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Modelling road pricing reform in Stockholm

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Abstract

Congested roads may seem to be an unavoidable trait of large cities. Transport economists and planners have regularly suggested that road pricing would be an appropriate and effective instrument in an overall policy to relieve congestion. Politicians and the public at large have usually been quite sceptical, however. Notwithstanding, the city of Stockholm is now on its way to set up a full-scale test of a congestion pricing system to be operational by the end of the year 2004. Whether the system will be permanent or not will be subject to a referendum in 2006. In this paper we present and compare three ex ante studies of transport and location effects of alternative road pricing systems. These studies have all provided a knowledge background to the system that is now considered. The first two studies deal with the effects on the traffic pattern of a zone-based and a distance-based road pricing system for the Stockholm area, respectively. In the third study also location effects are included in an analysis of optimal congestion charges in a stylised symmetric city adjusted to resemble Stockholm. All studies indicate a substantial reduction in vehicle distance travelled. For the zone-based system, traffic volumes in the inner city of Stockholm is predicted to decrease by 30 % for charged hours at a charge level equivalent to 3 SEK/km. For the distance-based system, traffic volumes in the inner city is predicted to be reduced by 35 and 19 % at charge levels of 4 and 2 SEK/km for peak and office hours, respectively. For the case of optimal congestion pricing, the reduction is 25 % at an average charge level of 2 SEK/km. Additional effects in the first study is that speed might go up on inner city roads and arterials by around 20 %. Moreover, accessibility to activities in the opposite half of the city will be reduced in a significant way. The most affected relation is the one between inner northern and inner southern suburbs. In that case a reduction of the number of vehicle trips by around 30 % is predicted. In spite of quite substantial transport effects, the location effects are predicted to be very limited.

1. Introduction

Congested roads may seem to be unavoidable in our large cities. Attempts to meet demand by a larger supply have often been unsuccessful. Addition of new roads to the existing network tends to induce new traffic that sooner or later neutralises the immediate relief of the situation. Transport researchers and planners have for a long time argued that road pricing has to be a vital element in a successful transport policy that could reduce the level of congestion and improve the efficiency of the transport system.

This conviction among many researchers and planners has generally been without parallel among politicians and the public at large. It has been difficult to convince decision-makers that road pricing is a sensible policy, and, accordingly, there are only a few implementations in the world of citywide road pricing schemes. The oldest one is the system in Singapore that dates back to 1975. It has recently been changed into an electronic system. Also the three toll rings in the Norwegian cities of Bergen, Oslo and Trondheim have been in operation for more than a decade by now. The most recent addition to this list is the congestion charging system of London from February 2003. Also Stockholm might be added to the list in the near future. According to a political agreement that secured a majority for the new Swedish national government after the recent election, a full-scale test of congestion pricing should be carried out in the city of Stockholm before the end of the present term of office, i.e. 2006. According to a decision in the Stockholm city council in June 2003, this test should start by the end of the year 2004. Whether the system will be permanent or not will be subject to a referendum in the city of Stockholm in connection with the general election in September 2006.

Road pricing is an ambiguous concept. It is here used as a general term for a pricing system that charges the road users for their right to use a certain road or to drive in a certain area. This terminology excludes parking fees and fuel and vehicle taxes from being seen as a kind of road pricing.

Road pricing has been advocated for different reasons. Above we referred to the efficiency objective or road pricing as a way of reducing congestion to an optimal level (going back to the seminal work of Vickrey, 1955). First-best congestion pricing would be to charge each road user a fee that is equivalent to the increased costs his/her presence on the road implies for all other road users. In such a system the charge level should theoretically vary not only with the time of the day and the type of the road but also with the time values of the road users who happen to be present on the road. This would be far too complicated. Any second-best congestion pricing scheme that would be a candidate for actual implementation has to be simplified in many respects and for acceptability reasons also predictable for the road user as to the charge level.

Road pricing has also been proposed as a way of reducing the environmental impacts of road traffic. The charge level in such a system should be related to the costs of pollution and noise that the traffic contributes to and could be added to the congestion-related charge.

A third, and among policy-makers more popular rationale for road pricing, is that of raising funds to finance transport infrastructure. In fact the Norwegian toll rings have all been set up with this objective in mind.

These different objectives for road pricing are partly in conflict with each other. A revenue-oriented system should allow for season tickets and it would also be tempting to choose charging points to avoid reductions of traffic flows. A congestion pricing system, on the other hand, aims directly at reducing the traffic flows. However, in order to increase the political acceptability of road pricing a combination of the objectives in an integrated strategy has also been considered (May and Roberts, 1995). One of the key issues for the political, and probably also public, acceptability is how the revenues from road pricing are spent (Goodwin, 1987; Small, 1992). This was also very consciously the idea behind the previous unsuccessful attempt to introduce road pricing in Stockholm – the so called Dennis package from 1992 (Johansson and Mattsson, 1995). This package included also road and public transport investments, partially financed by the road pricing system. The pricing system was deliberately designed to be a compromise between the two objectives of raising funds and reducing the traffic levels in the inner city.

A road pricing scheme might affect the road users in many ways. The direct effect is that the monetary cost of using charged road segments during charged hours will increase. As an indirect effect the time cost for the same segments will be reduced, since some road users will leave the road. For the typical user, this will to some extent, but not fully, compensate for the increased monetary cost. Those who leave the charged road segment will change their route, destination, frequency, mode or timing of the trip. In the long run car ownership and land use would also be affected.

