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A cost–benefit analysis of the Stockholm congestion charging system

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A B S T R A C T

This paper presents a cost–benefit analysis of the Stockholm congestion charging system, based on the observed rather than on the model-forecasted data. The most important data sources are travel time and traffic flow measurements made in the year before the charges were introduced (during April 2005) and during the first spring with the charges (during April 2006, 4 months after the charges were introduced). Using matrix calibration, effects on the non-observed link flows and travel times are extrapolated, enabling us to calculate the social value of changes in travel times and travel costs. Impacts on traffic safety and emissions are calculated using standard Swedish CBA relationships. The system is shown to yield a significant social surplus, well enough to cover both investment and operating costs, provided that it is kept for a reasonable lifetime: investment and startup costs are "recovered" in terms of social benefits in around 4 years.

1. Introduction

The so-called *Stockholm trial* consisted of two parts: a congestion charging scheme that was in place between 3 January and 31 July 2006, and an extension of the public transport supply that was in place between 31 August 2005 and 31 December 2006. The trial was followed by a referendum (the result of which is reported and described in Eliasson et al., 2009). The charges were then reintroduced as a permanent system on 1st August 2007.

A general description of the charging system can be found in Eliasson et al. (2009). It consisted of a cordon around the centre of the city of Stockholm, with a charge imposed 6.30–18.30 weekdays. The charge was 20 SEK during peak hours and 10 SEK during off-peak, levied in both directions across the cordon. The maximum amount payable per vehicle and day was 60 SEK. Various exemptions (for e.g. taxis, buses, and alternative-fuel cars and for traffic between the island of Lidingö and the rest of the county) meant that about 30% of the passages were free of charge.

The purpose of this paper is to present a cost–benefit analysis (CBA) for the congestion charging system. What separates this from most other transport investment CBAs is that it rests mainly upon measured data – that is, not on modelling results. Most of the data stem from extensive traffic measurements during April 2005 and April 2006. The first underlying assumption is that the changes in traffic between 2005 and 2006 were only due to the introduction of the congestion charges. These assumptions are discussed in Section 6, where we argue that even if there are other factors affecting the traffic between the two years, they are likely to be small in comparison. The second underlying assumption is that the effects that could be seen during the period when the charges were in place will remain also in the future. Obviously, the analysis presented here are only based on short-term effects. There are relevant reasons to argue both that long-term effects may be higher and that they may be lower. Long-term effects are also discussed in Section 6.

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A particular potential problem is separating the effects of the charges from the effects of the transit extension. The costs and benefits of the public transit extension as such are not analysed in this paper, although we take into account the increased transit crowding caused by the charges, and the extent to which this was ameliorated by the extended train services. The extension of train services was a comparably small part of the public transit extension (63 mSEK of over 1300 mSEK), while almost all the rest of the cost went to the purchases of new buses and operating costs for new bus lines. Since the congestion charges were postponed (due to legal complaints on the tendering process), it so happened that the public transit extension started earlier than the congestion charges, and its effects on car traffic could hence be separated out. It turned out that it had no measurable effect on car traffic at all, a finding which was corroborated by on-board surveys, where only 4% of the passengers stated that they were ‘‘former car drivers” (Brundell-Freij and Kottenhoff, 2009). Since the new bus lines had around 14000 boardings per day during spring 2006, this would mean that the effect of the new bus lines on car traffic amounted to somewhere around 600 car drivers per day. Comparing this to the decrease in car traffic caused by the charges (around 100000 less vehicles per day across the cordon during charged hours), it seems safe to assume that the traffic decrease was virtually exclusively caused by the charges, and the travel time gains in the cost–benefit analysis can hence be attributed to the charges.

Section 2 discusses investment and operating costs, and Section 3 the marginal cost of public funds. Section 4 presents in some detail the main benefit, namely the time gains. Section 5 presents other benefits – effects on traffic safety, emissions, transit crowding, etc. Section 6 discusses short- vs. long-term effects, and whether traffic was affected by other external factors between 2005 and 2006. Section 7 summarises all costs and benefits, and conclusions are drawn in Section 8.

1.1. Previous research

It is well known that optimal road pricing on a congested road will yield a social surplus, on an aggregate level. However, it is not evident that this holds for a real road pricing system, with its inevitable shortcomings. First, investment and operations costs may be higher than the social surplus resulting from the reduced congestion. Second, physical, technical, political and informational restrictions on the design of the charges will prevent theoretically optimal pricing. In fact, an ill-designed charge system may very well do more harm than good by inducing more congestion on non-charged roads than what is alleviated on the charged ones (Rich and Nielsen, 2007; Eliasson, 2000). Third, the standard transport economics textbook argument does not take unpriced effects on other markets into account, such as effects on the labour market (Parry and Bento, 2001) or crowding costs in the transit system. In this study, we will not study second-order effects outside the transport sector (e.g. effects on the labour and housing markets), but all the other considerations are a major part of the motivation for the study – in other words, whether the value of the travel time savings by the particular system implemented in Stockholm is enough to offset investment and operating costs, increased congestion on ring roads and increased crowding in the transit system.

There is a remarkable scarcity of published results on the welfare effects of real-world congestion charging schemes, where the value of time gains and environmental effects are compared to the cost of the system – at least compared to the vast literature on theoretical issues, equity effects, acceptability, etc. One exception is the London system: a cost–benefit analysis of the London congestion charging system was carried out by Transport for London (TfL, 2003), resulting in an estimated yearly benefit of 70 m€ (including investments and capital costs through the contract with Capita). A completely different result was obtained by Prud'homme and Bocarejo (2005), which obtained a net yearly *loss* of 80 m€. As shown by Mackie (2005) and Raux (2005), the main difference between the two results lies in the calculation of time gains (where Prud'homme and Bocajero do not include time gains outside the charged area, and also calculate smaller time gains inside the area than TfL) and the value of time used (where Prud'homme and Bocajero use a lower value of time than TfL, especially for business trips and distribution traffic).

Wilson (1988) analyses partial welfare effects (excluding commercial traffic) of Singapore's old pricing system, based on area licensing, concluding that it may have reduced welfare, since scheduling costs are higher than the value of time benefits. (The area licensing system was replaced by electronic charges in 1997.) Ramjerdi (1995) analyses welfare effects of the Oslo toll system introduced in 1989, concluding that the value of small congestion reduction is outweighed by the costs for toll collection. This is hardly surprising, since the Oslo was designed to raise revenues rather than to improve traffic conditions.

