The Gothenburg Congestion charges: CBA and equity

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Abstract
This paper performs an ex-post cost- benefit and equity analysis of the Gothenburg congestion charges introduced in 2013. We base the analysis on observed effects and a validated transport model. We find that the net social benefit of the charge is positive, however showing that the system is regressive. In other words, low income citizens pay a larger share of their income.

Keywords: Congestion charges, Cost-Benefit analysis, welfare analysis, equity, Transport policy, Decision support

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1 INTRODUCTION

Congestion pricing has proven to be an effective policy for reducing congestion and increasing welfare, but is still only implemented in a few cities: Singapore (Olszewski & Xie, 2005; Phang & Toh, 1997), London (Santos, 2005; Santos and Shaffer, 2004), Stockholm (Börjesson, Eliasson, Hugosson, & Brundell-Freij, 2012; Eliasson, 2009) and Milan (Carnovale & Gibson, 2013). Gothenburg, located on the Swedish west coast, introduced a time-of-day dependent cordon-based congestion charging scheme in January 2013. This paper presents a welfare and equity analysis of the Gothenburg system. Gothenburg adds to the literature because it is by far the smallest city (half a million citizens) ever introducing congestion charges. It has also less congestion, lower density and lower public transport share than the cities previously implementing congestion pricing.

Many studies examine welfare effects of congestion charges, most of which are theoretical (Arnott, De Palma, & Lindsey, 1994; Evans, 1992; Glazer & Niskanen, 2000; Verhoef & Small, 2004). Fewer studies explore the welfare of real-world examples. Danielis et al. (2012) find a welfare effect of Milan's Ecopass system of €7–12 million per year. Gibson & Carnovale (2015) show that the welfare benefits from reduced air pollution adds nearly another €2.7 billion per year. Eliasson (2009) finds a net benefit of €70 million per year for the Stockholm charges, but the consumer surplus is still negative. Börjesson and Kristoffersson (2014), however, show that when including network effects (travel time savings further out in the network), the intra-individual variation in value of travel time (VTT), and reduction in scheduling disutility, the consumer surplus of the Stockholm charges is in fact positive.

TfL (Santos & Shaffer, 2004) and Prud'homme and Bocarejo (2005) present different cost benefit analyses of the London congestion charges based on observed effects. The former study finds a net benefit of the charging system of approximately €70 million per year, whereas the latter find a net loss of the same magnitude. The main difference between the two studies is, according to Mackie (2005), the method of calculating travel time savings and the VTT: Prud'homme and Bocarejo do not consider travel time savings outside of the charging zone and apply a lower VTT.

Ramjerdi (2006) argues that no single equity measure is appropriate for road pricing. Eliasson and Mattsson (2006), however, undertake an equity analysis of the Stockholm system by exploring which groups that are affected by the charges and the spending of the revenues. In this paper we explore how the costs and benefits of the Gothenburg charges are distributed among different segments of the population distinguished by income, gender, age group, and place of residence.

In cities where high-income groups drive more, especially in the areas and times-of-day subject to charging, congestion pricing is expected to be a progressive tax instrument. This is the case for the Stockholm, and Eliasson and Mattsson (2006) found that the Stockholm charges are progressive. As pointed out by Arnott, de Palma and Lindsey (1994); Giuliano (1992); and Small (1983), congestion charges are likely regressive in cities where driving patterns among low-income and high-income groups are similar. This is often the case in cities with low public transport shares. Levinson (2010) concludes that high income groups in general benefit the most from HOT lanes. Ison and Rye (2005) and Rye at al. (2008) note the that without the use of revenues, the congestion charging systems in the UK (the London system and other suggested systems) and Singapore are not equitable.

In Gothenburg congestion is limited to a few highway junctions and the share of public transport trips is comparatively low: 26% for commuting trips in the relations where the charges apply (Björklind et al., 2014). The corresponding market share in Stockholm is 77% (SL, 2013). Although the average charge per trip in Gothenburg is approximately half of what it is in Stockholm, the system generates approximately the same revenue. Hence, a substantially larger share of the population regularly pays the charge, indicating that the system is more regressive than the Stockholm system.

Several authors have emphasized that the use of revenue should be taken into account to get a complete picture of equity effects of a congestion charging system (de Palma & Lindsey, 2004; Eliasson & Mattsson, 2006; Santos & Rojey, 2004; Small, 1983). Ison and Rye (2005) argue that preferred use of revenues is local public transport for equity reasons. This is also the case in London, where the revenues from the charging system are spent on local public transport. In Gothenburg the revenues co-finance a package of investments in Gothenburg (West Swedish Agreement, October 28, 2009). The largest investment in the package is the West Link (2.0 billion EUR), which is an 8-km-long rail link including a 6-km-long tunnel under central Gothenburg. Most of the benefits of the West Link will accrue to individuals residing close to train stations further out in the larger Gothenburg region, and not primarily to the individuals affected by the charging system.

Levinson (2010) and Ison and Rye (2005) underscore that distribution of cost and benefit of a charging system depends on the design of the system, including for instance exemptions and discounts. This is demonstrated by the Swedish congestion charging system, where the congestion charge is included in the "taxable benefit value" of company cars. Hence, company car owners are either exempt from paying the charge, or can deduce the charge from their gross income (which implies a discount of approximately 70%). This implies negative effects on equity, since company car users tend to have high incomes.

Levinson argues that the public opinion depends on the distribution (and perception of the distribution) of gains and losses to a proposed change. The Gothenburg system has indeed low public support: A consultative referendum was held in September 2014, where 57 percent voted against congestion charges, although the support did increase after introduction. Some authors (Eliasson and Mattsson, 2006; Levinson, 2010) have also argued that equity concerns coupled with low public acceptability is one of the main reasons why congestion charges are implemented in so few cities, but the experiences from Gothenburg speak against this: all traditional political parties are in favour of congestion charges in spite of the negative effect on equity.

The paper is organized as follows. Section 2 describes the charging system, Section 3 the CBA methodology, and Section 4 the CBA results. The method and results of the equity analysis is included in Section 5 and Section 6 concludes.

2 THE GOTHENBURG CONGESTION CHARGES

Gothenburg (Göteborg in Swedish) is the second largest city in Sweden with half a million inhabitants within the city and nearly a million in the larger 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. Gothenburg is a sparsely populated metropolitan area. Its planning does not support an efficient public transport system, implying a considerably lower share of public transport than in 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 increased, prompting a denser and more transit-oriented society.

A cordon-based congestion charging scheme was introduced in Gothenburg in January 2013 (see figure 1). The charge is time-of-the-day dependent, ranging from €0.8 to €1.8 during weekdays 6.00 – 18:30, while other time periods are free of charge. The maximum daily charge is 6 euros[1]. Vehicles are charged when passing the cordon in either direction using automatic number plate recognition. The main reason for introducing congestion charges was to raise yearly revenue of €100 million, co-financing a large infrastructure package, mainly a rail tunnel. Other objectives were to reduce congestion and improve the local environment. Congestion in Gothenburg is however mainly concentrated to the highway hub depicted in figure 1.

The average charge is approximately €0.5 per passage, compared €1 for Stockholm. In 2013 the number of passages was 132 million and the total revenue €71 million in Gothenburg to compare with 77.6 million passages and the total revenue of €75.6 million in Stockholm. Since Gothenburg is less than half the size of Stockholm, each citizen pays on average twice as much as in Stockholm.

Public resistance against the congestion charges resulted in a consultative referendum in conjunction with the regularly-scheduled general election to the national parliament and to the city council, held on 14 September 2014. The referendum question was formulated as: ‘‘Do you think that the congestion tax should continue after the 2014 election?’’. Fifty-seven percent of the population

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

in the municipality voted "No", but the newly elected city council decided to ignore the result and keep the charges.