The purpose of this paper is to discuss how road pricing might affect traffic, congestion and location. Assuming that each road user makes the adjustments that are most favourable to him/her, it is obvious that the consequences of a road pricing scheme will depend on how good the alternatives to the present travel decisions are. But these alternatives vary from city to city. If we should be able to say something more precise about the effects, we have to consider specific pricing proposals for specific cities. The most direct approach would be to compare the situation before and after a road pricing system has been implemented in a city (see Ramjerdi, 1995, for an excellent study of the Oslo toll system).

An alternative approach is an ex ante study where the effects of alternative pricing schemes are simulated by the use of some travel demand analysis system (see May and Milne, 2000, for a very interesting such study for Cambridge). Broad results from three ex-ante studies will be presented here. The first two studies deal with traffic effects of a zone-based and a distance-based road pricing system for the Stockholm area. In the third study location effects are also included. That study involves the use of an integrated transport and location model of a stylised symmetric city where the parameters have been adapted to situation in Stockholm.

2. Application of a zone-based road pricing system to Stockholm

In the first case study we consider the application of a zone-based road pricing system to the city of Stockholm. The particular study was carried out for the city executive board as part of an assessment of alternative road pricing systems (Mattsson, 1995). To reduce the amount of data to present we will concentrate on one road pricing system and compare it with a situation without road pricing.

2.1 Scenarios

In the zone-based road pricing system to be analysed the inner city of Stockholm[1] is subdivided into five zones (see Figure 1). A charge is imposed on each vehicle entering the area covered by these zones in inbound direction, i.e. crossing the outer boundary of the five zones. In addition, the same level of charge is also imposed on each vehicle crossing any of the boundaries between the five zones independent of direction. This means that a vehicle will not only have to pay for entering the inner city, but also for travelling within the inner city. The total charge on a vehicle will hence depend on the amount of travelling within the inner city, operationalised as the

[1] The charged area of the inner city of Stockholm has a diameter of approximately 5-6 km. In addition, the municipality of Lidingö – located on an island east of inner Stockholm – is also included in the eastern zone of the charged area. The reason for this is that the only road connection from that municipality goes through inner Stockholm.

number of times the vehicle is crossing the boundaries between any two zones. For the main semi-orbital route, Essingeleden (see Figure 1), which actually crosses the western part of charged area, vehicles are only charged for entering the outer boundary of the charged area. This implies that a vehicle can go between the northern and southern suburbs of Stockholm for a charge of one crossing.

Figure 1. Zone boundaries in the zone-based road pricing system for Stockholm

Such a zone-based system would be fairly complicated to implement. Some kind of electronic system would probably be necessary. The topography of Stockholm facilitates the practical implementation of the system. The construction of the zones makes to a large extent use of the natural subdivision of the inner city by water straits. This means that there will be relatively few road connections between the zones, often in form of bridges. It would be necessary to have 12 charging points to form the outer cordon of the area covered by the five zones and in addition to that 29 charging points for the boundaries between the zones inside the covered area, i.e., in total 41 charging points.

This zone-based road pricing system was intended to represent congestion pricing in so far that the charges are only imposed during Monday to Friday, 6 a.m. to 7 p.m. The charge level was set to 9.75 SEK for light vehicles[2]. For heavy vehicles (over 3 tonnes) the charge level was three times as high.

The analysis was carried out based on population, employment and car ownership forecasts for the year 2005. It was assumed that there would be no important upgrading of the transport network as compared to 1995.

The zone-base road pricing scenario will be compared with a reference scenario that is exactly the same except that no charges are imposed.

2.2 Modelling approach

To be able to predict the traffic effects of a scenario, we have to apply some kind of traffic simulation model. In this case we have used one of the most advanced traffic analysis system that was available for Stockholm at the time – the Fredrik system. The Fredrik system combines a travel demand model with a network model to allow the effects of the decisions of the travellers on the congestion of the roads to be properly modelled.

Road user charges may in principle affect a trip maker's choice of route, departure time, travel mode, destination and frequency. It may also affect the propensity for trip chaining and in the longer run car ownership and activity pattern by relocation of the trip maker's residence or of the activities to which the trip maker is travelling. Of these potential behavioural responses, the Fredrik system handles route, mode, destination and frequency choices. These adjustments

[2] To facilitate comparisons between the different studies in this paper, all monetary values are expressed in constant value of money of the year 2000.

probably represent the most important responses with one obvious exception – the choice of departure time. The likely consequence of this shortcoming is that the Fredrik system will underestimate the car traffic reduction effect of road pricing during the time periods when charges are in place, while overestimating the overall reduction effect.

2.3 Transport effects

Table 1 presents the effect of the zone-based road pricing system on the vehicle distance travelled subdivided by where the travelling takes place. The inner city in this table coincides almost perfectly with the charged area with the exception of Essingeleden, which is partly inside. Since the road pricing system is consciously designed to divert traffic to that route, its traffic volume is presented separately. Obviously the proposed road pricing system has a substantial effect on the traffic volumes in the charged area, i.e. the inner city. The system is designed to have a certain congestion pricing profile. In fact, only 39 % of the hours of a week are charged. Since the charges are in place during the most congested hours, however, the traffic reduction effect as an average over all hours of a week is as high as 19 % compared to 30 % when considering only charged hours. Some of the traffic that disappears from the inner city is diverted to Essingeleden, which will be more congested. It is also interesting to note that although only the inner city and to some extent Essingeleden are actually charged, there is a notable reduction of traffic in inner suburbs by 8 % for charged hours. The reason is that vehicle trips that in the reference scenario go between one inner suburb and inner city or another inner suburb on the opposite side of the inner city, may in the road pricing scenario change destination or mode or not even take place. Finally, it should be remembered that in a county like Stockholm as much as 60 % of the traffic takes place in the outer suburbs (in the reference scenario). Hence the traffic reduction effect of the proposed road pricing system on a county scale is only 4 % for charged hours and 3 % as a weekly average.

