state-of-practice transport model with static network assignment is able to accurately predict the effects of introducing congestion charging in Gothenburg. Accurate predictions of the effects of congestion charges are not only critical to designing and predicting revenues of congestion charging systems. They are also an important

tool for cost benefit analysis of congestion charging systems. We find that the effects on traffic flow and travel time in the peak were predicted with high accuracy in Gothenburg. Results from Eliasson et al., (2013), Berglund et al. (2014) and Engelson and van Amelsfort (2011) show that in the Stockholm case, with extensive spillback queues, a dynamic simulation model is necessary for capturing the full travel time reductions of congestion charges. This study shows that in Gothenburg, where queue spillback is not a large problem, a static assignment model can predict the travel time reductions with high accuracy.

In a network where congestion charges apply, the value of time and driving cost per kilometre determine whether the driver will take a detour or pay the charge. The topology of Gothenburg implies possibilities to avoid charging by detouring for drivers in many OD pairs. This made the forecast of the effect on traffic across the cordon and on the circumferential roads highly sensitive to the assignment parameters relating to travel distance, travel time and charge (more sensitive than in the Stockholm case). These parameters have so far received little attention in the research literature since they matter less where charges do not apply - travel time and distance are usually highly correlated. A considerable effort was therefore spent on determining the assignment parameters in the ex-ante forecast.

A particular problem for the Gothenburg model was the multi-passage rule, implying that the path disutility cannot be computed as a sum of link attributes. A hierarchical route choice in combination with a continuous VTT distribution was demonstrated as a successful method of modelling the multi-passage rule on the trip level. Where the multi-passage rule applies on the tour level, i.e. where both trip legs in a tour, back and forth, pass the cordon within one hour, the hierarchical route choice is less useful. This method can be applied to congestion charging systems resulting in non-additive link attributes, especially when there are similar discount structures (i.e., zone-based charges or similar).

The continuous VTT distribution was estimated from SC data from the Swedish value of time study (Börjesson et al. 2012). However, this VTT distribution was adjusted in the ex-ante analyses, since the predicted route choice effects were otherwise judged to be too large (and inconsistent with results from Stockholm). Given the adjusted distribution, we find that the route choice in general was predicted with fairly high accuracy, indicating that a VTT distribution from SC data should not be directly applied in route choice modelling.

The necessity to adjust VTT distribution adds to the body of evidence showing that VTT inferred from SC data might not reveal travellers' long-term preferences (De Borger and Fosgerau, 2008). Another possibility, however, is that there are other link attributes than distance, travel time and charge that drivers value. There are, for instance, indications that large arterials attract drivers even in cases where the measured generalized travel cost is higher than for other routes. The high VTT applied in this study to obtain an accurate forecast might then only serve as a proxy for some other underlying factors influencing the choice.

The less accurate predictions of off-peak traffic are likely due to difficulties in predicting the effect on discretionary travellers, who adapted in more heterogeneous ways than commuters in both Stockholm (Eliasson et al., 2013) and Gothenburg (Börjesson and Kristoffersson, 2015).

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