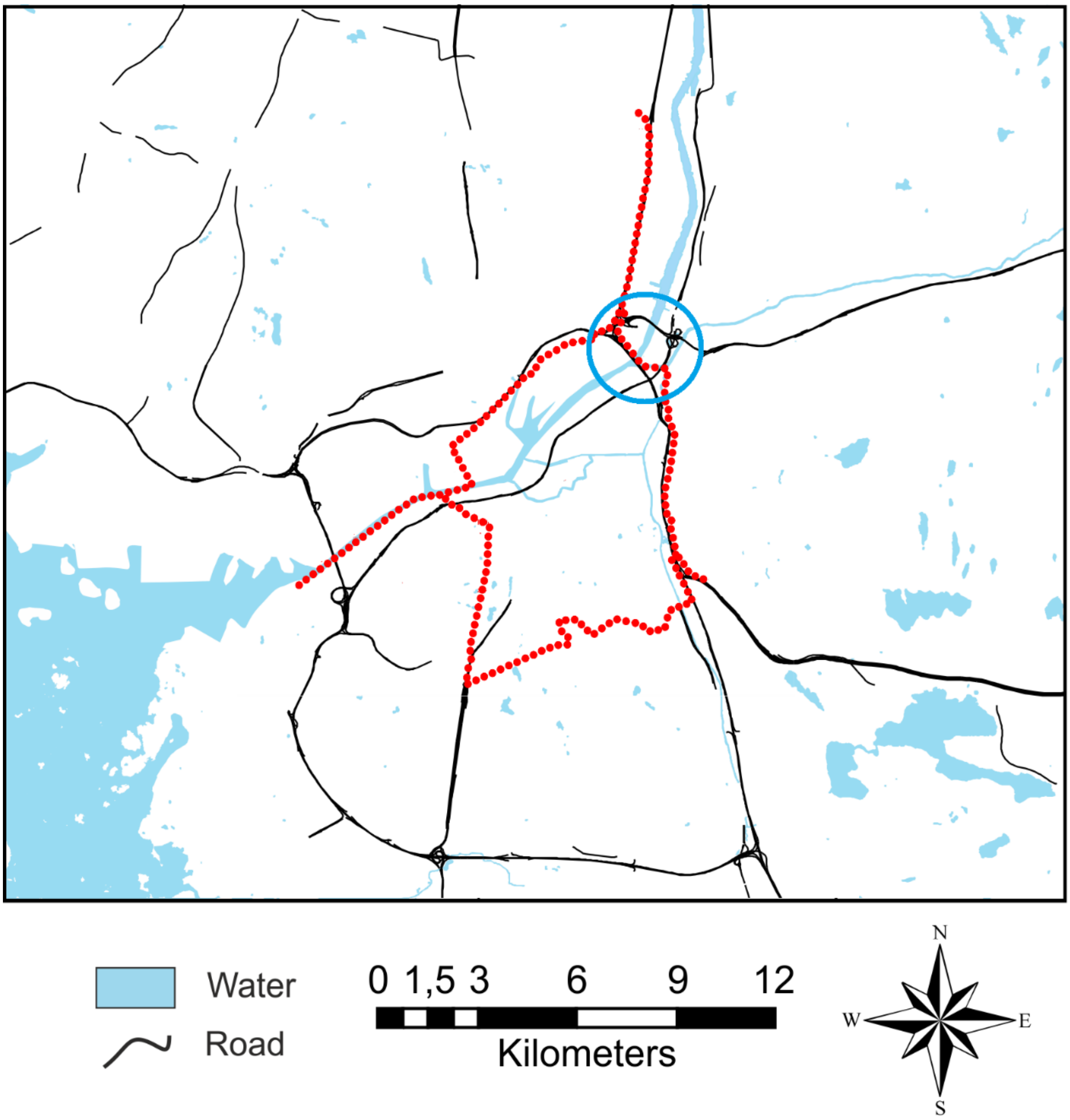

Fig. 1 Gothenburg with the toll cordon depicted in red, main roads in black and highway hub in blue

3 COST BENEFIT ANALYSIS

In the design phase, the traffic effects of the Gothenburg charges were forecast using the Swedish national transport model system Sampers (Beser Hugosson and Algers, 2002). The traffic volume across the cordon and other larger links in Gothenburg was observed before and after the introduction of congestion charges. Travel times were measured with cameras before and after the introduction of congestion charges (City of Gothenburg, 2013a) in all major links in Gothenburg.

The effects in terms of traffic volumes and travel times model simulated by the model correspond well to the observed effects (West et al, 2015). The observed reduction in traffic volume across the cordon was 10% while the model predicted 9%. On the links where the charges reduced travel times the most, (the arterials leading into and from the bottlenecks on the highway hub depicted in figure 1) the average travel time reduction predicted by the model was 11%, while the observed was 9%.

In Stockholm, where much of the congestion is dynamic and arising from spill-back queues and blocking of upstream intersections, travel time reductions on links outside the cordon were substantially underestimated by the transport model (Börjesson & Kristoffersson, 2014; Eliasson, Börjesson, van Amelsfort, Brundell-Freij, & Engelson, 2013).[2] The CBA for the Stockholm system was therefore based on observed travel times on relevant links (Eliasson, 2009). This presented a problem requiring some method development for the welfare calculations since the welfare analysis should be computed at the OD-pair level (see Neuberger, 1917).

The effect of the congestion charges in Gothenburg is limited to the arterials leading into and from the bottlenecks on the highway hub and spill-back queues are not a problem in the system. This is the main reason why the travel times were predicted with high accuracy by the static assignment model. Therefore we base our welfare analysis on model simulated effects, ensuring that the welfare effects are computed on the OD-pair level.

3.1 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 a separate model and kept constant in the forecast. It is however exogenous in the route choice model, implying that this traffic to some extent influences 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 matrices 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 matrices for each time period are then assigned to the network. The time-of-day dependent charge is approximated by a constant charge within each time period. The

[2] The model simulated travel time reduction on the links crossing the cordon was, however, close to the observed.

constant charge is computed as a weighted average across each 15-minute interval within the given time period, the weights being the observed traffic volume. The approximation errors are highest for the off-peak period, e.g. midday where the charge ranges from 0.8 to 1.3 euros and night time which is free of charge.

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)

$$U = \alpha T + \beta D + C, \tag{1}$$

with α being the VTT and β the distance cost. The VTT α (of the drivers in each OD pair) is taken to be a random variable X following the log-normal distribution $\ln \mathcal{N}(\mu, \sigma^2)$. The parameter β is constant in the population, equalling the average driving cost per kilometre. In a standard network assignment, the path disutility (such as the one defined by 1) of a route is assumed to be the sum of the disutilities of all links within the route. This assumption is valid for most transport networks. It is, however, not valid for the Gothenburg network where a multi-passage rule applies. Then a driver only has to pay one charge even if she uses more than one charged link within one hour.

To implement the multi-passage rule, a hierarchical route choice algorithm with two levels is applied in the assignment (West et al, 2015). 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 the first step (the lower level of the hierarchical route choice algorithm), the travel time T and travel distance D 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

$$U = \tilde{\alpha} T + \beta D. \tag{2}$$

with $\tilde{\alpha}$ being the median VTT and β the average driving cost per kilometre. The route choice differs between paying and non-paying drivers because the former may use the full road network while the latter use 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 $\tilde{\alpha}/\beta$, determines the route choice. We use the median VTT $\tilde{\alpha}$, and not the VTT distribution, in this step in order to produce a unique travel time and travel distance for each OD pair. Unique travel times and travel distances are required in the upper level of the route choice. The travel time and travel distance matrices for the paying drivers obtained by network skimming after the assignment are denoted $\boldsymbol{T}^p$ and $\boldsymbol{D}^p$. For non-paying drivers, the corresponding matrices are denoted $\boldsymbol{T}^n$ and $\boldsymbol{D}^n$.