The Saltsjö-Mälar water strait subdivides the Stockholm region in a northern and a southern part connected by five bridges. As the road pricing system is designed one cannot go between these parts without being charged. Trips that only use Essingeleden are only charged once, however. Table 2 shows how the road pricing system affects the vehicle volumes on these critical bridges during the charged hours. The results indicate a substantial reduction by more than 40 % of the vehicle flows across the central bridges in inner city. To some extent these flows are rerouted to the Gröndalsbron (which is a bridge of Essingeleden). The net reduction of the flows across the Saltsjö-Mälar passage is 25 %.

Table 1. Total vehicle distance travelled by subregion.

Subregion	Percentage of total distance travelled in reference scenario	Percentage change in road pricing scenario with respect to reference scenario	
		Mon-Fri, 6 a.m.-7 p.m.	Weekly average
Inner city	6	-30	-19
Essingeleden	2	15	10
Inner suburbs	32	-8	-5
Outer suburbs	60	0	0
County	100	-4	-3

Table 2. Vehicle traffic volumes across the Saltsjö-Mälar passage (thousand vehicles per workday, 6 a.m. – 7 p.m.)

Bridge	Scenario		Percentage change
	Reference	Road pricing	
Bridges in Old Town	56	32	-43
Central bridge	92	52	-43
Western bridge	41	22	-46
Gröndalsbron	109	117	7
Total	264	223	-25

The implementation of the proposed road pricing system will lead to less interaction between the different subregions of the County of Stockholm. This is clearly illustrated in Table 3, which displays percentage change in individual vehicle trips for charged time periods. It should be remembered, however, that the reduction in vehicle trips to a substantial extent is explained by a change of mode of transport. Inner city exhibits the largest overall change with a 15 % reduction of the vehicle trips to and from this subregion. Also the trips that are totally inside inner city are reduced substantially, or by 12 %. This is of course a consequence of the design of the road pricing system with zonal boundaries inside inner city. The largest reductions in vehicle trips are between suburbs on opposite sides of inner city. This is particularly the case for trips between the inner suburbs for which the reductions are about or slightly below 30 %. These trips are very dependent on priced links through the very city centre. Trips between the outer suburbs can to a larger extent use the less heavily priced Essingeleden. As a consequence they are not reduced to the same extent. Considering the county as a whole, the number of vehicle trips goes down by 5 %, which is about the same reduction as was noticed for the vehicle distance travelled (cf. Table 1). In sum, the road pricing system will have an evident effect on the spatial pattern of interaction. This is partly a consequence of the particular structure of the Stockholm road network. All vehicle trips between the northern and southern parts have to go through inner city and will be more or less heavily priced.

Table 3. Percentage change in vehicle trips between subregions for road pricing scenario with respect to reference scenario for workdays, 6 a.m. to 7 p.m.

To From	Outer northern suburbs	Inner northern suburbs	Inner city	Inner southern suburbs	Outer southern suburbs	Total
O. n. suburbs	2	2	-9	-21	-15	-1
I. n. suburbs	2	4	-16	-30	-23	-5
I. city	-10	-17	-12	-23	-13	-15
I. s. suburbs	-22	-28	-21	6	4	-5
O. s. suburbs	-16	-21	-13	4	3	0
Total	-1	-5	-15	-5	-1	-5

The next two tables present the effects of the proposed zone-based road pricing system on average vehicle speed and trip travel time. Table 4 indicates that the road pricing system has a substantial impact on the level of congestion in inner city. The system leads to an increase in speed on inner city roads by 17 % and on inner city arterials by 24 %. As noticed, the road pricing system will cause some of the traffic to be rerouted from inner city roads to Essingeleden (cf. Table 1). This route will hence be more congested and its speed will actually go down.

Although the road pricing system only charges car driving in inner city, it has a perceivable effect on the speed in inner suburbs as well – an increase by 9 %, whereas there is no such noticeable effect in outer suburbs.

Table 4. Average vehicle speed (km/h) during workdays, 6 a.m. – 7 p.m.

	Scenario		Percentage
	Reference	Road pricing	change
Inner city roads except arterials	24	28	17
Inner city arterials	29	36	24
Essingeleden	41	37	-8
Inner suburbs	42	45	9
Outer suburbs	63	63	0

Table 5 displays the impact on vehicle travel time per trip by subregion of the origin. The largest effect is in the inner suburbs, where the travel time goes down by 7-8 %. This is a result of a combination of shorter trip length (not shown here) and higher speed (as was shown in the previous table). For trips originating in the inner city, there is only a slight reduction in travel time per trip, though there was a substantial increase in average speed on inner city roads and arterials. This is a consequence of an increase in travel distance per trip in this subregion, which in turn may be an effect of rerouting to avoid passing charging points in inner city.

Table 5. Vehicle travel time per trip (min.) during workdays, 6 a.m. – 7 p.m.