Model-based calculations are more common, even if not many analyses compare travel time benefits with estimated investment and operating costs. Of particular interest are studies from Oslo, since they can be compared with actual operations costs (around 100–150 mSEK/year, including investment costs). Grue et al. (1997) analyse a time-differentiated version of the Oslo cordon toll, calculating social benefits to be 380 NOK/capita/year (around 370 mSEK/year in total), only including time gains. Minken et al. (2001) analyses a similar system, estimating the value of time gains to 593 NOK/capita/year (around 580 mSEK/year in total). The difference stems from using different transport models and Grue's CBA methodology to be simpler (Minken et al., 2001).

Rich and Nielsen (2007) is also a model-based study, but special in the sense that it also includes benefits of traffic safety and reduced emissions, and compares the total benefits with anticipated investment and operating costs. The authors conclude that the scheme designs should be refined, since time gains do not outweigh the losses for evicted travellers (even after an assumed lump-sum transfer of revenues). When other benefits are taken into account, such as reduced emissions and accidents, total benefits increase, but still do not outweigh the estimated investment and operating costs for the systems.

With the forecasted traffic growth and the corresponding increases in congestion, two of the analysed systems would be socially profitable if they were implemented from 2015 onwards, since potential time gains are then higher. In later work (unpublished), refined designs of the systems have been shown to yield significant social surplus.

2. Investment and operating costs

2.1. Investment and startup costs

As "investment cost", we will use the entire start-up cost of the system: in other words, not only the costs prior to the start of the system, but also the operating costs during 2006 together with certain other additional minor costs, such as those for traffic signals, and the services of the Swedish Enforcement Agency and the Swedish Tax Agency. Besides purely "technical" investments, this start-up cost also includes system development in a wide sense: educating and training the staff, testing the system, public information, etc. Also included are the Swedish Road Administration's costs for closing down the system and evaluating the results during the second half of 2006. This entire initial cost for the system amounted to approximately 1900 mSEK (of which 1050 mSEK was incurred prior to the start of operations). A significant part of the costs prior to the start in early 2006 was extensive testing – the system would only be operational for 7 months, making it absolutely necessary that everything worked right from the start. From a cost–benefit analysis point of view, the cost for the extremely extensive testing and public information presents somewhat of a problem. Since these costs (which were a large part of startup costs) were motivated by the need to make the system absolutely reliable from the start, and also make sure that the public knew what to do, one would want to include a corresponding *benefit*. As it now stands, the CBA will carry the full *cost* for technical reliability and redundancy, but nowhere does the *benefit* of this reliability show up. It may be worth pointing out that, first, this will tend to underestimate the net social surplus of the system, and, second, that had the political context been such that a certain period of technical or informational glitches been acceptable, the startup costs could probably have been lower.

Since the system was improved in several ways during spring 2006, not all costs incurred during 2006 were "operating" costs. Actual operating costs decreased significantly by each month, when it became obvious that things in fact worked out better than planned. The number of complaints and legal actions was, for example, considerably lower than what had been anticipated, reducing costs for legal and tax administration. Further, the number of calls to the call centre (the single biggest item in operating costs) turned out to be around 1/20 than what had been anticipated – around 1500 calls per day instead of 30000. This meant that the call centre was oversized, and during the spring, it was downsized – a considerable reduction of operating costs. This means that startup costs could probably have been reduced quite substantially if the conditions (and not least the time constraints) had been different.

2.2. Yearly operating costs and revenues

The National Road Administration, which is responsible for the system, estimates future yearly operating costs to be around 220 mSEK. This also includes necessary reinvestments and maintenance such as the replacement of cameras and other hardware, and also anticipated additional costs such as moving charging portals when the building up of a northern bypass starts.

As a comparison, the Oslo system, which has been running for around 15 years and is about the same size in terms of the number of passages, has an operating cost of about 100–150 mSEK/year (Fjellinjen, 2004) (it is difficult to give the figure exactly, since it includes value-added taxes and also depends on the conversion rate between Swedish and Norwegian currencies). The figure is also well above average Norwegian operating costs analysed in Amdal et al. (2007). Compared to the Oslo system (and other Norwegian systems), the Stockholm system is less labour intensive: there are no manual payment booths, for example. On the other hand, the payment system in Stockholm is more heavily regulated by legislation, since the charge is a tax (not a fee) from a legal point of view, making it a bit harder to choose really cost-effective payment systems. Moreover, the "Lidingö exemption" – that vehicles travelling through the charged area between the island of Lidingö and the rest of the county are exempted from charge – makes it necessary to identify basically 100% of the vehicles, in order not to miss a "Lidingö exemption-vehicle".

Total revenues during the 7 months of the trial (including fines and reminder fees) amounted to 470 mSEK. Accounting for seasonal variations, total traffic during the 7 months of the trial account for a little more than 58% of yearly traffic. This means that yearly revenues can be projected to be 804 mSEK. Hence, net financial revenues are projected to be around 580 mSEK/year (this excludes effects on other public revenue sources, such as increased net revenue of the transit operator and decreased fuel tax revenues). This means that the investment will be recovered in financial terms in around 3.3 years.

3. Marginal cost of public funds

As customary in Swedish CBA, the net public expenditure is multiplied with the marginal cost of public funds (MCPFs). The MCPF can be defined as "the factor by which the marginal resource cost of a public project should be scaled to take into account that the project is financed through distortionary taxation" (Atkinson and Stern, 1974; Browning, 1976; Lundholm, 2005). The value of Swedish MCPF is generally taken to be 1.3 (ultimately based on Hansson, 1984; see also Lundholm, 2005; SIKA, 2002) The net public expenditure is in this case the sum of gross charge revenues, operating costs, increased public transit fare revenues, increased transit operating costs and decreased fuel tax revenues. When comparing net yearly benefits to the investment/startup cost, this cost should also be multiplied with the MCPF.

The use of MCPF means assuming that the project at hand is an "additional" project to other expenditures. In the standard case of investments, the argument is that making the investment will not reduce other public expenditure, i.e. additional tax revenues have to be raised to cover the investment cost. In the case of congestion charges, the argument is exactly analogous: we assume that, in the long run, total public expenditure will not be affected by the introduction of the congestion charges, and hence the need to raise funds using (distortionary) taxes will decrease. Clearly, both these assumptions may be contested; but it seems reasonable to treat the two cases analogously, to be able to compare benefit/cost ratios with each other, for example.