The second step (the upper level of the hierarchical route choice) determines the share of paying drivers in each OD-pair. The random distribution of α implies that some drivers in the OD-pair are better off paying a charge to save time, while others are not. A driver in OD-pair (o, d) with VTT α^* is better off paying the charge C and take the faster route if $\alpha^* T_{o,d}^p + \beta D_{o,d}^p + C < \alpha^* T_{o,d}^n + \beta D_{o,d}^n$. The driver with the trade-off value of time, $k_{o,d}$, will be indifferent to paying the charge or to take a detour. This trade-off value is computed as

$$k_{o,d} = \frac{C + \beta D_{o,d}^p - \beta D_{o,d}^n}{T_{o,d}^n - T_{o,d}^p}. \tag{3}$$

The share of paying drivers in each OD pair is

$$q_{o,d} = P\left(X > k_{o,d}\right) = \int_{k_{o,d}}^{\infty} \ln \mathcal{N}(\xi; \mu, \sigma)\, d\xi. \tag{4}$$

In the third step the paying and non-paying drivers are assigned to the network simultaneously. The iteration is then repeated from the first step until convergence is reached. Because different trip purposes have different VTT distributions, the calculation is done separately for each trip purpose, but this is left un-notated to simplify the formulas.

The parameters μ and σ of the VTT distributions originate from the national VTT study (Börjesson & Eliasson, 2014). For commuting trips median value of time, $\tilde{\alpha}$, is 5.1 €/h and mean value of time, $\bar{\alpha}$, 10.8 €/h. For business and freight trips median VTT is 27.3 €/h and mean VTT 29.1 €/h, and for other private trips median VTT is 2.5 €/h and mean VTT 4.9 €/h. However, the VTT distributions applied in the hierarchical route choice is stretched to the right (i.e., μ is increased) compared to the distribution from the national VTT study. Otherwise the observed route choice behaviour is not reproduced by the model; more drivers than observed are then forecast to take a detour to avoid paying the charge. The value of time distribution for commuting trips applied in the route choice for instance has median 10.2 €/h.

We underscore that there is no strong reason to believe that the stretched VTT distribution represents the drivers' true distribution. One possibility is that the stretching of the VTT distribution controls for deficiencies in the coding of the network (such that the travel times on small roads and streets are underestimated in the model). Another possibility is that the route choice is influenced by attributes not represented in the network model that are correlating with travel time, such as the preference for larger arterials rather than smaller streets due to for instance comfort. For this reason, we apply the original, not stretched, value of time distribution by trip purpose in the welfare calculation in Section 3.2.

3.2 The consumer surplus

In this section the consumer surplus is derived. The consumer surplus depends on the paid charge, the travel time gains, the changes in driving costs, and the adaptation cost for drivers priced-off the road. Benefits from reduced travel time reliability are not included in the transport model but are assessed separately from camera data (see Section 3.3). Welfare losses for public transport users due to more crowding are approximated to zero for the reasons stated in Section 3.4.

For drivers in OD-pairs without the choice between an uncharged and a charged route alternative, the value of the changes in travel time is computed as

$$\Delta v_{o,d} = \bar{\alpha}\left(T_{o,d}^{0} - T_{o,d}^{1}\right), \tag{5}$$

where $\bar{\alpha}$ is the average VTT, and $T_{o,d}^{1}$ and $T_{o,d}^{0}$ are the travel times in the situation with and without congestion charges, respectively. The average VTT does not vary across OD pairs.

For OD pairs where there is a choice between a charged and an uncharged route, the value of the travel time gain is calculated as

$$\Delta v_{o,d} = \bar{\alpha} T_{o,d}^{0} - \left(\left(1 - q_{o,d}\right)\alpha_{o,d}^{n} T_{o,d}^{1n} + q_{o,d}\alpha_{o,d}^{p} T_{o,d}^{1p}\right), \tag{6}$$

where $\alpha_{o,d}^{n}$ is the average VTT for the non-paying drivers, $\alpha_{o,d}^{p}$ is the average VTT for the paying drivers, and $T_{o,d}^{1p}$ and $T_{o,d}^{1n}$ are the travel times for non-paying and paying drivers in the situation with charges.

The average VTT for paying drivers is

$$\alpha_{o,d}^{p} = \mathrm{E}\left[X \middle| X > k_{o,d}\right] = \frac{g_{o,d}}{q_{o,d}}, \tag{7}$$

where $g_{o,d}$ is the partial expectation with respect to $k_{o,d}$ for the log-normal random variable, defined as

$$\begin{aligned} g_{o,d} &= \alpha_{o,d}^{p} q_{o,d} \\ &= \mathrm{E}\left[X \middle| X > k_{o,d}\right] P\left(X > k_{o,d}\right) \\ &= \int_{k_{o,d}}^{\infty} \xi \ln \mathcal{N}(\xi; \mu, \sigma^{2})\, d\xi \\ &= \bar{\alpha}\Phi\left(\frac{\mu + \sigma^{2} - \ln k_{o,d}}{\sigma}\right). \end{aligned} \tag{8}$$

Here Φ is the standard normal cumulative distribution function. The derivation of the VTT expectation for non-paying drivers is straight-forward since $\bar{\alpha} = \left(1 - q_{o,d}\right)\alpha_{o,d}^{n} + q_{o,d}\alpha_{o,d}^{p}$;

$$\alpha_{o,d}^{n} = \frac{\bar{\alpha} - q_{o,d}\alpha_{o,d}^{p}}{1 - q_{o,d}} = \frac{\bar{\alpha} - g_{o,d}}{1 - q_{o,d}}. \tag{9}$$

Combining (7) and (9) with (6) we have

$$\Delta v_{o,d} = \bar{\alpha} T_{o,d}^{0} - \left(\left(\bar{\alpha} - g_{o,d}\right) T_{o,d}^{1n} + g_{o,d} T_{o,d}^{1p}\right). \tag{10}$$

Note that for OD pairs where there is not choice between charged and non-charged routes, $g_{o,d} = 0$ and (10) collapses to (5).

The consumer surplus is

$$W = \frac{1}{2}\sum_{o \in O}\sum_{d \in D}\left(s_{o,d}^{0} + s_{o,d}^{1}\right)\left(\Delta v_{o,d} + \Delta b_{o,d} - c_{o,d}\right), \tag{11}$$

where $s_{o,d}^{0}$ and $s_{o,d}^{1}$ are the OD specific demand before and after the introduction of congestion charges, $\Delta v_{o,d}$ is the change in travel time (derived by (5) for drivers in OD-pairs not affected by the charges, and by (10) for drivers in OD pairs affected by the charges), $\Delta b_{o,d} = \beta\left(D_{o,d}^{0} - \left(\left(1 - q_{o,d}\right)D_{o,d}^{1n} + q_{o,d}D_{o,d}^{1p}\right)\right)$ is the change in driving cost, and $c_{o,d} = q_{o,d}C$ is the paid congestion charge per trip. Then (11) can be rewritten as

$$W = \sum_{o\in O}\sum_{d\in D} s_{o,d}^{1}\left(\Delta v_{o,d} + \Delta b_{o,d} - c_{o,d}\right) - \frac{1}{2}\sum_{o\in O}\sum_{d\in D}\left(s_{o,d}^{1} - s_{o,d}^{0}\right)\left(\Delta v_{o,d} + \Delta b_{o,d} - c_{o,d}\right), \qquad (12)$$

where the first term is the loss for the remaining drivers and the second term is the loss for drivers priced-off the road.

3.3 Travel Time Variability

The improved travel time variability can be measured as the reduction in standard deviation of the travel time on the inner arterial links. Since the travel times on other links than these inner arterials are not affected, and since the congestion is limited to the inner arterials, travel time variability on the arterial links corresponds well to the variability in travel times on the OD pair level for the traffic on the affected links. This calculation of the benefit from improved travel times we describe below is a rough approximation and link based rather than based on the OD-pair level. It still gives an indication of the magnitude of the effect of improved travel time reliability relative to other effects. As we will see in the results, the consumer surplus arising from reduced travel time variability is small in relation to the benefit of shorter travel time.

The ratio between the valuation of standard deviation and the valuation of mean travel time, usually denoted the reliability ratio, is estimated to be close to 1 for drivers in Sweden (Börjesson, 2008), which corresponds well to what is found for other countries (Bates et al. (2001)). We therefore apply the reliability ratio 1 in this paper.

The travel times by day and 10-minute interval are available for 2012 och 2013 for the morning peak 7.00 – 9.00 (City of Gothenburg, 2013a). Table 1 shows the standard deviation averaged over the twelve 10-minute intervals in the peak, over six weeks in September and October for 2012 and 2013.