Subregion of trip origin	Scenario		Percentage
	Reference	Road pricing	change
Outer northern suburbs	26.0	25.2	-3
Inner northern suburbs	22.5	20.8	-8
Inner city	28.7	28.4	-1
Inner southern suburbs	22.4	20.9	-7
Outer southern suburbs	23.3	22.6	-3
County	24.5	23.4	-4

It is also of interest to estimate the level of revenue that the road pricing system would give rise to. Table 6 shows that the number of crossings of the outer boundary of the charged area is of about the same magnitude as that of the boundaries inside the area. This means that of the total daily revenue of 5.7 million SEK from the road pricing system, about half comes from the outer and half from the inner boundary crossings. This implies an average charge level of 3.1 SEK per workday and inhabitant in the Stockholm County.

The total annual revenue can be estimated to be 250 times the revenue for a workday. In the present case this amounts to 1.4 billion SEK/year or 780 SEK per year and inhabitant in the Stockholm County. Net of collection costs, the total revenue would amount to 1.2 billion SEK/year (see Mattsson, 1995, for the calculation of collection costs). If the total net revenue would be refunded to the inhabitants in the County of Stockholm on a per head basis, the refund would be 680 SEK/year.

Table 6. Number of charging point crossings and revenue from charging for a workday, 6 a.m. – 7 p.m., in the road pricing scenario

Place of charging	Number of crossings	Revenue (million SEK)
Outer boundary of the charged area (inbound direction)	240,000	2.9
Zone boundaries inside the charged area (both directions)	230,000	2.8
Total	470,000	5.7

The average charge level per crossing is 12 SEK, which is higher than the charge level for a light vehicle because of a certain share of heavy vehicles in the traffic flow. The charge per vehicle distance travelled during charged hours in the county as a whole is 0.21 SEK/km. Since the charge is actually imposed only in inner city it might be more appropriate to calculate the charge per vehicle distance travelled in inner city including Essingeleden, which amounts to 3.0 SEK/km. This could be compared to other vehicle operating costs that are assumed to be 1.1 SEK/km for private trips. It is also interesting to calculate an approximate arc elasticity of vehicle distance travelled with respect to total vehicle operating costs[3]. This calculation leads to an elasticity for the proposed road pricing system of -0.23. According to a review by Goodwin (1992) the long term elasticity with respect to fuel cost (which represent the main part of the operation cost) could be around -0.33 and the short term elasticity around -0.16. The present value is therefore well inside this interval and does not represent any extreme assumption about the trip makers' cost sensitivity.

3. Application of a distance-based road pricing system to Stockholm

The next case study is of a more recent date. It concerns the application of a distance-based road pricing system to the city of Stockholm and its inner suburbs. This particular study was carried out by the Transek consultancy firm on the commission of the Swedish National Environmental Protection Agency (Lindqvist Dillén et al., 2001). The purpose was to illustrate to what extent some kind of congestion pricing, in this case operationalised as a distance-based road pricing system, could reduce congestion and improve passability in the city.

3.1 Scenarios

In this distance-based road pricing system, the densely built-up area of Stockholm is subdivided into two charged areas – inner city and inner suburbs. Inner city is defined almost exactly as in the previous case study[4], whereas inner suburbs are only roughly defined in the same way. When driving in these charged areas during peak hours or office hours a distance-based charge is levied on each vehicle. Peak hours are defined as workdays, 7 a.m. to 9 a.m. and 4 p.m. to 6 p.m., and office hours as workdays, 9 a.m. to 4 p.m. Two different road pricing scenarios are studied – a high and a low scenario. The charge levels in scenario high are defined in Table 7. The levels in scenario low are simply half of these levels.

Compared to the previous case study, the period of charging is reduced by two hours. Moreover, the idea of congestion pricing is more pronounced, since peak hours are priced more

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[3]Let T_R and T_0 be the total vehicle distance travelled during charged hours in the county as a whole in the road pricing and the reference scenario, respectively. Furthermore, let S be the total revenue and c operating vehicle cost per unit of distance excluding possible road charges. The arc elasticity of total vehicle distance travelled with respect to total vehicle operating cost per unit of distance can then be approximated by $\frac{(T_R - T_0)/(T_R + T_0)}{S/(2T_R c + S)}$.

[4]The municipality of Lidingö was not included, however. Cf. footnote 1.

heavily than office hours. The area that is charged is larger during peak hours, since also inner suburbs are included then. The previous system was found to be equivalent to a charge level of 3.0 SEK/km in inner city, which is midway between the levels for peak hours and office hours in the present scenario high.

Table 7. Distance-based charge levels in the road pricing scenario high (SEK/km)

	Inner city	Inner suburbs
Peak hours	4	1
Office hours	2	0

To implement a distance-base road pricing system an electronic system would be necessary. Such technique is under development. The technical issues will not be discussed further here, however.

The analysis will be carried out for the year 2015. Assumptions about population, employment and economic development are chosen in agreement with the present regional plan. As for the transport system, Essingeleden has been extended by Södra Länken and Norra Länken (see Figure 1) as compared to today. In addition a number of other road and public transport investments are assumed to have been completed.

The distance-based road pricing scenarios high and low will be compared to a reference scenario that is exactly the same except that no charges are imposed.

3.2 Modelling approach

Recently a new national transport model, Sampers, has become operational (Beser and Algers, 2002). Sampers includes a regional model that covers the Stockholm region, and which is the specific model that has been applied in the present study. It treats similar choice dimensions as the Fredrik system that was applied in the previous case study. This means that most of the important behavioural responses to road pricing are treated – with the exception of the choice of departure time.

