



Co-introduction of charges on urban roads and motorways in metropolitan areas: a model-based investigation

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Abstract

This paper explores the relationship between charges on motorways and on other types of road. It draws on a model-based study of different pricing scenarios which was conducted within an EU-funded investigation of differentiated infrastructure charges (the DIFFERENT project). The scenarios covered strategies ranging from full charging on all roads irrespective of category, on motorways only, on motorway access roads, on urban roads only, and at cordons. A number of different charge levels were tested. The test results suggested that positive impacts and revenues are maximised by applying charges to each link which reflect the contribution to externalities made by the marginal user of that link - irrespective of whether it is a motorway link or an urban link. However, when implementation costs are taken into account, the best performing scheme was a cordon charge combined with a per-km charge for use of motorways outside the cordon. Fixed per-km charges on motorways or on urban roads are much less effective than charges which are differentiated to reflect congestion on individual links. The introduction of charges only on motorways produces little benefit and causes unwanted diversion to urban roads, and although the introduction of a charge designed to protect the level of service enjoyed by strategic motorway traffic succeeds in achieving that goal, it yields little revenue and has little overall impact on delay or other externalities. The paper highlights the practical implications of these results and notes that, although it is likely to be easier to gain political support for introducing charges on motorways than on other types of road, the benefits from so doing are generally lower than can be obtained by introducing charges on congested urban roads.

Keywords: Road pricing; Model; Motorway; Metropolitan; Differentiation.

1. Introduction

1.1. Background and scope

Tolls are commonly applied on motorways. They are generally designed to yield a revenue stream to offset the costs of the original construction or ongoing maintenance

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and, perhaps, to generate funds to support future expansion in capacity. Most tolled motorways serve long/medium distance traffic but many pass close to centres of population and there are an increasing number of tolled motorways in urban areas – Melbourne’s City Link and Toronto’s Highway 407 being prominent examples. Charges are less commonly levied on users of general purpose urban roads but schemes in London and Stockholm exemplify increased interest in this policy option and, as demonstrated in Singapore, the introduction of charges in the city centre, on urban expressways and on major arterials offers a powerful tool with which to manage demand throughout the network. The objectives of charges on urban roads generally differ from those of motorway tolls in that they include an explicit goal of reducing demand and thus alleviating congestion – although the generation of revenue may still be an important aspect.

Motorways and urban roads have different functions and generally serve different types of traffic. However, when motorways pass through, or near, metropolitan areas these distinctions may become blurred and it becomes impossible to optimise the performance of one type of road without considering its interaction with the other. The introduction of charges on one category of road is, of course, likely to have impacts on the usage of other nearby roads. This may be a result of diversion (e.g. drivers choosing to use uncharged routes in preference to charged ones) or of changes in trip patterns (e.g. as when introduction of charges in one part of the network suppresses trips and thereby relieves congestion across the whole network).

It is a well-known principle of transport economics that maximum efficiency is not achievable in a transport network in which some links cannot be tolled¹. In such situations, the best result is achieved, not by introducing marginal social cost prices on those links which can be tolled, but by setting tolls which take account of the effect on un-priced capacity (Lévy-Lambert, 1968; Marchand, 1968). The welfare gains from this kind of pricing are lower than those achievable when all links can be charged but are better than those achieved simply by optimising only for those links which can be priced (e.g. Liu and McDonald, 1998).

Since it is usually much easier, politically, administratively and technically, to introduce tolls on motorways than to introduce charges on urban roads, more consideration has been given to the effect that introduction of motorway tolls might have on urban roads than vice versa. Recognition of the possibility of diversion of traffic from motorways onto adjacent roads has long been recognised by policy analysts (e.g. MVA, 1993) and has generally been seen as a potential problem. Although some analysts have suggested that any unwanted diversion might be prevented by local traffic management measures, others have concluded that it would be safer simply to avoid introducing charges on motorways near urban areas. (Atkins (2006), acting as consultants for the Greater Bristol Transportation Study, decided to exclude urban motorway charges from their list of potentially useful charging structures on just such grounds.) This approach, pragmatically justified though it may be, clearly leaves important questions unanswered.

This investigation seeks to examine the relationship, within metropolitan areas, between charges on motorways and on other types of road, to explore the case for a coordinated approach to setting tolls on motorways and other roads and to consider the constraints which might make this difficult to achieve. The paper presents the results of

¹ This is one example of the difference between first best and second best pricing.

some previous modelling exercises before presenting some new modelling work in which the performance of different charging schemes is examined. Conclusions are then drawn on the interaction between charges on motorways and on other roads in urban areas and recommendations are put forward on the basis of these results and in the light of practical constraints and considerations which impinge on the design of road pricing schemes.