Table 1 Travel time standard deviation on arterial links and the calculated gain from the reduction

	Number trips 7-9 am 2013	Std.dev. (min) 2012	2013	Reduction	VTT (€/h)	Benefit (€)
Bäckebol - Tingstad	11 100 000	2.3	2.2	0.1	8.7	170 000
Ullevi - Tingstad	5 600 000	1.2	1.0	0.1	8.7	90 000
Munkebäck - Tingstad	3 700 000	1.3	1.0	0.3	8.7	180 000
Kallebäck - Tingstad	2 200 000	2.6	1.6	1.0	8.7	310 000
Sum	22 600 000					750 000

The total yearly traffic volume in the morning peak 7.00 – 9.00 on all links where the standard deviation in travel time is measured is 22 600 000 vehicles. The total daily traffic volume on these links is roughly five times the volume in the morning peak: 100 million. We assume that standard deviation in the travel times for all traffic outside the morning peak 7.00 – 9.00, is on average 25 percent of the reduction in the morning peak. This means that the consumer surplus from the improved travel time variability is twice that of the morning peak or €1 500 000 per year.

3.4 Public transport

The producer surplus for the transit operator consists of increased fare revenues minus costs for providing additional capacity to the passengers diverted from driving. Compared to 2012, transit ridership and sales of monthly and yearly tickets increased by 7%, but approximately 2% is considered to be due to factors other than the congestion charges (the sales of monthly and annual travel cards increased by on average 2 % yearly over several years prior to 2012, due to population growth and various marketing campaigns continuing during 2013). The number of public transport trips also increased by 5% in the charged OD pairs according to the travel survey conducted before and after the introduction of the charges (Börjesson and Kristoffersson, 2015). The 5% increase in sales of monthly and annual travel cards corresponds to a 77 m€ increase in yearly revenue for the public transport operator.

The operating cost for the public transport in the entire county (larger than the metropolitan area) increased by 5% corresponding to 316 m€/year. However, the operating costs increased even more the previous years (5-11%), suggesting that it was not directly the increased public transport demand due to congestion charges that increased the operating costs (Västtrafik, 2013). Moreover, crowding in the public transport system in Gothenburg is not a large problem, so one could also argue that additional public transport supply to reduce crowding were required (the share of buses and commuting trains where anyone has to stand up is less than 3% (Björklind et al., 2014)). For this reason we assume that the public transport producer surplus and crowding stay unaffected by the congestion charges. Changes in the public transport network and lane priority were introduced during 2012 and up until two weeks prior to the introduction of the congestion charges, but these changes are not parts of the CBA in the present paper.

3.5 External costs

The external costs of car use are taken from the Swedish CBA guidelines (ASEK, 2014). It is in total 0.051 per vehicle kilometre, the components being traffic safety (€0.022 per vehicle kilometre), noise (€0.019 per vehicle kilometre), emissions other than CO2 (€0.009 per vehicle kilometre) and CO2 emissions (€0.023 per vehicle kilometre). According to the CBA guidelines all these components depend on the local environment, and we use the ones for city environments, where the external cost per vehicle kilometre is assumed to be higher than for Sweden on average.

3.6 Government cost and revenue

The Government's costs and revenues come from the paid charge, changes in fuel tax, and operating and maintenance costs of the government. The revenue from the paid charge is only a transfer from the drivers. The fuel tax corresponds to approximately €0.059 per vehicle kilometre in Sweden according to the guidelines, which is slightly less than the external effect per vehicle kilometre.

According to Transportstyrelsen, the operating and maintains cost of the charging system was M€ 12 in 2013. The investment cost of the system was 70 M€.

3.7 Marginal cost of public funds

According to the Swedish CBA guidelines net public expenditure is multiplied with the marginal cost of public funds (MCPF). The underlying assumption is thus that an infrastructure investment requires a marginal increase in the tax revenue (assuming that total public expenditure on other measures remains constant). Sørensen (2010) estimates MCPF to 1.3 in Sweden.

In the case of revenue generated from congestion charges, the analogous argument can be made; if the revenue from congestion charges allows a marginal reduction in tax revenue (assuming that total public expenditure on other measures remains constant) the revenue should be multiplied with the MCPF. However, since the Gothenburg congestion charges were introduced to finance an infrastructure investment package that would not have been realized had the congestion charges not been implemented, this assumptions may be contested. The political agreement (West Swedish Agreement, October 28, 2009) explicitly required partial funding from congestion charges. For this reason we do not include MCPF in the net social benefit of the congestion charges. On the other hand, the cost of the investments included in the package should not be multiplied by the MCPF in the CBA of these investments.

4 CBA RESULTS

Table 2 summarizes the result of the cost-benefit analysis. The figures in the left column are computed using the assumption that the value of time is constant in the population and hence that $\Delta v_{o,d} = \bar{\alpha}\left(T^{0}_{o,d} - \left(1 - q_{o,d}\right)T^{1n}_{o,d} - q_{o,d}T^{1p}_{o,d}\right)$. The figures in the right column are computed according to equation (10), assuming that the value of time is distributed in the population, and that drivers in OD pairs where there is a choice between charged and uncharged routes are sorted between the routes depending on their value of time.

Verhoef and Small (2004) and Börjesson and Kristoffersson (2014) show that ignoring heterogeneity in VTT in a system with uncharged routes leads to underestimation of social benefits, by disregarding the efficiency gains due to sorting of the drivers with respect to VTT. In this case, the travel time gains increase 43 percent.

Table 2 shows that the Gothenburg congestion charging system is beneficial for society even if not taking into account the benefit of the sorting of drivers between route with respect to their value of time. Table 2, however, does not take the investment cost into account. The investment cost of the system was €70 million. Assuming the social benefit from the right hand column €20 million, the system will have recovered the investment cost in terms of social benefits in a little less than four years. In financial terms, investment cost is recovered after just over one year, the yearly revenue being €59 million.

Table 2 Cost benefit analysis of the Gothenburg congestion charges

	Loss/gain MEUR/year	
	Constant VTT	VTT distribution
Paid charge	-77	-77
Travel time saving	23	33
Travel time variability saving	2	2
Driving cost increase	-1	-1
Loss for evicted drivers	-3	-3
Consumer surplus	-56	-46
Traffic safety effects	2	2
Noise reduction	2	2
Pollution reduction	1	1
Reduction of CO2 emissions	2	2
External effects	7	7
Paid charge	77	77
Fuel tax decrease	-6	-6
Operating cost	-12	-12
Government	59	59
Net social benefit, excl. investment cost	**10**	**20**

The relative efficiency of the pricing scheme can be calculated as ratio of the total net welfare benefits and the total revenue collected from the congestion charges. In this case, the relative efficiency is 20/77 = 0.26 (the right column in Table 2). This can be compared to the Stockholm system, where the relative efficiency was 65/80 = 0.81 (Eliasson 2009). Hence, the sum of money that is redistributed in the population compared to the social benefit is substantially larger in the Gothenburg case than in the Stockholm case.

The consumer surplus can be split up on trip purpose according to Figure 2. A majority of the travel time savings accrue to business and freight trips due to their high value of time, even though private car drivers (work trips and other) pay a large part of the toll.