3.3 Transport effects

The effects of the distance-based road pricing system on vehicle distance travelled are displayed in Table 8. The first observation is that the proposed pricing system leads to a substantial reduction in travel distance. The reduction level varies in an expected way between peak and office hours and between the high and low charge scenario. On the overall the reduction is at the same level or possibly somewhat lower than in the previous case study. There we observed a reduction by 30 % for charged hours in inner city at an equivalent charge of 3.0 SEK/km. Here we have a reduction in inner city by 35 and 19 % for peak and office hours at a charge of 4 and 2 SEK/km, respectively. The high scenario has exactly twice as high charges as the low scenario. The reduction is almost proportional to the charge level in the inner suburbs, whereas it is less than proportional in the inner city. It can also be noted that there is a spill-over effect of the pricing system in so far that there is a discernible reduction of travel distance in the inner suburbs also during office hours when the charge in that area is zero.

Table 8. Total vehicle distance travelled by subregion

Subregion	Percentage change with respect to reference scenario			
	Road pricing scenario high		Road pricing scenario low	
	Peak hours	Office hours	Peak hours	Office hours
Inner city	-35	-19	-21	-13
Inner suburbs	-22	-5	-11	-3

The traffic volumes on the bridges across the Saltsjö-Mälar passage are also reduced in a substantial way (see Table 9). The rerouting effect is less pronounced compared to the previous zone-based road pricing system, however. In the latter case the volume on the Central bridge was reduced by 43 %, while the volume on Gröndalsbron increased by 7 % (see Table 2 and Figure 1). Here the volume on the Central bridge is reduced to a lesser extent, and the volume on Gröndalsbron is reduced rather than increased. In the present system the vehicles pay strictly for driven distance in the charged area, whereas in the previous system Gröndalsbron as part of Essingeleden was consciously lower priced to offer a rerouting option. The present system is less effective in reducing traffic though the city centre. By pricing Essingeleden less heavily than inner city roads, it would probably be possible to attain a larger reduction of the traffic through city centre. In an electronic implementation of a distance-based road pricing system, such fine-tuning would be technically feasible.

Table 9. Vehicle traffic volumes on bridges across the Saltsjö-Mälar passage

Bridge	Percentage change with respect to reference scenario			
	Road pricing scenario high		Road pricing scenario low	
	Peak hours	Office hours	Peak hours	Office hours
Central bridge	-24	-13	-20	-12
Gröndalsbron	-12	-6	-10	-5

The revenues that would be generated by the present pricing system are 2.7 and 1.6 billion SEK/year for the high and low scenario, respectively. This represents a charge level of 1,280 and 730 SEK per inhabitant and year, respectively. Of these revenues 1.8 and 1.0 billion SEK/year, respectively, are from driving in inner city. The corresponding value for the zone-based system was 1.4 billion SEK/year, all of which collected in inner city.

4. Application of optimal congestion pricing to a generic city

So far the analysis has been focussed on the most immediate behavioural responses to road pricing such as route, mode, destination and frequency choices. There are also long-term effects that may be important. The most prominent examples are changes in car ownership and in the location of traffic generating activities. How road pricing affects location is an issue that has been subject to varying opinions among researchers and public debaters. This motivates that we in this final case study also include location effects of road pricing in our analysis. In the previous case studies, we have assessed systems for road pricing where the charge levels have been fixed in advance. Here we take a normative approach and evaluate transport and location effects of a system of optimal congestion pricing, i.e., a system where the charge levels are determined endogenously to internalise the external effects of congestion and hence will vary with level of congestion on the different links in the road network. For the moment such a system would not be technically possible to implement in a real city. It should rather be seen as a benchmark for other more feasible systems.

4.1 Modelling approach

To analyse optimal congestion pricing a combined transport and location model of a generic city will be applied. The city is completely symmetric in all respects, which simplifies the analysis a lot. The model will be described very briefly. For a full account, see Eliasson and Mattsson (2001).

The city consists of 8 symmetric rays from the city centre, with 4 suburban zones on each ray at every 5th kilometre. There is radial network, where links consisting of two lanes in each direction connects the zones on each ray. In addition, the zones in the ring immediately outside the city centre are connected by a ring road, also with two lanes in each direction. Since the city is completely symmetric in all respects, it will be sufficient to look at only one ray when presenting the results. The zones will then be denoted 1 to 5, from the city centre to the outermost suburbs, and the links A to D, from the innermost links to the outermost ones (see Figure 2).