1.2. The results of previous modelling exercises

A number of studies have used models to examine scenarios for the introduction of charges on motorways and other roads in urban/metropolitan areas. The following paragraphs summarise some relevant results.

Motorway Charging in West Yorkshire

Mauchan and Bonsall (1995) used a fixed matrix SATURN assignment model to assess the effect of different forms of motorway toll on traffic diversion to the non-motorway network in West Yorkshire. The study area was about 45 kms by 45 kms, had a population of about 2.2 million concentrated in 5 urban agglomerations and, at that time, included about 90 kms of motorway much of which passed quite close to the urban areas. Four charging regimes were tested: (i) a simple per-km charge on all motorways; (ii) a flat rate charge, irrespective of distance travelled, for any traffic using the motorway system; (iii) a per-km charge on traffic using the “strategic” motorways; and (iv) a flat rate charge on traffic using the “strategic” motorways. The flat rate regimes were designed to dissuade traffic from using the motorways to travel short distances while the “strategic motorway” charge regimes were designed to exempt local traffic.

Tolls were assumed to be imposed on all traffic throughout the day and night with no distinction between different types of vehicle or between peak and off-peak times. Sensitivity analyses were conducted to gauge the sensitivity of results to the level of charges (per km charges were tested in the range of Eurocents 3 to 12 per km, whilst flat rate charges were tested in the range of cents 15 to 30 per trip).

The key findings of the study were:

- that the introduction of charges on the motorways caused traffic flows to increase significantly on the main non-motorway roads, especially in the off-peak period;
- that, with charges in place, peak period congestion increased on the minor non-motorway roads (via a knock-on effect whereby motorway traffic moved onto the major non-motorway roads and in turn displaced traffic from these roads onto the more minor ones);
- that the distance-based charge diverted more traffic than did flat rate charges yielding the same overall revenue (the per distance charges typically caused increases of up to 25% in the flow on the major non-motorway roads - five to ten times as much as was caused by the flat charges - because the motorway routes tend to be longer and were thus less attractive when charges were based on distance travelled);

- that tolls introduced on only the “strategic” motorways caused 25% less diversion to non-motorway roads than tolls levied for all motorways – even though the tolls were set to produce a similar overall revenue;
- that traffic was diverted away from ‘feeder’ motorways even when they themselves were not tolled; and
- that diversion of traffic away from motorways caused increases in overall travel time and overall mileage in the network.

The authors concluded that the introduction of tolls on motorway in or near urban areas could have significant deleterious effect on the urban network, if tolls were not simultaneously introduced on those urban roads. Their broader conclusion was that differentiation by type of traffic (long-distance vs. short distance) and by type of motorway (strategic vs. general purpose) can be used to control the impacts on the surrounding network.

The South and West Yorkshire Multi-Modal Study (SWYMMS)

The South and West Yorkshire Multi-Modal Study (SWYMMS) (MVA (2002), although not focussing exclusively on road charging, considered a number of strategies for road charging and is relevant to the current paper because the study area includes motorways running close to major conurbations. The investigations, reviewed by Coombe (2004) in the context of the UK Department for Transport’s Road Pricing Feasibility Study (DfT, 2004a), included charges at cordons around the centres of the three major cities; charges at cordons around the main urban areas; charges for travelling within urban areas; a per km charge for using any part of the motorway network²; and various combinations of these.

The performance of these schemes was predicted, for the year 2020, by a strategic scale multi-modal model which, although employing a spatially aggregate representation of the network, included a disaggregate representation of traveller type and trip purpose and allowed trip frequency, destination, mode and time of day to vary in response to changes in the generalised cost of travel. The model produced estimates of equilibrium flows, journey times and costs, and of revenues. An aggregate measure of total time and money benefits was also calculated.