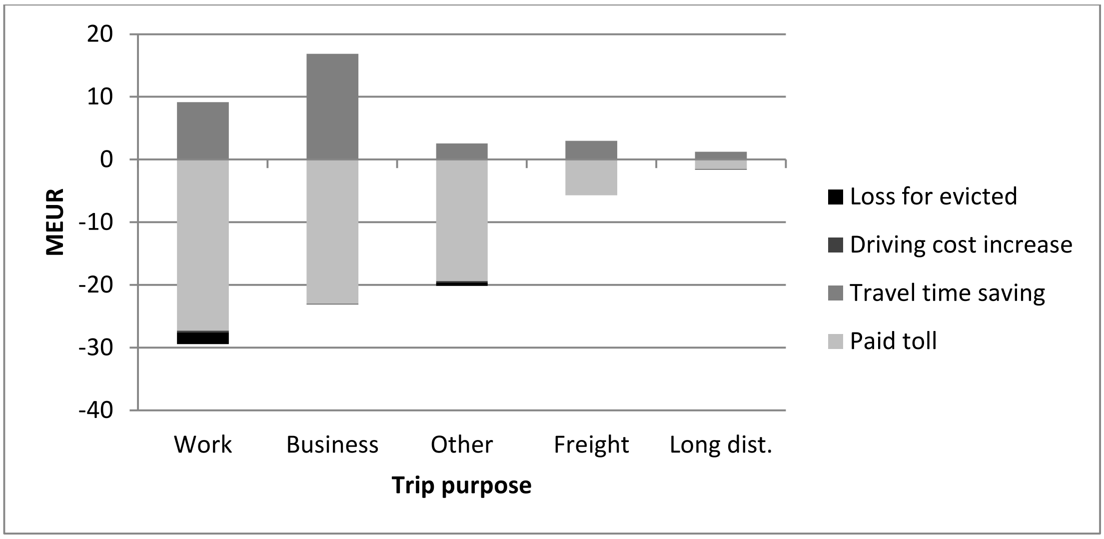

Fig. 2 Consumer surplus by trip purposes

5 DISTRIBUTION OF THE BENEFITS AND LOSSES

In this section we explore how the costs and benefits are distributed across segments of the population. In Section 5.1 we describe the method of computing the distribution effect with respect to income. In Section 5.2 we describe the data that is input to the analysis and in Section 5.3 the result. In section 5.4 we summarize the distributional effect with respect to age, gender and residential area.

5.1 Method

We assume that the costs and benefits of the reform depend on i) the value of time, ii) the frequency of charged trips, iii) access to company car (meaning either that the driver pays nothing personally or receives roughly a 70% discount, see the introduction). These factors are all functions of income, and costs and benefits will therefore depend on the income level. Moreover, the frequency of charged trips and income level varies across residential areas.

The transport model operates at a zonal level. The zones are 0.1-1 km^2 in built-up areas. The population of residents in each zone o is divided into 12 different income classes i. The number of individuals in each income class i in zone o is n_o^i. To compute the cost and benefits for drivers by residential area and income class, we need i)-iii) by residential area and income class. Since only trips originating from the resident zone can be linked to the residents of each zone we restrict the distribution analysis to commuting trips. Other trips do not always start in the zone where the driver resides.

The variables i)-iii) by income class and zone are derived as follows:

i) Value of time

The value of time distribution for income class i is assumed to be lognormally distributed $\ln \mathcal{N}(\mu_i, \sigma^2)$. The standard deviation σ^2 is kept from the main analysis and mean of the middle income class 5, μ_5, is assigned μ from the main analysis. The parameter μ_i of the other income classes are derived from the median values of time, $\tilde{\alpha}_i$, which in turn is determined assuming the income elasticity 0.5 (estimated in the Swedish value of time study (Börjesson & Eliasson, 2014)).

ii) Frequency of charged trips

For each zone o the transport model generates the total number of charged trips s_o^1. The model does not generate the number of charged trips by income class. However, the number of charged trips by income class can be derived from a survey (see Section 5.2), but only on the aggregate level for the urban area and not by zone. To approximate the number of charged trips per inhabitant aged over 16 by zone and income class, let δ_i be the number of charged trips per inhabitant in income class i, and let n_o^i be the total number of individuals in income class i in zone o. Then the share of all trips s_o^1 starting in zone o that are made by the individuals in income class i is

$$r_o^i = \frac{\delta_i n_o^i}{\sum_{i \in I} \delta_i n_o^i}. \tag{13}$$

The number of trips per individual in income class i residing in zone o is then $r_o^i \sum_{d \in D} s_{o,d}^1 / n_o^i$.

iii) Access to company car

From aggregate data we know the average number of company cars per inhabitant by income class on the national level. From this we calculate the share of the drivers with access to a company car in each income class, γ_i.

Welfare effect

To compute the welfare effect by income group and zone, we compute the share of paying and non-paying drivers by zone and income class. As in the main analysis in 3.2, $k_{o,d}$ is the threshold VTT between paying and non-paying drivers in each OD-pair. Based on the value of time distribution for income class i and $k_{o,d}$ for each OD pair we computed the share of paying drivers by income class and OD pair $q_{o,d}^i = \int_{k_{o,d}}^{\infty} \ln \mathcal{N}(\xi; \boldsymbol{\mu_i}, \sigma^2)\, d\xi$.

Following the derivation of (9) in Section 3.2 we find that the value of travel time gains for all drivers (paying and non-paying)

$$\Delta v_{o,d}^i = \bar{\alpha}_i T_{o,d}^0 - \left(\left(\bar{\alpha}_i - g_{o,d}^i \right) T_{o,d}^{1n} + g_{o,d}^i T_{o,d}^{1p} \right), \tag{14}$$

where $g_{o,d}^i = \int_{k_{o,d}}^{\infty} \xi \ln \mathcal{N}(\xi; \mu_i, \sigma)\, d\xi$.

The aggregate welfare effect for the remaining drivers in income class i is

$$W_i = \sum_{o \in O} r_o^i \sum_{d \in D} s_{o,d}^1 \left(\Delta v_{o,d}^i + \Delta b_{o,d}^i - c_{o,d}^i \right), \tag{15}$$

where $\Delta b_{o,d}^i = \beta \left(D_{o,d}^0 - \left(\left(1 - q_{o,d}^i\right) D_{o,d}^{1n} + q_{o,d}^i D_{o,d}^{1p} \right) \right)$ and $c_{o,d}^i = (1 - \gamma_i) q_{o,d}^i C$. Here we do not calculate the number of drivers priced off the road for each income class separately. As shown in Table 2, their loss is relatively small compared to the loss for the remaining drivers.

5.2 Data

The frequency of trips to be charged in different segments of the population is derived from a two wave travel survey conducted in Gothenburg in November 2012 and November 2013 (Börjesson, Eliasson, & Hamilton, 2016). The surveys were sent to random samples of adult residents in relatively central parts of the Gothenburg region (the municipalities of Göteborg, Mölndal, Partille and Öckerö, and the postal areas Mölnlycke and Landvetter in Härryda municipality), resulting in 1582 (2012) and 1426 (2013) useable responses, with response rates of 40% and 38%, respectively.

The survey included questions on general travel behaviour, socio-economic questions and questions relating to congestion charging and parking. The survey included a broad set of questions on various topics to avoid policy bias. The respondents were reminded of the design of the charging system by a map and times when the charge applies. The respondents were asked how often they paid the congestion charge (or would pay it in the 2012 wave).

Table 3 reports the frequency of charged trips by income class in the situation without the charges according to the survey. The income classes in the survey do not match the income classes in the transport model. The values in Table 3 were therefore interpolated to the income classes in the model, shown in Table 4.

Table 3 Paying trips per day (δ) for each income class

Income €/month	δ_i
– 1 500	0.16
1 501 – 2 500	0.29
2 501 – 3 500	0.40
3 501 – 4 500	0.49
4 501 –	0.56
Average all individuals in the survey	0.35

The share of the drivers with access to a company car, γ_i, is taken from the report (Ynnor, 2014). Table 4 shows the parameters needed to compute i) – iii) by income class and zone o.

Table 4 Median VTT ($\tilde{\alpha}_i$), mean VTT ($\bar{\alpha}_i$), paying trips per day (δ_i) and share of the drivers with access to company car (γ_i) for each income class

i	*income (k€/year)*[3]	$\tilde{\alpha}_i$ *(€/h)*	$\bar{\alpha}_i$ *(€/h)*	δ_i	γ_i
0	0	0	0	0.00	0.0%
1	0.1 – 3.9	1.7	3.6	0.04	2.0%
2	4 – 7.9	3.0	6.2	0.11	2.0%
3	8 – 11.9	3.8	8.0	0.17	4.3%
4	12 – 15.9	4.5	9.5	0.23	3.1%
5	16 – 19.9	5.1	10.8	0.28	2.5%
6	20 – 23.9	5.7	11.9	0.33	2.2%
7	24 – 27.9	6.2	13.0	0.38	2.4%
8	28 – 39.0	6.6	13.9	0.42	4.0%
9	32 – 35.9	7.1	14.8	0.46	7.7%
10	36 – 39.9	7.5	15.7	0.49	15.8%
11	40.0 –	7.8	16.5	0.53	51.3%

5.3 Income distribution effects

Figure 3 shows the welfare effect per car commuting trip by income group

$$\frac{W_i}{s^i} = \frac{\sum_{o\in O} r_o^i \sum_{d\in D} s_{o,d}^1 \left(\Delta v_{o,d}^i + \Delta b_{o,d}^i - c_{o,d}^i\right)}{\sum_{o\in O} r_o^i \sum_{d\in D} s_{o,d}^1}. \tag{16}$$

Figure 3 shows that drivers in all income segments except the highest are worse off with the charges; the gains offset the losses only for the highest income segment. In general, the income influences the gains more than the losses. The income effect on the gain side is driven by the income effect on the value of time. The income effect on the loss side is smaller because all drivers pay a similar charge per trip. The highest income segment pays the smallest charge because they have to a larger extent access to company cars and receives thereby a discount of approximately 70%.