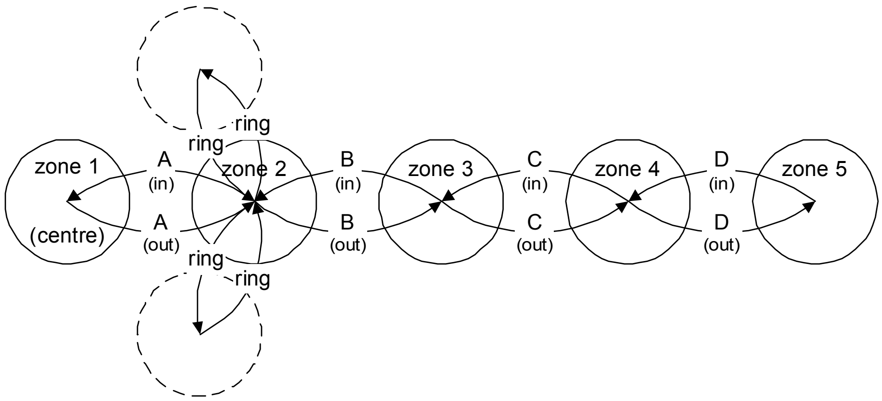

Figure 2. A representative ray of the star-shaped city with the ring road added

There are four types of activities that are located into the zones in the city: households, workplaces, shops and service establishments. The location of the activities depends on where all other activities are located and on the generalised costs to travel between the activities. The travelling between the activities can be carried out by three different modes: car, public transport and slow mode (the latter one is an aggregate of biking and walking). All modes can use all radial links. Cars only can use the ring road. The generalised link travel costs for cars are increasing functions of the car flow on the link. For public transport, on the other hand, the generalised link travel costs are decreasing functions of the volume of passengers. The assumed mechanism behind this is that when passenger volumes go up, the density and/or frequency of the public transport lines can be increased. In both cases the effective travel time will go down. The slow mode has generalised travel costs that are proportional to distance. The travelling can take place during three different time periods: morning peak, office hours and afternoon peak. The worker of the household travels every workday to work during morning peak and returns home during afternoon peak. Shopping and service trips take place during office hours or afternoon peak with a frequency that depends on the accessibility to these activities. In addition, there are deliveries using the road network from the workplaces to the shops and the service establishments during office hours at fixed frequencies.

In sum: The travel demand for different trip types depends on where different activities are located and what the generalised travel costs are on the different links in the transport network. The travel times (and in case of congestion pricing also the travel costs) depend on the number of people choosing the different modes for the different links, i.e., on the travel demand. The location of activities, finally, depends on the accessibility to other activities in the different zones, which in turn depends on the location of other activities and the generalised costs between the zones. The model has been calibrated with the intention to replicate location and transport patterns of the densely built-up area of Stockholm for the year of 1996.

4.2 Scenarios

Optimal (first-best) congestion pricing is achieved by charging each car user on a link the social marginal congestion cost of driving on that link[5]. If all car users would have the same value of time, τ, the optimal charge for a specific link as a function of the flow f on the link would be

$$charge(f) = \tau \frac{dt(f)}{df} f \, ,$$

where $t(f)$ is the travel time, which is assumed to be an increasing function of the car flow on the link[6]. This level of charge has an intuitive interpretation. To achieve optimal congestion pricing, each car user on a link should be imposed a charge that is equivalent to the additional cost his presence on the link imposes on all other users of the same link, which is the additional

[5] To be theoretically correct economies of scale in the public transport system and land congestion should also be optimally priced.

[6] We have assumed that only travel time, and not operational costs, varies with the traffic flow.

travel time caused by him, $dt(f)/df$, times the number of car users affected, f, times their value of time, τ. For computational reasons we apply consistently a common average value of time of τ = 42.6 SEK/h.

A congestion pricing scenario, where optimal congestion pricing according to the specification above is applied, will be compared to a reference scenario with no road pricing. Scenarios with an inner or outer cordon toll ring have also been analysed in Mattsson and Sjölin (2003) but will not be discussed here.

4.3 Transport and location effects

In the present study the road user charges are endogenously determined as optimal congestion charges for each link and time period. Since all links have the same capacity, the charges will directly reflect the levels of congestion on the links. Table 10 presents the resulting congestion charges on a per kilometre basis. Since the differences between link directions are small, we only present averages over the two directions here and in forthcoming tables. Interestingly, the level of charge varies between 0 and 4 SEK/km, which is very much the same as was assumed in the previous two case studies. The charges and hence also the congestion levels are highest for the ring road, link B and A during morning and afternoon peaks. For the outermost link D during office hours optimal congestion charge is practically zero.

Table 10. Optimal congestion charges by time period and link (SEK/km)

Time period	A	B	C	D	Ring
Morning peak	3.1	3.5	1.9	0.8	4.3
Office hours	1.1	1.7	0.4	0.1	1.7
Afternoon peak	2.1	2.2	1.2	0.5	3.2

With these levels of congestion charging the total revenue collected per inhabitant would be 9.5 SEK per workday or 2,380 SEK per year[7]. This is a much higher annual charge for the inhabitants than was the case for the zone-based system, 780 SEK, or for the distance-based

[7] The model is expressed in workers rather than in inhabitants. We have applied the average inhabitant to worker ratio for Stockholm to obtain this result. In addition we have assumed 250 workdays per year and that congestion charging is effective only on workdays.

system, 1,280 SEK and 730 SEK for the high and low level of charge, respectively. One reason is that we in the present model have assumed that the population is much more densely located than actually is the case in the Stockholm region. In addition, the road system is sparser in the model than is the case in Stockholm, which leads to high levels of congestion and hence of congestion charges.

Table 11 presents the effects of congestion pricing on total distance and time travelled by mode. Congestion pricing leads to a substantial reduction in car distance travelled by 25 %, again of the same magnitude as for the congested parts of Stockholm in the previous studies. The effect on total car travel time is even more dramatic, which reflects that the link speeds are much higher in the congestion pricing scenario than in the reference scenario (see Table 12). Part of the car traffic reduction is an effect of change of mode from car to both public transport and the slow mode. Since we have assumed increasing returns to scale with respect to public transport travel time, total distance travelled by public transport goes up more than total time does.

Table 11. Total distance and time travelled by mode. Percentage change in the congestion pricing scenario with respect to the reference scenario

Car		Public transport		Slow mode	
Distance	Time	Distance	Time	Distance	Time
-25	-59	17	12	25	25

Table 12. Car link speed by time period and scenario (km/h)

Link	Morning peak			Office hours			Afternoon peak		
	Reference	Congestion	%	Reference	Congestion	%	Reference	Congestion	%
A	14	24	72	23	34	48	13	28	119
B	13	23	79	17	30	74	12	28	141
C	21	29	40	37	41	12	22	34	54
D	33	37	10	45	46	2	35	39	12
Ring	11	20	83	17	30	74	9	24	161

The car link speeds during morning and afternoon peaks on the most congested links (Ring, A and B) are quite low in the reference scenario, 9 to 14 km/h. This is too low to reflect the situation in Stockholm (cf. Table 4). The road network of our generic city is too sparse to represent the Stockholm network in a realistic way. Because of that we also obtain unrealistically large speed increases in response to the introduction of congestion pricing. Some qualitative conclusions can still be drawn. By assumption there are only work trips during morning peak, while there are also shopping and service trips during afternoon peak. Since the latter kinds of trips are elastic with respect to trip frequency and also can change time period, speed increases are higher for afternoon peak than for morning peak. We can also note that when the level of congestion is low (speed is high) in the reference scenario, the speed increase is low. Link D during office hours is the most extreme example.