The results suggested that the simultaneous introduction of charges in urban areas and on the motorways would yield very significant revenues, very significant reductions in journey times, particularly during peak periods, and significant overall benefits to road users. The introduction of charges on all roads in urban roads – with no charge being imposed on motorways – produced somewhat lower, but still significant, revenues and benefits (the imposition of charges at cordons around the urban areas also yielded significant revenues and user benefits but charges at cordons around the city centres generated only modest revenues, caused increased journey times and led to net disbenefits to car drivers and goods vehicle traffic). The introduction of charges on the motorways – with no charges for use of urban roads - yielded reasonable revenues but resulted in some increases in car journey times (presumably because some traffic diverts from motorways onto more congested routes) and produced only modest overall benefits. Interestingly, the SWYMMS model predicted that the introduction of charges

² Defined for the purposes of the investigation to include the strategic A1 trunk road.

in urban areas would result in *reduced* flow on the motorway network (whether or not it too was charged) – indicating that, taking motorways as a whole, the general reduction in trips caused by urban charging would have more impact than any local diversion of trips onto motorways.

These results indicate that, in areas where motorways pass close to urban areas and serve local as well as strategic traffic, the combination of urban congestion charges (at a high rate per km) with motorway charges (at a lower rate per km) appears to perform better than charges introduced only on the motorways or only on the urban roads. However, the SWYMMS study also noted that there were circumstances in which the introduction of charges on motorways might be justified even in the absence of charges on urban roads. For example, the authors of the study suggested that, where motorway capacity has been increased, the introduction of motorway charges could be used to dissuade additional traffic and so help to “lock in” the benefits of the capacity increase³.

2. New modelling work

2.1. The model

The new modelling work sought to go beyond the studies outlined above by exploring a wider range of scenarios for the co-introduction of charges on motorways and other roads in metropolitan areas. It sought to improve on the work conducted by Mauchan and Bonsall (1995) by allowing for the effect that the introduction of charges might have on total trip numbers and to include a more realistic representation of the network than had been attempted in the SWYMMS work (MVA, 2002).

The new work used a user-equilibrium traffic assignment model, with a single user class and an elastic trip matrix. The assignment model used BPR-type link performance functions and employed the Frank-Wolfe method to iterate through to an equilibrium solution. The demand function used to modify the trip matrix is of the power law type, with a constant elasticity e such that the demand function is:

$$\frac{Q}{Q_0} = \left(\frac{C}{C_0} \right)^{-e}$$

where Q_0 and C_0 are the demand and travel cost for an OD pair in the “no charges” scheme; and Q and C are the equilibrium demand and travel cost in any other scheme (i.e. when tolls are applied).

An iterative process is applied to adjust the demand, starting from the base demands of Q_0 until convergence is obtained (that is, the demands applied are in balance with the travel costs, according to the demand function above). Good convergence (to within 0.1% of each OD’s demand) was found to be obtained in around six or seven of these outer loops.

³ The economic case for using charges to “lock in” the benefits of new capacity presupposes that the increase in capacity is insufficient to eliminate congestion from the network. It differs from the case, frequently made, that tolls should be imposed to raise revenue pay for a previous increase in capacity.

The network and trip matrix used for the modelling were chosen to be broadly representative of a medium sized metropolitan area and are loosely based on the city of Edinburgh. The full network diagram, shown in Figure 1, consists of 175 (mainly) two-way links (= 344 one-way links) and represents a total road length of 490 km - of which 143 km is of motorway or near-motorway standard, including a short section of urban motorway near the central area. The motorways, which include major approach routes to the city from the north, west and east, and a southern route passing to the south of the city centre, run parallel with other, non-motorway routes, in places.

The study area covers an area approximately 30 km by 20 km and is made up of 25 zones connected to the network via 52 centroid connectors. The total demand (representing the morning peak) consists of approximately 110,000 movements in the base case, spread over 550 OD pairs. The study area is divided, for the purposes of analysis, into two regions. Region A comprises that part of the network that is inside the dotted line in Figure 1, consisting of most of the urban area, extending out to the circumferential motorway, and containing 14 of the 25 zones, the trips from which comprise 62% of the morning peak trip origins and 77% of the trip destinations. Region B covers the remainder of the region (outside the dotted line) and contains the remaining 11 zones.



Figure 1: Diagram showing the modelled network (with motorway links shown in bold).

The network and trip matrix were originally developed for a study of road charging in Edinburgh (Sumalee et al, 2005) and were subsequently used in a study of the effect that differentiation of road charges might have on overall scheme performance

(Bonsall et al, 2007). More recently they, together with the model described above, were used by Maher (2008) to explore a methodology by which the performances of different road user charging schemes might be fairly compared and displayed.