[3] When computing the value of time for income class *i* applying the elasticity 0.5, we assume the income in each class is the mid-point in the interval.

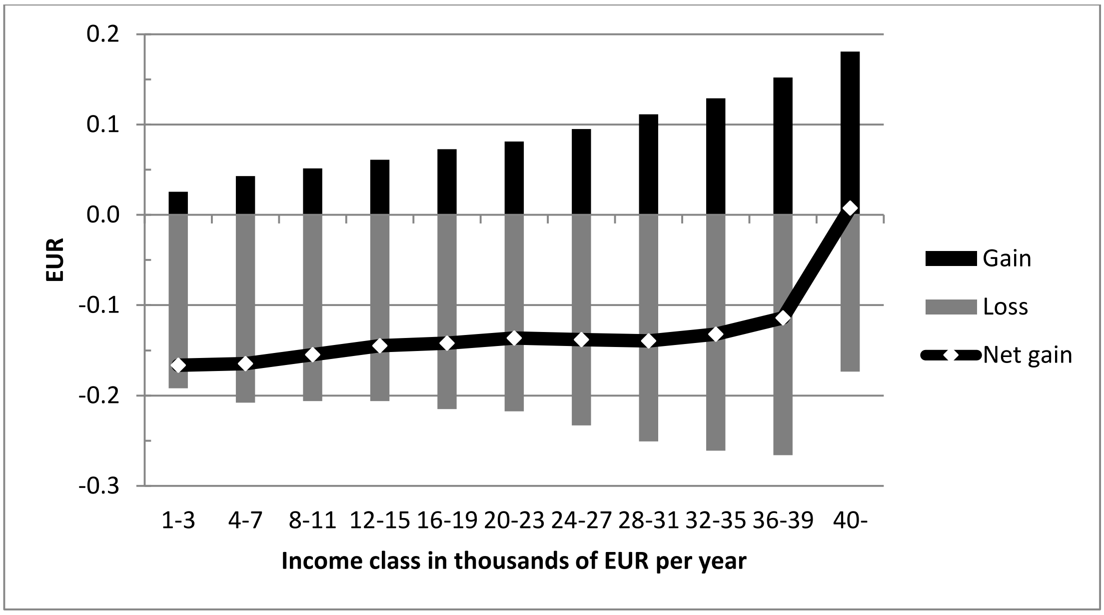

Fig. 3 Gains and losses of congestion charge by income group for car drivers residing in the Gothenburg Labour Market

To analyse the distribution effects of the congestion charge, it is more relevant to consider the full population and not only the drivers. Such analysis takes into account that high income individuals undertake charged trips more frequently than low income individuals. Figure 4 shows the welfare effect per inhabitant by income group

$$\frac{W_i}{n^i} = \frac{\sum_{o\in O} r_o^i \sum_{d\in D} s_{o,d}^1 \left(\Delta v_{o,d}^i + \Delta b_{o,d}^i - c_{o,d}^i\right)}{\sum_{o\in O} n_o^i}. \tag{17}$$

With the exception of the individuals in the highest and the lowest income class, the individuals in all income groups are on average worse off with the charges. Except for the highest income class, the losses increase with income, because individuals with higher incomes undertake charged trips more frequently. The richest third pays three times more than the poorest third. Eliasson and Mattsson (2006) found that in Stockholm the richest third pays four times more than the poorest third. For the highest income class, however, the losses are offset by the gains due to the considerably higher access to company cars.

Figure 5 displays the gains and losses as a share of income, showing that the net benefit relative to income increases with income. Hence, the congestion charge is a regressive tax instrument. Moreover, in Gothenburg the revenue are not spent to improve the local public transport system to benefit local low income groups. It is rather spent on a rail tunnel that will mainly benefit commuters from surrounding neighbourhoods. As long as a congestion charge is justified from the perspective of economic efficiency and to price externalities, negative distribution effects may be less of a problem. But since the congestion charge in Gothenburg is mainly implemented for fiscal reasons, to finance the rail tunnel and other infrastructure projects, the equity concern may be more problematic.

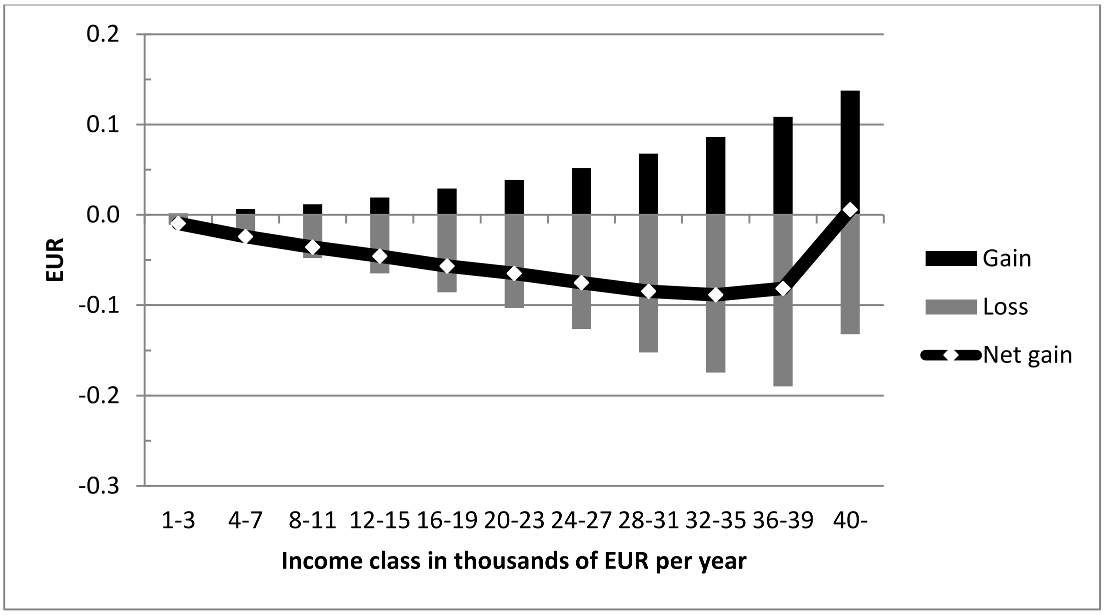

Fig. 4 Gains and losses of congestion charge by income group for all individuals residing in the Gothenburg Labour Market