The costs for resources spent in the project should further be multiplied with the average indirect tax on consumer goods, to convert the costs from producer prices to consumer prices – valuations are measured in consumer prices. The estimated average indirect tax in Sweden is 1.23 (see SIKA, 2002).[2]

4. Travel times and travel costs

Extensive traffic measurements were carried out before and after the charges were put into place, covering both travel times and traffic flows. These data are the basis for most of the calculations of effects. The data were collected mainly in April 2005 and April 2006, but many of the measurements were made continuously from April 2005 through June 2006 – most importantly the travel time measurements (through automatic travel time measurement systems). Eventually, travel times for six consecutive weeks in April–May 2005 and 2006 were used. This means that the risk is small for temporary circumstances to affect measurements: the measured travel times during these 12 weeks were checked for consistency against several months of measurements.

The number of vehicles per 15 min period was registered on 245 links during 10 weekdays. Traffic flows from 189 of these links were then used to calibrate OD matrices representing the situation "with" and "without" the charges (using forecasts for the situation with and without the charges as "prior" matrices). Assigning these OD matrices to the network gave the flows on the remaining links. Separate OD matrices were calibrated for different parts of the day, but the crucial figure is really only the 24 h flow on each link (see below). To obtain this reliably, however, it was necessary to calibrate several OD matrices for the morning peak, afternoon peak, etc. The 189 links used for the flow calibration represented around 7% of the vehicle kilometres travelled (VKT) in the county, and around 15% of the VKT in the central parts of the county.

Measurements of travel times with/without the charges were available for 867 links. These links represented nearly 40% of the county VKT, and nearly 60% of the VKT in the central parts. The remaining travel times were calculated based on the traffic flows, using the volume–delay functions previously developed for Stockholm. When total time gains had been calculated, the measured travel times turned out to represent 80% of the total time gains.

Decreased revenues from fuel taxes were calculated based on the estimated decrease in vehicle kilometres travelled, also based on the calibrated link counts.

4.1. Definition and calculation of consumer surplus

It is well known that the consumer surplus from a change in travel times and/or travel costs should in general be calculated at the level of origin–destination pairs (see Neuberger, 1971). Calculating the consumer surplus on the link level will introduce an error as long as the route-link incidence matrix – which links belong to the optimal route between an origin and a destination – is affected by the change. This presents a problem in this context, since we have detailed data on travel times, travel costs and traffic flows on the link level – but not on the level of OD pairs. Constructing time, cost and flow matrices on the OD level from such link data is theoretically possible, but with available methods, one will almost inevitably lose information about the time-dependent variation in flows and travel times: in practice, it would mean resorting to OD matrix estimation using static equilibrium assignment, with all its well-known shortcomings. The question hence arises if it would not be preferable to calculate the consumer surplus on the link level, given the special circumstances that the time variations of travel times, costs and flows are of special interest to us and may be very important, and that the route-link incidence matrix is unchanged for many OD pairs (since we are dealing with a toll cordon). In other words, is it likely that the benefit of being able to closely represent the time-varying conditions on the roads, rather than having to resort to using flows and travel times more coarsely aggregated across time, outweighs the error introduced by calculating link-based consumer surplus? We can answer this by estimating a magnitude of this approximation error, showing that the error introduced by this approximation is relatively small. This depends on the fact that we are dealing with a toll cordon, and hence that the link-route incidence matrix is unaffected for most OD pairs. The rest of this section will be devoted to showing this.

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[2] In fact, the official Swedish guidance recommends that a total factor of 1.53 (the sum of 1.3 and 1.23) is used, rather than the product of the two factors.

For simplicity, assume that the only relevant costs are the congestion charge and the travel time. Let T_{ij} be the OD flow from origin i to destination j, and c_{ij} and t_{ij} the corresponding congestion charge and travel time multiplied with the value of time (just to reduce notation). Let f_a be the flow on link a, and c_a and t_a the corresponding congestion charge and travel time. Let superindex 0 denote the situation without charges and 1 the situation with charges. Since $c_{ij}^0 = c_{ij}^0 = 0$, we can drop those terms.

Assume that the network is in user equilibrium, and let δ_{ija} be the route-link incidence matrix, i.e. $\delta_{ija} = 1$ if the flow from i to j uses link a and 0 otherwise. We assume that there is only one optimal route from i to j; in an operational traffic model, the ij-flow may be divided across several routes if the network is congested, but if we assume (for the sake of the derivation) that the zones (i and j) are very small, then this phenomenon will be uncommon. Hence, we have $t_{ij} = \Sigma_a \delta_{ija} t_a$ and $f_a = \Sigma_{ij} \delta_{ija} T_{ij}$. Note that we may have $\delta_{ija}^0 \neq \delta_{ija}^1$, i.e. the optimal route from i to j may change by the introduction of the charges. The consumer surplus W, evaluated through rule-of-a-half, can then be written as

$$\begin{aligned}
W &= 1/2 \sum_{ij} (T_{ij}^0 + T_{ij}^1)(t_{ij}^0 - t_{ij}^1 - c_{ij}) \\
&= 1/2 \sum_{ija} T_{ij}^0 (\boldsymbol{\delta}_{ija}^0 t_a^0 - \boldsymbol{\delta}_{ija}^1 T_a^1 - \boldsymbol{\delta}_{ija}^1 c_a) + T_{ij}^1 (\boldsymbol{\delta}_{ij}^0 a t_a^0 - \boldsymbol{\delta}_{ija}^1 t_a^1 - \boldsymbol{\delta}_{ija}^1 c_a) \\
&= 1/2 \sum_{ija} f_a^0 t_a^0 - T_{ij}^0 \boldsymbol{\delta}_{ija}^1 (t_a^1 + c_a) + T_{ij}^1 \boldsymbol{\delta}_{ija}^0 t_a^0 - f_a^1 t_a^1 f_a^1 c_a
\end{aligned}$$

Compare this to the approximate consumer surplus W', which is evaluated using link flows and costs:

$$\begin{aligned}
W' &= 1/2 \sum_a (f_a^0 + f_a^1)(t_a^0 - t_a^1 - c_a) \\
&= 1/2 \sum_{ija} f_a^0 t_a^0 - f_a^0 (t_a^1 + c_a) + f_a^1 t_a^0 - f_a^1 t_a^1 - f_a^1 c_a \\
&= 1/2 \sum_{ija} f_a^0 t_a^0 - T_{ij}^0 \boldsymbol{\delta}_{ija}^0 (t_a^1 + c_a) + T_{ij}^1 \boldsymbol{\delta}_{ija}^1 t_a^0 - f_a^1 t_a^1 f_a^1 c_a
\end{aligned}$$