2.2. The tests

Eight scenarios were specified which, between them, cover a number of different ways in which charges might be introduced on motorways and other roads in a metropolitan area. (Note that in what follows, for simplicity of terminology, all links of motorway or near-motorway standard are referred to here as “motorways”, and all other links are referred to simply as “urban” links):

1. “*First best*”; optimal tolls applied on each link in the network without specific regard to whether it is an urban road or a motorway link (optimal tolls being those which reflect the contribution to delay and externalities by the marginal vehicle on each link). Under this scenario the (flow-weighted) average toll charged on urban roads is 39.9 cents per km while that on motorways is 16.2 cents per km.
2. “*Best urban*”; the “optimal” tolls defined in scenario 1 are applied to urban roads only (leaving motorways un-tolled). Note that the tolls on each urban link are the same as in Scenario 1; they were not re-calculated to be optimal for a situation in which motorways are not tolled.
3. “*Constant urban*”; a constant (39.9 cents) per km toll was charged on every urban link (leaving motorways un-tolled). The 39.9 cents value being the flow-weighted average of the rates charged on urban roads under scenario 1 (and therefore also under scenario 2). This scenario was designed to test how much of Scenario 2’s benefit would be lost by applying a simplified, but comparable, charging regime.
4. “*Best motorway*”; the optimal tolls defined in scenario 1 are applied to motorway links only (leaving urban roads un-tolled). Note that the tolls on each motorway link are the same as in Scenario 1; they were not re-calculated to be optimal for a situation in which urban roads are not tolled.
5. “*Constant motorway*”; a constant (16.2 cents) per km toll was charged on every motorway link (leaving urban roads un-tolled). The 16.2 cents value being the flow-weighted average of the rates charged on motorways under scenarios 1 (and therefore also under scenario 4). This scenario was designed to test how much of Scenario 4’s benefit would be lost by applying a simplified, but comparable, charging regime.
6. “*Cordon only*”; a €15 charge to cross an inbound cordon. The cordon surrounds the main built-up area just inside the circumferential motorway (following the dotted line in Figure 1, and separating Regions A and B) but intersects some motorway spurs and the traffic on these spurs has to pay the cordon charge. The charge was chosen, after inspection of the performance of a number of different values, as one likely to achieve significant reduction in delay per trip without suppressing total trip numbers by more than 10%.
7. “*Cordon & motorway*”; the cordon defined in scenario 6 plus a 10 cents per km charge for using motorways outside the cordon. The 10 cents charge was chosen, after inspection of the performance of a number of different values, as one likely to yield a revenue approaching that of the “first best scenario”.

8. “Access charge”; a €3 charge was levied on all trips accessing the motorway network. The same charge applied irrespective of the distance travelled (unless the driver left the motorway and then rejoined it – in which case he would pay a second access charge). The justification for such a structure was that it would dissuade local traffic from using the motorways and preserve it for strategic traffic – for whom the one-off charge would be quite modest. Charges of this kind are sometimes referred to in policy debates as a means of “protecting” strategic traffic. The charge level for this scenario was selected after testing a range of values – the €3 charge being the one which minimised congestion (and total externalities).

2.3. Evaluation of results

The effect of introducing charges was measured using a variety of statistics which, between them, attempt to reflect the impact on demand, congestion and other externalities, the revenue generated, and an indicator of overall benefit. The impacts on demand are measured in terms of vehicle trips, vehicle kilometres and vehicle hours travelled – with an indication of the demand in different parts of the network and of average trip length and duration. Congestion and other elasticities are expressed in money values (using a resource value of time of € 0.1413 per person minute⁴ for delay and € 0.03219 and 0.03278 per vehicle kilometre⁵ on principal roads, and other roads respectively). An average car occupancy of 1.2 is assumed. Total revenue is a useful measure but net revenues are more revealing because they reflect the fact that the scheme implementation and operating costs are likely to be different for different scenarios. The scenario costs have been estimated following the principles set out in the UK’s Road Pricing Feasibility Study (DfT, 2004b)⁶. It is assumed that scenarios

⁴ Based on the assumption that our peak period matrix is 50% commuters, 10% workers and 40% other and using the UK department for Transport’s recommended resource values of time of £4.17, £22.11 and £3.68 for these three purposes respectively (see DfT, 2007).

⁵ Based on estimates by Sansom et al (2001) for small and large cars in outer metropolitan areas in peak periods (and assuming that our fleet consists of equal proportions of small and large cars). The main component (about 77%) of this cost is attributable to accident costs with smaller amounts for local air pollution (about 15%), climate change (about 6%), noise (about 1%) and infrastructure wear and tear (less than 1%).