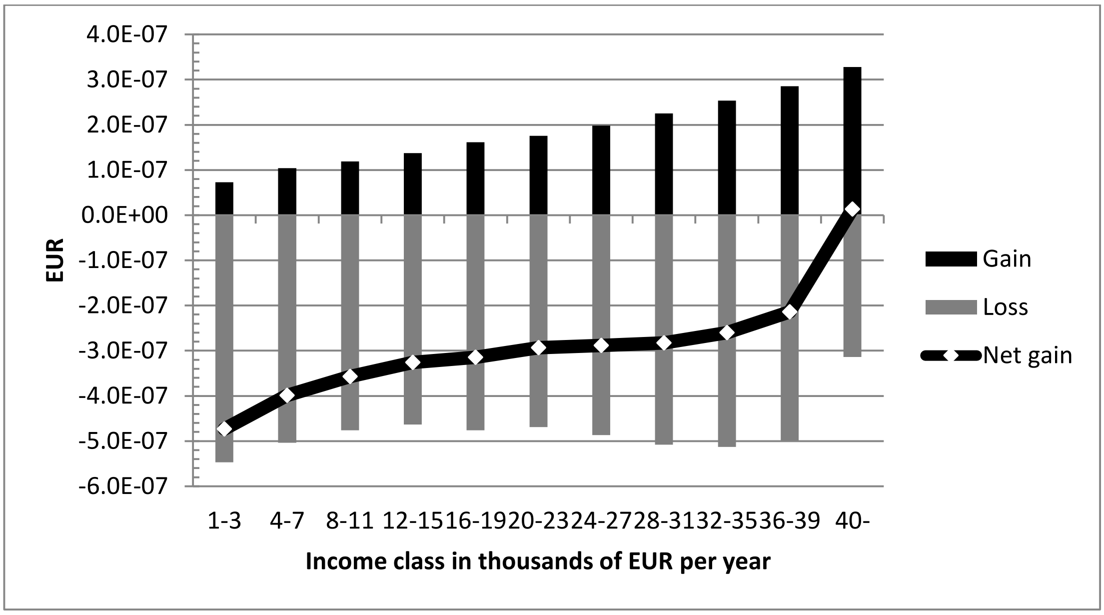

Fig. 5 Gains and losses, of congestion charge divided by the income, by income group for all individuals residing in the Gothenburg Labour Market

5.4 Gender and age distribution effects

We continue by analysing the gains and losses by gender and age group. According to the survey, men and women undertake on average the same number of charged trips per day. According to the value of time study, the average value of time does not differ between men and women. However, 28% of the men, but only 6% of the women, have access to a company car (Ynnor, 2014). This means that men and women benefit from the charges to the same extent, but women on average suffer larger losses than men.

Again according to the survey, the average frequency of charged trips differs by age group. Also the access to company car differs by age group, see Table 5. The value of time study does not indicate that the value of time varies with age.

Taking account of the frequency of charged trips and the access to company cars, the distribution of gains and losses are distributed between age groups according to Figure 6. The age group 56-64 years suffers the largest losses, and the group 36-55 benefit the most. The net loss is fairly constant across all groups except for the oldest.

Table 5 Paying trips per day and share of drivers with access to company car for each age group

Age group	δ_i	γ_i
18–25	0.26	0.05
26–35	0.32	0.03
36–55	0.45	0.14
56–65	0.41	0.10
65–75	0.26	0.04
over 75	0.12	0.01

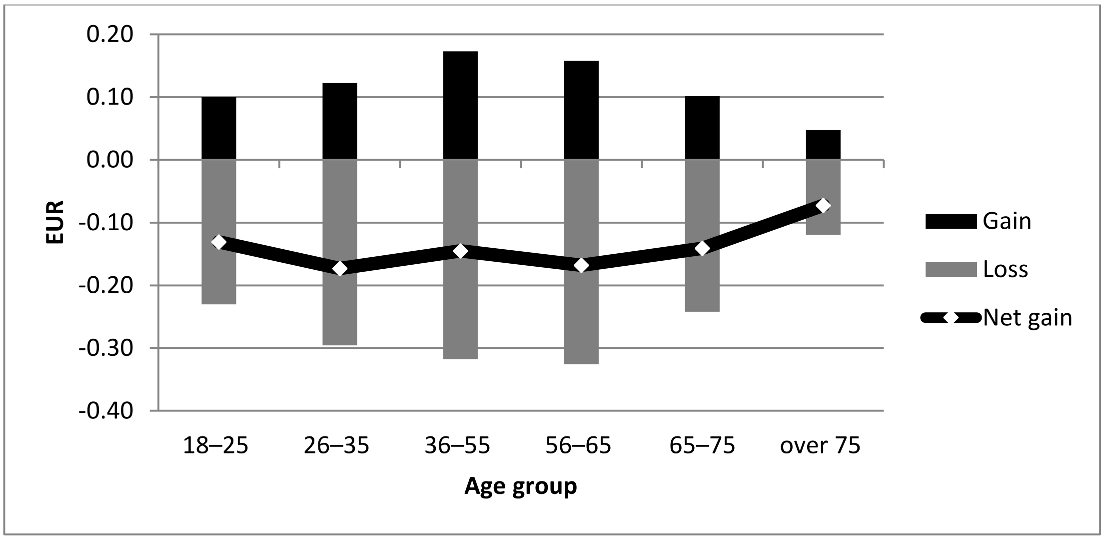

Fig. 6 Gains and losses of the congestion charge by age group for all individuals residing in the Gothenburg Labour Market

5.5 Geographical distribution effects

Finally, we analyse the geographic distribution of gains and losses. We also compare them to the outcome of the referendum held in September 2014, to explore to what extent the outcome of the referendum is driven by self-interest.

Figure 7 shows the loss per inhabitant by zone of residence. Residents of the neighbourhood just outside the toll cordon pay the most, because of their high frequency of charged trips. Figure 8 shows that the largest travel time gains are concentrated along the largest arterials, especially along the north-south link, E6, were the travel times reduced the most. Figures 7 and 8 combined show that residents of neighbourhoods north and west of the toll cordon, where the average income is low, suffer the largest net losses. They have low values of time and low access to company car benefits. The residents of the inner city both gain and lose less than the residents just outside the cordon, because they undertake fewer charged trips.