The error ε introduced by using W' rather than W is

$$\begin{aligned}
\boldsymbol{\varepsilon} \equiv W' - W &= 1/2 \sum_{ija} -T_{ij}^0 \boldsymbol{\delta}_{ija}^0 (t_a^1 + c_a) + T_{ij}^1 \boldsymbol{\delta}_{ija}^1 t_a^0 + T_{ij}^0 \boldsymbol{\delta}_{ija}^1 (t_a^1 + c_a) - T_{ij}^1 \boldsymbol{\delta}_{ija}^0 t_a^0 \\
&= 1/2 \sum_{ija} T_{ij}^0 (\boldsymbol{\delta}_{ija}^1 \boldsymbol{\delta}_{ija}^0)(t_a^1 + c_a) + T_{ij}^1 (\boldsymbol{\delta}_{ija}^1 \boldsymbol{\delta}_{ija}^0) t_a^0
\end{aligned}$$

The first term is negative, since $\sum_a \boldsymbol{\delta}_{ija}^1 (t_1^a + c_a) < \sum_a \boldsymbol{\delta}_{ija}^0 (t_a^1 + c_a)$ by definition: $\boldsymbol{\delta}_{ija}^1$ is the most generalised cost-efficient route choice with the charges in place. The second term is positive, since $\sum_a \boldsymbol{\delta}_{ija}^1 t_a^0 + > \sum_a \boldsymbol{\delta}_{ija}^0 t_a^0$ by definition. Hence, the error ε can be positive or negative.

The crucial step is to note that if the optimal route between i and j is not changed by the introduction of the charges, i.e. $\delta_{ija}^0 = \delta_{ija}^1$ for a pair (i, j), the corresponding error ε_{ij} will be zero. Hence, ε will only consist of approximation errors stemming from OD relations (i, j), where the optimal route is changed by the charges. The simple geography of Stockholm and the fact that the charging cordon is a closed circle make it possible to estimate the magnitude of ε: the only important example of where the optimal route is changed by the charges is travellers originally driving through the city centre, switching to the western ("Essinge") bypass instead once the charges are introduced. In this case, the first term in ε can be thought of as adding a negative term to W corresponding to the loss one would incur if one chooses to go through the city centre instead of around, with the charges in place. The second term can be thought of as adding a positive term to W corresponding to the gain one incurs if one chooses to go through the city centre instead of around, without the charges in place.

To estimate the magnitude of ε, let T be the traffic flow between the north and the south of the county outside the cordon, during charged hours. T^0 and T^1 are hence the total north–south flows before and after the charges, excluding trips with origin or destination in the inner city, during charged hours.[3] These drivers have the choice of either going through the city or on the bypass. Let δ_{by} and δ_{city} be the share of this flow going on the bypass and through the city, so $\delta_{by} + \delta_{city} = 1$. Let t_{by} and t_{city} be the travel times on the bypass and through the city, and c_{city} the congestion charge through the city. As before, superindices 0 and 1 denote the situation before and after the charges. ε', the part of the error relating to the north-southern trip relations (which is the essential part of ε), can then be written as

$$\begin{aligned}
\boldsymbol{\varepsilon}' &= 1/2[T^0(\boldsymbol{\delta}_{by}^1 - \boldsymbol{\delta}_{by}^0) t_{by}^1 + T^0(\boldsymbol{\delta}_{city}^1 - \boldsymbol{\delta}_{city}^0)(t_{city}^1 + t_{city}^1)] + 1/2[T^1(\boldsymbol{\delta}_{by}^1 - \boldsymbol{\delta}_{by}^0) t_{by}^0 + T^1(\boldsymbol{\delta}_{city}^1 - \boldsymbol{\delta}_{city}^0)(t_{city}^0 + t_{city}^1)] \\
&= [\boldsymbol{\delta}_{city} \equiv 1 - \boldsymbol{\delta}_{by}] \\
&= 1/2[T^0(\boldsymbol{\delta}_{city}^1 - \boldsymbol{\delta}_{city}^0)(c_{city} + t_{city}^1 - t_{by}^1)] 1/2[T^1(\boldsymbol{\delta}_{city}^1 - \boldsymbol{\delta}_{city}^0)(t_{city}^0 - t_{by}^0)]
\end{aligned}$$

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[3] We suppress OD index here. The argument can be made more precise, at the cost of decreased readability, by fixing an OD pair (i, j), giving the same argument for that particular OD pair, and summing across OD pairs.

There are no actual measurements of these numbers, but the model-predicted numbers fit the observed traffic flows well. According to traffic model simulations, we have $\boldsymbol{\delta}^0_{city} = 0.24, \boldsymbol{\delta}^1_{city} = 0.15$ and T^0 = 118 000, T^1 = 111 000. The average charge can be estimated from the traffic flow measurements on the bypass, and is c_{city} = 27 kr.

The differences in travel times are more difficult to estimate. Börjesson et al. (2007) use travel survey data and model-calculated travel times to calculate the value of time for this particular sample of drivers, arriving at a value of time of 180 kr/h – considerably higher than the average value of time used in the current paper (122 kr/h). Using this value of time and the data from this paper, we can calculate the weighted-average travel time differences to $t^1_{city} - t^1_{ess} = 16$ kr and $t^0_{city} - t^0_{ess} = 12$ kr. Plugging these values into the formula above, we get

$$\boldsymbol{\varepsilon}' = 0.6 \text{ m SeK/year}$$

That the error is so small is not surprising, partly since the two terms of ε' have different signs and partly since neither $\boldsymbol{\delta}^0_{city}$ nor $\boldsymbol{\delta}^1_{city}$ is zero. This means that traffic will move from the inner city out to the bypass until the marginal driver has a generalised cost that does not differ between the inner city and the bypass.

The formula used to calculate the consumer surplus W is hence

$$W = 1/2 \sum_{lr} (T^0_{lr} + T^1_{lr})(\theta^0_{lr} t^0_{lr} - \theta^1_{lr} t^1_{lr} - c_{lr})$$

Here, l denotes link and r time period (the day is divided into 15-min intervals). T_{lr} is the number of vehicles passing link l during time period r, t_{lr} the travel time on link l during time period r and c_{lr} the congestion charge on link l during time period r. Indices 0 and 1 denote the situation with/without charges, and θ_{lr} denotes the value of travel time per vehicle on link l during time period r. The sum is taken across all links and 15 min periods. We assume that the monetary travel cost on each link is unaffected by the charges, apart from the charges themselves; i.e. fuel costs are unchanged. Hence, the only monetary cost that enters the expression for W is the congestion charge. (Only such "sub-markets" or "alternatives" – combinations of, e.g. mode, departure time, and destination – where travel costs or times change enter the consumer surplus calculation. This means that travel times and costs of other alternatives than car trips do not enter the formula, since these are assumed to remain unchanged by the congestion charges; costs for increased congestion in the public transport system is discussed below).