Table 13 shows the effects of congestion pricing on link mode shares. The model predicts fairly large decreases in car shares for all links, also the outer ones. The increases are slightly higher for slow mode than for public transport.

Table 13. Absolute change in mode shares by link for the congestion pricing scenario with respect to the reference scenario (percentage units)[a]

Mode	Link			
	A	B	C	D
Car	-8	-11	-10	-7
Public transport	3	5	4	3
Slow	5	7	6	4

[a] For the Ring road, which is only open for cars, there are no mode changes by assumption

The effects of congestion pricing on the location pattern are displayed in Table 14. The most striking result is that the effects are generally very small. Congestion pricing leads for most of the zones to a relocation of less than 1 % of the activities. The most notable exception is a relocation of shops from the suburbs connected by the ring road, i.e. zone 2, to the city centre. Congestion pricing makes it more expensive to use the ring road for shopping trips. This makes it more attractive to locate shops in the city centre. In general, there is a slight tendency to move out activities from zone 2 to the next zone farther out. Congestion pricing hence seems to have a slight decentralising effect. This is in contrast to what was found when congestion pricing was applied to the same generic city but without the ring road (Eliasson and Mattsson, 2001). The location effects of congestion pricing were in general somewhat larger in that case. But more interestingly, they went in a centralising direction. The explanation for the present result may be that the ring road makes the interaction between the outer suburbs easier. When congestion pricing makes it more expensive to use the congested central links of the road network, the outer suburbs may become more attractive. The overall conclusion is that the location effects of congestion pricing are ambiguous also in a highly stylised city as in our case. They seem to depend on the specific design of the road network and of the cost of interaction.

Table 14. Percentage change of the location of activities in the congestion pricing scenario with respect to the reference scenario

Activity	Zone				
	1 (city centre)	2	3	4	5
Households	0.3	-0.8	0.9	0.4	0.7
Workplaces	-0.3	-0.8	1.5	0.5	-0.5
Shops	8.4	-1.6	0.6	-0.1	-0.8
Services	-2.1	-0.3	2.8	-0.6	-2.1

5. Conclusions and implications for the implementation of congestion pricing in Stockholm

The subject of this paper is transport – and to some extent location - effects of road pricing. General conclusions about such effects would indeed be very useful. One can raise doubts about whether this is possible, however. There are two different ways of investigating the subject. The most direct way is to compare the situation before and after a road pricing system has been implemented. The other way is to carry out an ex ante study by analysing what happens in an urban transport – and possibly also location – model. That is the approach chosen here.

The effects of road pricing depend heavily on what alternatives the inhabitants have. Can they avoid paying the car user charges by changing route, mode, destination, or even postponing some trips? This can be studied for a specific pricing system and a specific city by a reasonably sophisticated travel demand analysis system. Although this may give us reasonably reliable results for the particular case, we may still have problems to draw conclusions about the effects in general.

By comparing different studies it may be possible to draw more reliable conclusions about the effects. This is the philosophy behind the present paper. In the first two studies that have been presented, different road pricing systems for Stockholm have been analysed by two different travel demand analysis systems. In the third study, location effects were also included. In that case, the model was not applied specifically to Stockholm. It was rather applied to a stylised completely symmetric city, although inspired by the situation in Stockholm. It should be noted that all applied models are different and have been estimated on independent data sets. So if they give similar results, this should increase the credibility of the conclusions.

Comparing the results from the three studies, there are many striking similarities. First the road pricing systems are not so different despite the fact that one is zone-based, one is distance-based and one is based on the principle of optimal congestion pricing. The distance-equivalent charge level varies between 0 and 4 SEK/km. It is particularly interesting that the optimal congestion charges varied around the levels that were applied in the other two studies. When it comes to the transport effects, all three studies indicate a substantial reduction in vehicle distance travelled at the assumed charge levels. For the inner city the reduction is 30 % for charged hours at a charge level equivalent to 3 SEK/km for the zone-based system as compared to reductions by 35 and 19 % at a charge of 4 and 2 SEK/km for peak and office hours, respectively, for the distance-based system. In the third study based on the stylised city model, the reduction was 25 % for an area that also included less congested suburbs.

There are also some interesting differences between the studies. The first study predicts larger traffic reductions on the Central bridge through the inner city than the second study. This can be traced to the fact that Essingeleden is less heavily priced in the first study. This stimulates re-routing of trips from the inner city. This result indicates that the precise design of a pricing system is very important in order to achieve the effects that are desired.

When there are fewer vehicles on the roads, congestion will go down and speed will go up. The first study predicts that this will result in an increase in speed for inner city roads and arterials during charged hours by around 20 %.

Both the zone-based and the distance-based road pricing systems that have been analysed would price all vehicle passages through inner city. Since there are no alternative unpriced routes between the northern and southern halves of Stockholm, this will reduce the accessibility to the activities in the opposite half of the city in a substantial way. This is clearly illustrated in the first study. The most affected relation is the one between inner northern and inner southern suburbs. In that case a reduction of the number of vehicle trips by around 30 % is predicted.