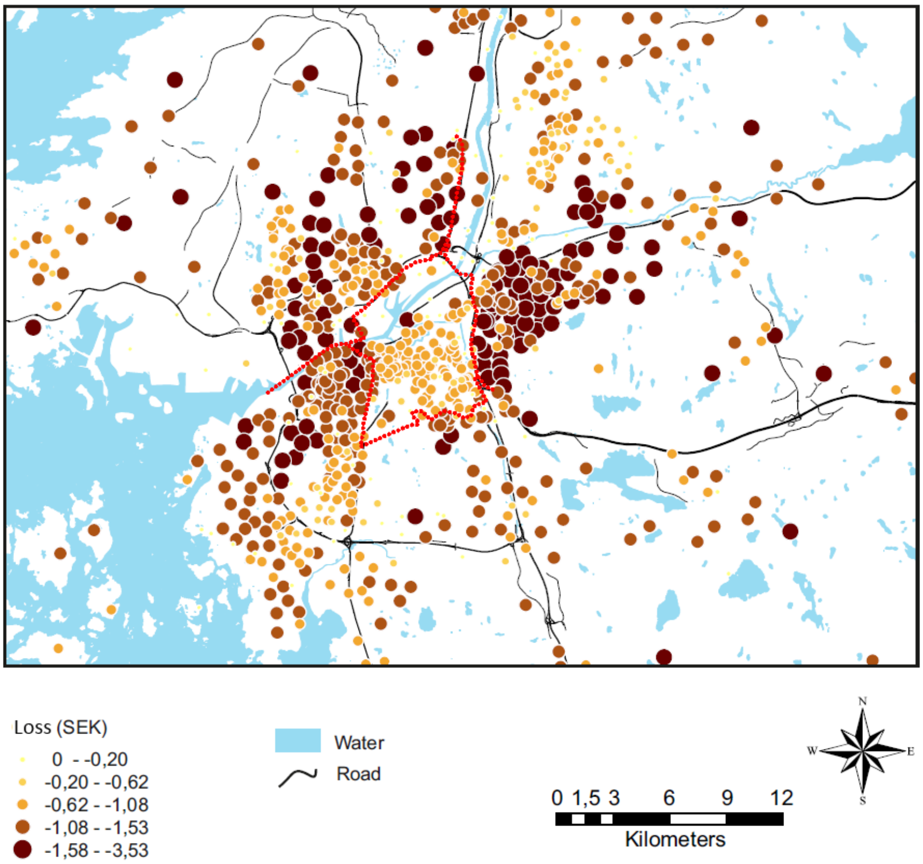

Fig. 7 Geographical distribution of loss

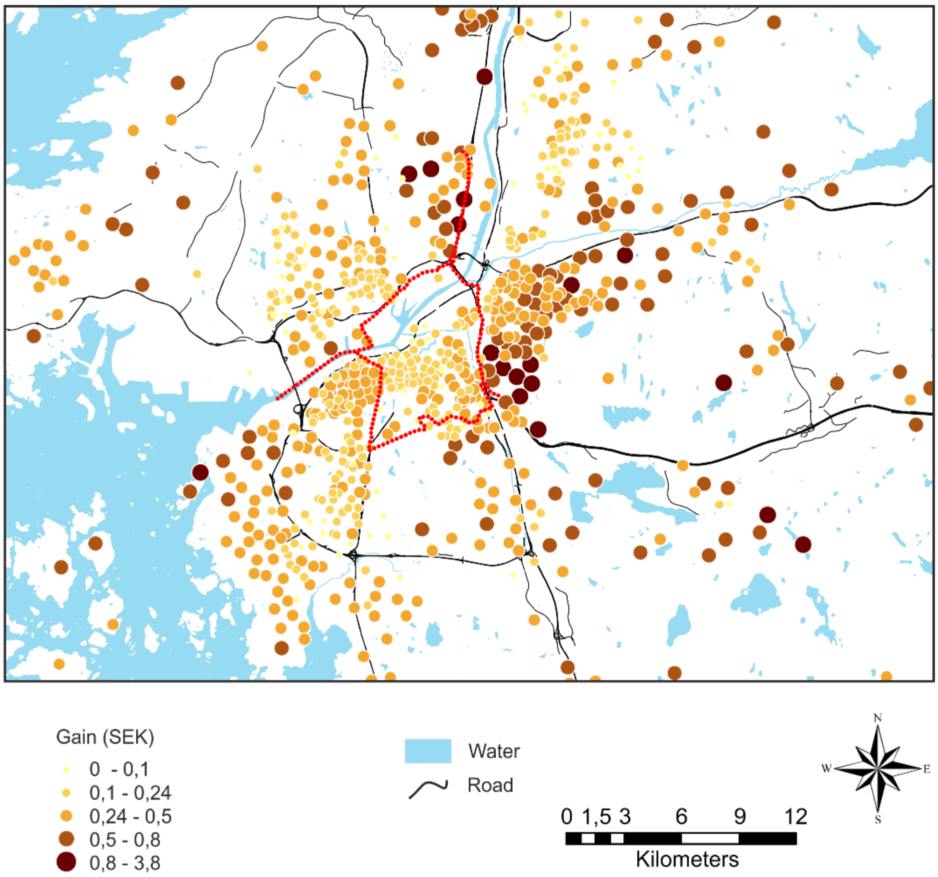

Fig. 8 Geographical distribution of time gain

Figure 8 shows the referendum results. The referendum was only held in the municipality of Gothenburg. It shows clearly that residents of central Gothenburg are more positive to the charges, whereas residents of further out in the region are more negative. This pattern is consistent with the pattern of losers of the charges in Figure 7; residents further out in the municipality lose more. However, the darkest areas on the map, east and south-west of the charging zone, where the residents are most positive, also lose a lot from the charges. As found by Börjesson et al. (2016), the attitudes to congestion charges is not only formed by self-interest, but also by more stable attitudes such as environmental attitudes and general attitudes to taxation.

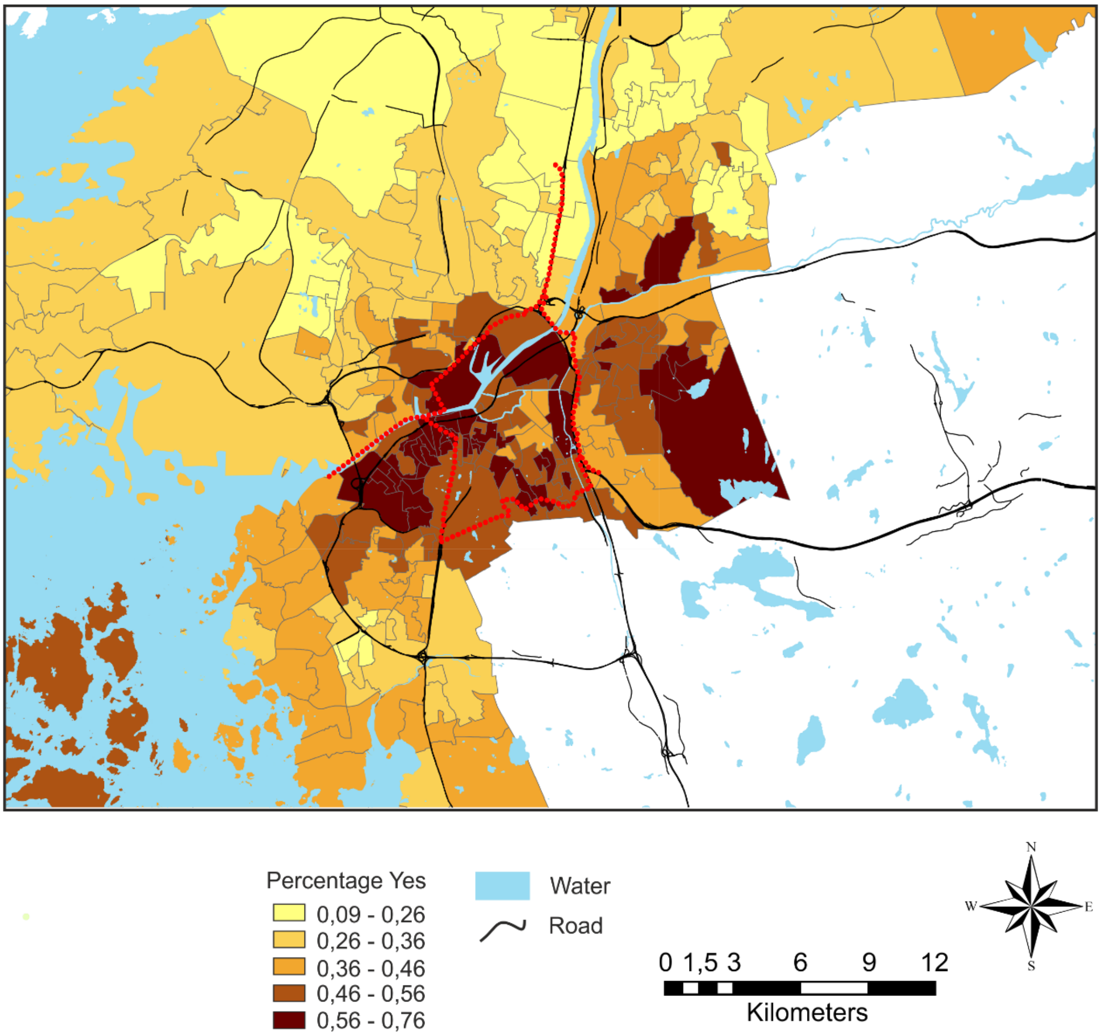

Fig. 9 Geographical distribution of referendum results

6 CONCLUSIONS

Although Gothenburg is a small city with congestion limited to the highway junctions, the congestion charge scheme is socially beneficial, generating a net surplus of €20 million per year. The investment cost was from a financial perspective repaid in slightly more than a year and is from a social surplus perspective repaid in less than four years. However, the sums that are redistributed are substantially larger than the net benefit. Analysis of the equity effects is therefore central.

The distribution analysis shows that the congestion charge is regressive, for several reasons. First, even low income individuals are highly car dependent in Gothenburg, due to the relatively low public transport share (26% in the charged relations). Second, workers in the highest income class have considerably higher access to company cars, and are therefore either exempt from paying the charge, or can deduce the charge from their income tax (which implies approximately a 70% discount). Third, high income individuals have higher values of time.

Except for individuals in the highest income class the average consumer surplus is negative for all individuals. Since most residents of Gothenburg suffer a net loss from the charges, and because of the negative distributional effects, the spending of the revenue is important. However, the revenue is spent mainly on a rail tunnel which primarily gives benefits to commuters from surrounding regions. This is potentially the main reason behind the negative public opinion in Gothenburg.

7 ACKNOWLEDGEMENTS

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