In our calculations, we simplify the formula by assuming that the values of time θ^0_{lr} and θ^1_{lr} are independent of link and time period, and equal with and without the charges. This will typically underestimate the consumer surplus, since it is travellers with the highest value of time that will remain on the road.

The consumer surplus W can be rewritten by separating it into four terms:

$$W = -\sum_{lr} T^1_{lr} c_{lr} + \sum_{lr} T^1_{lr} \theta (t^0_{lr} - t^1_{lr}) - 1/2 \sum_{lr} (T^0_{lr} - T^1_{lr}) c_{lr} + 1/2 \sum_{lr} (T^0_{lr} - T^1_{lr}) \theta (t^0_{lr} - \theta t^1_{lr})$$

The first term is the revenues from the system, which are readily available (Section 2.2). The second term is the value of the time gains with the charges in place. The third and fourth terms may together be called "adjustment costs": it is the loss for travellers "leaving the road" (or adjusting their behaviour in other ways). Using that the total traffic decrease across the cordon was 22%, the third term can be calculated to be – ½(1/(1–0.22) − 1) ∗ [total revenues], which is −113 mSEK/year. The fourth term is calculated (using the same methodology as the second term – see Section 5.2) to be 39 mSEK/year.

It turns out that somewhat more than 60% of the time benefits arise in the city centre and its immediate vicinity (links crossing the cordon). On the non-charged western and southern bypasses, traffic increased somewhat due to the charges, yielding a time loss of 21 mSEK/year (4% compared to total time gains). 43% of the time gains come from private traffic, 31% from business trips and 26% from distribution traffic (this can be calculated using the details given in Table 2 below).

4.2. *Calculating the value of time gains*

As explained above, traffic measurements on 189 links were used to calibrate OD matrices for the situations with and without the charges, which then gave 24 h link flows for each link in the county. The figure below shows the measured flows in 2005 and 2006. Dots above the 45° line are flows that increased, dots below it are flows that decreased. Note that a few of the highest flows increased somewhat: these are flows on the non-charged western bypass around the charged area (see Fig. 1).

To obtain link flow per 15 min time period, "flow profiles" were constructed describing the percentage of the 24 h flow traversing the link during each 15 min period. After quite a bit of experimentation, 12 types of such flow profiles were used – different depending on the flow on the link (less or more than 25 000 veh/day), geography (inner suburb, outer suburb, city centre) and whether the flow was "morning peaked", "afternoon peaked" or "similarly peaked". The figure below shows the examples of the flow profiles (see Fig. 2).

Using these profiles and the measured and imputed link flows, respectively, we calculated the link flow per 15 min time period for each link in the county with and without the charges.

Travel times were calculated using the same logic. For 867 links, measured travel times with/without charges were used. For the remaining links, travel times for the morning and afternoon peaks were calculated using volume–delay functions, based on the link flows from the matrix calibration with/without the charges. Fig. 3 shows the travel time measurements

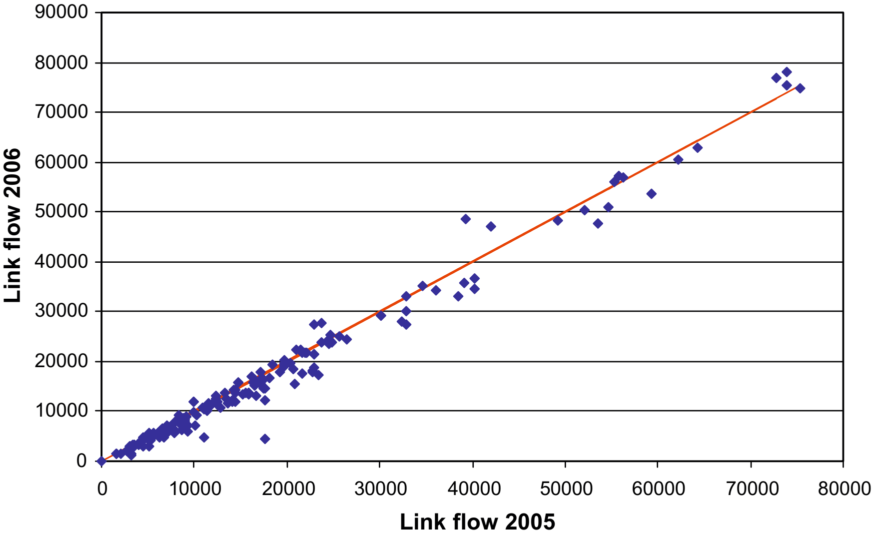

Fig. 1. Measured 24 h link flows 2005 and 2006.

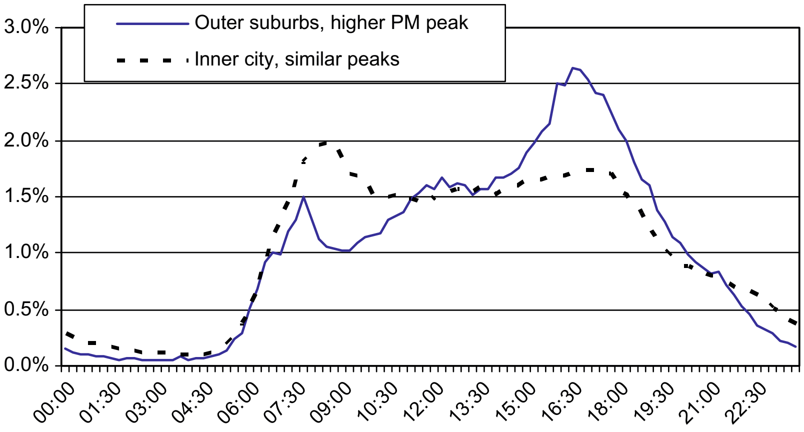

Fig. 2. Two examples of flow profiles.

for morning and afternoon peaks. The data were averaged over several weeks each year, giving very reliable point estimates of the average travel time per 15 min period. Where automatic travel time measurements were not available, floating car measurements were used (not shown in the figure). These data were less reliable; measurements only covered 2 days each year, and considering the high variance of travel times, this is strictly speaking too short a period for evaluation purposes. But after checking the data for consistency against link flows and model data, much of these data were considered to be usable anyway.

To obtain travel times for each 15 min period, "travel time variation profiles" were constructed, giving the delay per 15 min period (additional travel time in percent compared to free-flow travel time), relative to measured peak travel times. The average travel time during the morning peak (7.00–9.00) was taken to be "100% delay", and the travel time for other periods from 5 a.m. to 12.30 a.m. was expressed relative to this. Hence, the worst quarters (around 8.30) have delays above "100%". Afternoon travel times were constructed in the same way, with delays expressed as fractions of the average afternoon peak travel time. Examples of these "travel time profiles" are given below (see Fig. 4).