Location effects of transport policies are not so often considered (see Eliasson and Mattsson, 2001, for a brief review of the literature)[8]. They are included in the third study, however. The general conclusion is that the location effects are small, in spite of the fact that the transport effects are substantial. In the public debate there has often been a fear that congestion pricing might negatively affect the attractiveness to locate shops into the city centre. This study rather indicates the opposite; congestion pricing increases the number of shops in the city centre. It should be remembered, however, that the location effects reported are based on a highly simplified stylised model of a symmetric city. On the other hand, small location effects are reported in many other studies as well (see the review in Eliasson and Mattsson, 2001)[9].

In an ongoing study we have interviewed a number of representatives for shops, service establishments and other firms in the Stockholm region. Although the general tendency is that they are negative to congestion charging and fear that activities located in the city centre will suffer, different representatives estimate the effects on their own business differently seemingly dependent on their specific kind of activity.

Despite all difficulties to get political acceptability for road pricing, the Stockholm city council decided in June 2003 to continue the planning for a full-scale congestion pricing experiment to start by the end of 2004. The previous reviewed studies have been part of the knowledge basis that has been used when designing the system[10]. A simple electronic zone-based system with two zones is proposed – the inner city is divided into a northern and a southern half. The car users will only be charged during workdays from 7 a.m. to 6.30 p.m. The charge level is suggested to be 20 SEK for crossing the boundary of the charged area in any direction during peak hours and 10 SEK during off-peak. The fee for passing between the two halves is suggested to be 10 SEK (in any direction) and will only be collected during peak hours. Essingleden will

[8] The EU project PROSPECTS: Procedures for Recommending Optimal Sustainable Planning of European City Transport Systems: http://www-ivv.tuwien.ac.at/projects/prospects.html and its sister projects within The Land Use and Transport Research Cluster: http://www.ess.co.at/LUTR/ represent interesting recent research.

[9] Wegener (1996) reports small location effects in a simulation of drastically increased petrol prices for Dortmund.

[10] The proposed system has been prepared by J. Eliasson and M. Lundberg at the consulting firm Transek.

be exempted from charging, which gives the car users a possibility to go between the northern and southern suburbs without paying any fee. The collected revenues are suggested to be used for investments in the public transport system in the Stockholm region. Whether the system will be permanent or not will be decided through a referendum in the City of Stockholm in connection with the general election in September 2006. That the date for the referendum is tied to the date for the general election, leads to a very tight time table for the implementation phase and causes difficulties for the implementation. Doubts have been raised whether the time table is realistic or not. So far all public opinion surveys have indicated that there is a majority against congestion charging in Stockholm. Accordingly, if the idea of congestion pricing should have any chance to gain a majority, it is necessary that the implemented system will be very successful technically as well as with respect to its effects on congestion.

A special legal issue is whether congestion charges are fees or taxes according to the Swedish law. If they are fees, municipalities would have the right to collect them and to decide how they could be spent. If they are taxes, the Swedish Parliament has to take all formal decisions including the fee levels and the use of the revenues. A governmental committee has been commissioned to investigate the issue and to formulate a proposal for a congestion charging act. According to their standpoint, congestion charges are a form taxes and hence all decisions need to be taken by the Parliament[11]. This makes the implementation and management of a congestion charging system more complicated. In the Stockholm region, there is a general distrust from various stakeholders whether the collected revenues actually will be channelled back to the region. The fact that such a decision has to be taken by the Parliament, adds to the lack of confidence from the stakeholders in the Stockholm region. In this respect the referendum may be an advantage. If the revenues will not be paid back to the region, it is very unlikely that it will be possible to win a majority for the congestion pricing system.

Road pricing is a controversial transport policy that is discussed a lot among researchers, planners, policy makers and the public at large. One reason for continuing research is to provide these discussions with better information about the likely effects. Such information has to be as reliable, factual, unbiased and comprehensive as possible. Those indicators that have been presented in this paper are all fairly aggregate. Now when congestion pricing is on the political

[11] According to the report *Congestion charges* of June 5, 2003, by the Stockholm Committee.

agenda again in Stockholm and elsewhere, one of the main questions has turned out to be the distributional effects. This question has many dimensions.

First we have the spatial dimension. In the present discussion in Stockholm, suburban municipalities outside the charged area seem to be almost unanimous against the proposed system. They fear that their accessibility to the city centre as a centre of job opportunities and as a service centre will be reduced. In addition, the topography of the Stockholm road network is such that much of the traffic between the northern and southern halves of the region go through the proposed charged area. Consequently they fear that the region will not continue to function as an integrated labour market to the same extent as before, indeed supported by some of our findings. This has also a social dimension, since the jobs, and especially the more well-paid ones, are unevenly distributed across the region. Would congestion pricing benefit/harm rich or poor people, men or women, single persons or families with children? This is another part of the social dimension of the distributional effects.

The answers to these questions are also related to how the charge revenues will be used. To elucidate these distributional effects of road pricing, including how the revenues could be used to compensate those who otherwise would loose on such a reform, is an important research task that would need much more efforts in the future. In the Stockholm case, where vital decisions have to be taken by the Parliament, there is also a lack of confidence in whether the collected revenues actually will be channelled back to the region. So the use of the revenues, including guarantees that the money will be channelled back, is probably a key issue to gain political and public acceptance for congestion pricing in a city like Stockholm.

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