The table below shows how the value of time per vehicle was calculated. The values of time were taken from recommended Swedish values, except the value for private car trips which were taken from a stated preference study of Stockholm car drivers (Eliasson, 2004). The recommended Swedish value of time for private trips is only 42 SEK/h, but several studies have shown that the value of time for car drivers in Stockholm is considerably higher, due to, e.g. higher incomes, higher share of working trips and a high public transit share combined with self-selection (those with the highest value of time choose car over public transport).

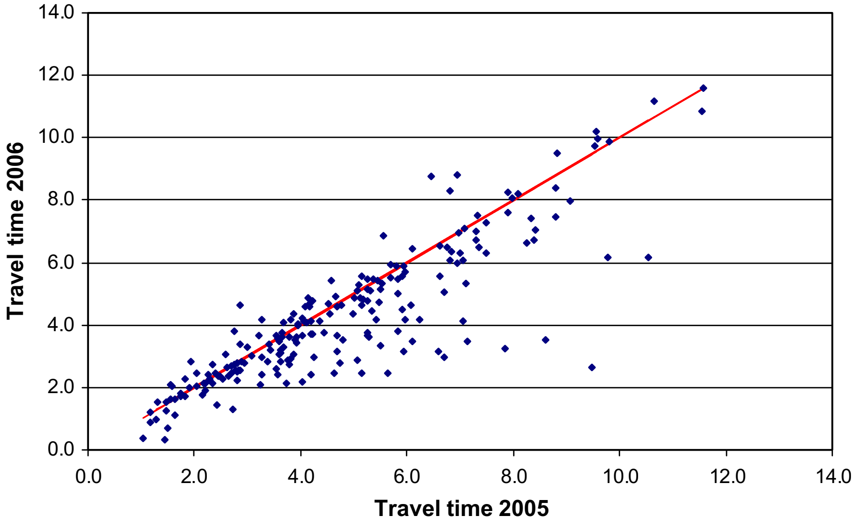

Fig. 3. Measured afternoon peak and morning peak travel times 2005 and 2005.

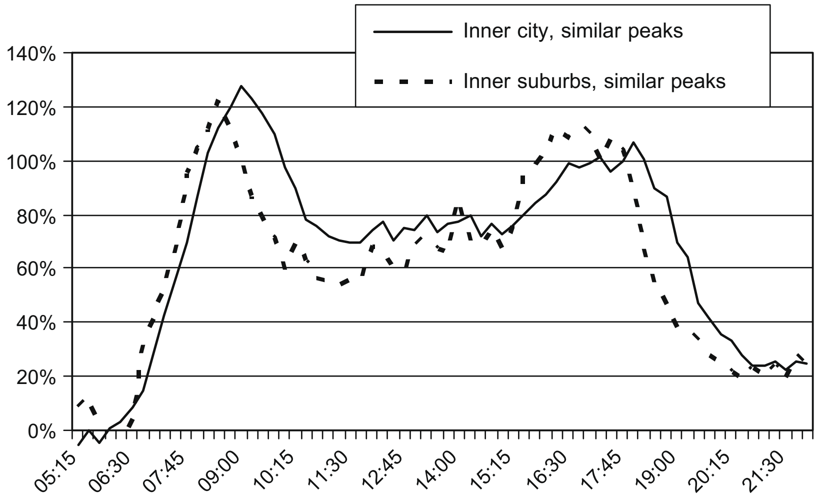

Fig. 4. Two examples of link travel time profiles.

Table 1
Traffic composition and values of time.

Value of time, private trips	65 SEK/h
Travellers per vehicle	1.26 persons
Value of time, business trips	190 SEK/h
Value of time, distribution traffic	190 SEK/h
Value of time for goods transport (added to VoT for distribution traffic)	10 SEK/h
Share of business trips	20%
Share of distribution traffic	16%
Average value of time per vehicle	122 SEK/h

The shares of private trips, business trips and distribution traffic were taken from travel surveys, as was the number of persons per vehicle (see Table 1).

4.3. The value of increased reliability

The unreliability of travel times in congested areas is a big problem. During the last couple of years, quite a lot of research has been dedicated to trying to incorporate this phenomenon in CBA. The most recent Swedish CBA guidelines recommend that reliability benefits are included in the analysis. It was decided that this aspect should be included in the CBA for the

Table 2
Benefits and costs, million SEK per year.

	Loss/gain	See section:
Consumer surplus		
Shorter travel times	536	4.1–4.2
More reliable travel times	78	4.3
Loss for evicted car drivers, gain for new car drivers	−74	4.1
Paid congestion charges	−804	2.2
Increased transit crowding	−15	5.3
Consumer surplus, total	−279	
Externalities		
Reduced greenhouse gas emissions	64	5.1
Health and environmental effects	22	5.1
Increased traffic safety	125	5.2
Externalities, total	211	
Government costs and revenues		
Paid congestion charges	804	2.2
Increased public transit revenues	138	5.3
Decreased revenues from fuel taxes	−53	4
Increased public transport capacity	−64	5.3
Operating costs for charging system (including reinvestment and maintenance)	−220	2.1–2.2
Government costs and revenues, total	606	
Tax effects, etc.		
Marginal cost of public funds	182	3
Correction for indirect taxes	−65	3
Net social benefit, exclusive investment costs	654	

congestion tax – especially since reducing travel time variability could be anticipated to be one of the major benefits of the congestion tax.

Travel time variability was valued as $0.9 * (\text{value of time}) * (\text{standard deviation of travel time})$, following Noland and Small (1995), Bates et al. (2001), Eliasson (2004) and Hamer et al. (2005). As described in Eliasson (2007a), the following principal relationship between travel time, free-flow travel time and the standard deviation of the travel time was used:

$$\sigma = const * travel\ time^{1.2} * \sqrt{\frac{travel\ time}{free\text{-}flow\ travel\ time} - 1}$$

where the constant depends on the length of the link, whether the queues are building up or dissipating and on the speed limit of the road. This formula was originally estimated based on data from the autumn of 2005 (published in Eliasson, 2007a), but later work (Eliasson, 2007b) has confirmed that approximately the same relationship holds when estimating on data from spring 2005 and spring 2006.

5. Other costs and benefits

5.1. Emissions

The decline in traffic as a consequence of congestion charging is estimated to reduce the emissions of greenhouse gases from traffic in Stockholm County by 2.7% (42.5 ktons). This estimation is based on the matrix calibration against link counts. With the recommended Swedish valuation of 1.50 SEK/kg CO_2, this constitutes a benefit of 64 mSEK/year. Other emissions are estimated to decrease between 1.4% and 2.8% in the county. In the densely populated city centre, the decrease is estimated to be between 10% and 14%. The estimated effect for the county comes from the matrix calibration based on link counts. The recommended Swedish valuations of emissions other than CO_2 also take into account the number of people affected, etc. Using recommended valuations and calculation procedures (SIKA, 2006), we end up with a benefit of 22 mSEK/year. Part of this benefit is health effects: the reduced emissions are estimated to save five life-years per year (for Stockholm County as a whole). Several recent medical studies indicate that this effect might be much higher – recent figures indicate that the number of life-years saved could be 60 times as high (see Aga et al., 2003 for an overview of the field). The other part of this benefit is reduced pollution and environmental damage.

5.2. Traffic safety

Effects on traffic safety were calculated using traffic safety relationships developed by the National Road Administration (as implemented in the Swedish CBA tool "SamKalk"; SIKA, 2006). Traffic effects were obtained using the calibrated OD matrices. The reduction in traffic and the subsequent speed increase were together estimated to lead to a 3.6% reduction in the number of traffic accidents. The number of people killed and severely injured on the roads is expected to decrease by approximately 14 per year, while the number of people slightly injured is expected to fall by just over 50 per year. This translates to a benefit of 125 mSEK/year (using recommended Swedish valuations of 17.5 mSEK per statistical life saved, 3.1 mSEK per avoided severe injury and 0.17 mSEK per avoided slight injury).

5.3. Transit revenues, supply and crowding

The producer surplus for the transit operator consists of increased fare revenues minus costs for providing additional capacity to the new passengers. The increased fare revenues were calculated using the current average fare revenues times the increase in ridership measured by the Stockholm Public Transport Authority, but controlled for an increase due to other factors. Current fare revenues are 4079 mSEK/year, of which around 75% come from trips during weekdays. Compared to spring 2005, transit ridership increased by 6%, but around 1.5% of this is considered to be due to factors other than the congestion charges (increased employment, population and fuel prices). Subtracting this, transit revenues are estimated to have increased by 138 mSEK/year due to the congestion charges.

The cost for additional capacity has been calculated to be 64 mSEK/year, using standard methods developed by the National Rail Administration. Clearly, such averages need not apply to the particular situation in Stockholm. An alternative method would be to assume no new capacity, and instead try to quantify the increased congestion for transit passengers (higher risk for having to stand, etc.). During the trial, additional capacity was provided primarily through more train departures and longer trains. The cost for the extra train services was 63 mSEK/year. This did not quite manage to avoid an increase in the share of standing passengers, however. Assuming that the value of travel time when standing is twice the normal value of travel time, the cost for the increased risk of standing can be estimated to be around 15 mSEK/year. According to this calculation, the cost for accommodating the additional transit passengers would add up to 78 mSEK/year. This, however, is the short-run cost: in the long run, the cost for additional train services is likely to decrease somewhat. The difference between the 64 mSEK/year we arrive at using the Rail Administration's method and the 78 mSEK/year we arrive at using the transit operator's costs plus the increase in "standing costs" is fairly negligible compared to other uncertainties in the CBA.

6. Short-term vs. long-term effects

The present analysis is based upon the assumption that the effects seen between spring 2005 and spring 2006 are in fact the long-run effects of the congestion charges. Clearly, this need not be true: First, there may be other factors affecting traffic between the two years. Second, long-term (several years) effects may be different than short-term (one year) effects. Third, traffic growth is likely to change the effects. Below, we discuss these issues one at a time.

6.1. Has traffic been affected by other factors?

Traffic across the cordon (i.e. to and from the city centre) increased at the same pace as the traffic in the county as a whole from the early 1970s (when regular measurements started) until the early 1990s, when traffic across the cordon stopped growing. Traffic in the rest of the county, however, continued growing at the same pace, as did the number of transit trips across the cordon. The most likely explanation of this sudden end to traffic growth is simply that the road capacity to and inside the city centre was reached (see Fig. 5).

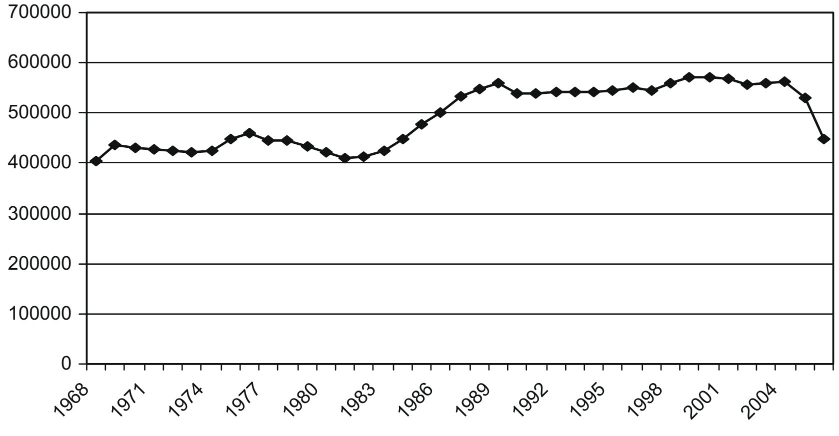

Fig. 5. Traffic across the cordon 1968–2006. Between 2004 and 2005, the southern bypass was opened, causing traffic across the cordon to drop 5%. Between 2005 and 2006, congestion charges were introduced. (The figures have been adjusted for a change in the cordon definition 1991.)

A time series analysis was conducted to estimate the impact of a number of explanatory variables, using data from 1973 to 2004. The most important variables turned out to be fuel price, number of employed and car ownership. The combined impact of changes in these variables between 2005 and 2006 was estimated to be a traffic decrease of less than 1%. We concluded that the effects of other factors than the congestion charge were likely to be very small compared to the effect of the charges. This conclusion is also supported by the fact that the traffic variations in the last 15 years have been so small, despite significant changes in employment levels, fuel prices, etc. over these years.

6.2. Difference between long-term and short-term effects

There are two reasons why the long-term effects could be *smaller* than the short-term effects. First, there is the "acclimatisation" effect: after a while, people might get used to the charge, and consider it less important when making their travel choices. This could be especially important if it is, at first, a little difficult to pay the charge – and the extra "cost" of actually making the payment might decrease with time. Second, the freed-up road space induces new traffic – travellers with higher values of time, or travellers making car trips not crossing the cordon. In fact, the latter effect was visible during the trial: there were, e.g. signs in one of the travel surveys that both the number of car trips outside and within the cordon increased somewhat, and that these trips to a larger extent were made during rush hours (there was less reason to avoid rush hours, since congestion had decreased so much).

There are also a number of reasons why the long-term effects could be *larger* than the short-term effects. Several long-term choices, such as choices of workplace, car ownership and residence, will not be affected in the short run – especially since the charges were only a trial – but are likely to be affected in the long run. The fact that this was only a "trial" might also mean that people decided to "wait it out", not thinking it was worthwhile to change their travel habits when it was just half a year.

All in all, we are inclined to believe that long-term effects are most likely to be similar to the short-term effects, but more likely to be larger than to be smaller. This is because it seems that the "transient" effects seem to have faded out already during the trial: the percentage decrease in traffic across the cordon stayed virtually unchanged after the first one or two months. Meanwhile, the long-term effects on the choice of workplace, residence, etc. most likely do exist – even if they may be small compared to the immediate effects on mode and route choice, for example. Another reason for this view is that long-term effects in London seem to remain similar to the short-term effects: before the charge was increased (in July 2005), the traffic reduction had remained stable at around 18% for nearly 2.5 years. Even if there is no conclusive evidence, it seems very unlikely that long-term effects will be so different from the short-term effects that this significantly alters the conclusion of the CBA.

6.3. Effects of traffic growth

As shown above, the traffic across the cordon essentially stopped growing in the early 1990s, despite continuing traffic growth in the rest of the county. It could be logical to believe that the current traffic decrease will, at least partially and gradually, will be used up by new traffic. It is not obvious whether this means that future *benefits* will decrease or increase. The issue becomes complicated because of non-linearities and network effects. In a simple aggregated analysis, it is straight-forward to show that an increase in the underlying demand (moving the demand curve "outwards"), benefits will grow at a slightly higher pace (due to the non-linearity in the cost function) than the underlying demand. However, it is not clear that this is always true in more complicated networks. If we assume that benefits will grow at the same pace as expected traffic growth (1.5% per year), this would mean that the net present value increases from 6.3 billion SEK to 7.6 billion SEK (assuming a lifetime of 20 years and a discount rate of 4%).

7. Summary of results

The table below summarises yearly costs and gains. The effects have been divided into consumer surplus effects, "other" effects directly affecting the citizens, public costs and revenues and finally marginal cost of public funds and correction for indirect taxes. Note in particular that the investment cost is not included in the table below; we discuss it further below. The right-most column indicates which section of the paper details the calculation.

1 € is about 9.40 SEK (September 2007).

The congestion charges produce a net social benefit of about 650 mSEK/year (around 70 mEuro/year). Consumer surplus is negative, as expected, but the value of the time gains is high compared to the paid charges – time gains amount to almost 70% of the paid charges, which is very high compared to most theoretical or model-based studies. This is partly due to "network effects", i.e. significant amounts of traffic that do not cross the cordon and hence do not pay any charge but still gain from the congestion reduction, and partly due to a large share of professional traffic with high values of time but low cost elasticity.

The yearly social surplus of 654 mSEK should then be compared to the investment cost. Assuming the cost for investment and startup to be 1900 mSEK, the investment is "recovered" in terms of social benefits in around 4.5 years (including the marginal cost of public funds and average indirect taxes. See Section 3). To calculate the net present value of the investment, we need to assume a lifespan. Since reinvestment and maintenance costs are included in the running costs of 220 mSEK/year, a possible lifespan of 20 years seems to be a cautious estimate. Norwegian systems, for example, have been running for around 15–20 years, and there seem to be no technical reasons for them to stop any time soon. This would give a net present value of around 6.3 billion SEK (assuming the Swedish recommended discount rate of 4% per year, and assuming that all benefits and costs remain constant). Assuming instead that the benefits increase at the same rate as expected future traffic growth (1.5% per year), we get a net present value of 7.6 billion SEK.

The benefit/cost ratio, defined as the net present value of all costs and benefits save operating costs and startup costs, divided by the net present value of operating costs and startup costs, becomes 2.5 with constant yearly benefits, and 2.6 with a benefit growth of 1.5%/year.

The cost–benefit analysis carried out here does not cover all relevant effects. The two most important effects left outside the analysis is probably the benefit of increased bus speed and punctuality, and user compliance costs. The speed and punctuality of buses increased appreciably when the charges were in effect, although data are too scarce to admit a thorough quantitative analysis. Compliance costs of users, most importantly the hassle for users to actually pay the charge, is a true cost, but also difficult to quantify. Over time, the share of users using automatic debit account can be expected to increase (being about 2/3 of the passages during the trial), making this less of an issue over time.

8. Conclusions

Even if it is well established that perfect congestion pricing will yield a social surplus, it is neither evident that it will be enough to cover investment and operating costs, nor that a real congestion pricing system, with all its practical and political limitations, will be socially beneficial.

The present analysis demonstrates that the Stockholm system yields a large social surplus, well enough to cover both investment and operating costs. The value of the time gains compared to the paid charges is remarkably high compared to most theoretical examples. This seems to depend on that such examples neglect network effects – for example, that many travellers not paying the charge will benefit from decreased congestion, and that bottleneck effects may lead to reduced congestion far away from the charged area.

It is difficult to predict the development of costs and benefits in the long run. It seems likely that operating costs would decrease over time, from the 220 mSEK/year currently forecasted by the National Road Administration perhaps down towards the 100–150 mSEK/year of the Oslo system. It also seems likely that the benefit of a congestion reduction would increase over time, since the level of congestion will almost certainly increase. In reality, this may make it prudent to change the charge levels with increased traffic volumes, but the analysis of that question is left outside this paper. Finally, it is difficult to predict or even define the lifetime of the system – depending on whether this means the hardware (which is a fairly small cost), the computer programs (a larger cost), the system architecture (an even larger cost, and more durable) or is seen as a socio-technical-political “construction” – the latter being the most difficult and expensive to obtain. But given that the political will to keep the system remains, it seems that a lifetime over at least 20 years is a conservative estimate. According to the analysis carried out here, the system will have recovered its investment cost in terms of social benefits in about 4 years. In financial terms, investment costs are recovered in around 3.5 years.

Hence, it seems that the encounter between the “theoretically irrefutable” idea of road pricing [in the words of the Smeed report (Ministry of Transport, 1964)] and reality will end in road pricing proving its case – even in a case where investment and operating costs certainly could have been lower, had the political process leading up to the implementation worked more smoothly.

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