⁶ Costs for scenarios 1, 2 & 3 were taken from the upper estimate for DfT’s scenario 7b (wide area schemes with mandatory OBUs) reduced to reflect the fact that the population in this study area is about 3.6% of that for which the DfT study produced its estimates. Two estimates were made for the costs for all other scenarios. The first was based on the estimate for DfT’s scenario 5a (motorway and trunk schemes with mandatory OBUs) deflated to reflect the fact that, whereas the DfT scheme required 117 charging points, our scenarios 4, 5 and 8 require 15, our scenario 6 requires 17, and our scenario 7 requires 32. The second estimate was based on the lower estimate for DfT’s scenario 7b (lower because the GNSS for motorways and cordons need not be so accurate as for general urban roads) reduced, as above to reflect the relevant population. Interestingly, using these figures, all scenarios were found to cost less using GNSS technology than DSRC technology.

All costs assume that the scheme we are considering is one of several similar schemes in the country and thus can share some fixed costs. The costs have been inflated to allow for optimism bias and, strictly speaking, relate to 24hr schemes (some reduction in costs might be expected for peak-hour-only schemes but, given that the cost profiles are dominated by fixed costs, the reduction might not be great). The DfT report quotes total costs over 20 years; these have been converted into daily costs simply by dividing by 20x250.

1, 2 & 3 require GNSS onboard units whereas all other scenarios, because the charges are imposed at a limited number of locations, can be implemented via DSRC units.

The indicator of overall benefit is simply defined for each scenario as the reduction in delay and other externalities minus the costs of scheme operation (i.e. [base delay and other externalities] – [scenario delay and other externalities costs] - [scenario operation costs]). It thus treats revenue as a transfer payment and takes no account of loss of consumer surplus, loss of tax revenues, long term impacts on land use and the economy, etc. The implications of excluding these aspects are discussed in Section 3.1 below but, meanwhile, this naïve definition of benefit has the advantage of simplicity.

A comprehensive evaluation of each scenario would need to use a more sophisticated indicator of economic benefit and would need to consider such aspects as well as the practical and political feasibility of the proposed charging regime. Although these aspects were not covered in the modelling work reported in this paper, they are addressed in Section 3 below.

2.4. The results

Results for the 8 scenarios specified in Section 2.3 are summarised in Table 1.

It appears that the greatest reduction in vehicle trips occurs under the “first best” scenario, that applying charges only to urban links has slightly less impact than the first best scenario, and that applying them only to motorways has relatively little impact. Constant charges have virtually the same impact on trip numbers as link-specific charges.

The picture for vehicle kilometres is similar, with the first best scenario again seeing the greatest reduction and the effect of urban-only charges being again greater than that of motorway-only charges. The cordon charge, with or without the accompanying motorway charge, has a greater effect on vehicle kilometres than do any of the other second best charges – even though they have less impact on overall trip numbers (this is presumably because many trips are unaffected by the cordon but those that are, are severely affected).

The constant urban charge has more impact than the per-link urban charge (presumably because, with a constant charge, long journeys are penalised even though they are not congested).

Unsurprisingly, introduction of tolls solely on motorways causes a diversion of trips to the urban roads and vice versa. The constant motorway charge diverts more traffic to urban roads than does the best motorway charges (again this is presumably because, with a constant charge, long journeys are penalised even though they are not congested). Interestingly, the cordon has no impact on the balance between urban and motorway traffic volumes. The motorway access charge leaves a significant proportion of vehicle kilometres on the motorway – its main impact being to divert short distance trips from the motorway onto the urban network.

Turning now to the impact on delay, it appears that the greatest reduction is achieved under the “first best” scenario, followed in turn by the cordon & motorway charge, the cordon-only charge, the best motorway charge and the best urban charge. The constant charges on motorways and on urban roads do not perform at all well in terms of their impact on delay - with the constant urban charge performing worst of all (presumably because the charges are not related to congestion and cause very inefficient routing by people attempting to minimise the distance they travel). The motorway access charge

does not manage to reduce congestion very much (any reduction in congestion on the motorways is counterbalanced by increased congestion on the urban roads).

The greatest reduction in externalities other than delay is achieved under the “first best” scenario and the least under the scenarios which have charges only on motorways. The cordon scheme, particularly if combined with a motorway charge, performs almost as well as the first best scenario. Charges on motorways only, or on urban roads only, do not perform at all well - particularly when constant charges per km are applied.

Table 1: Results of Scenarios.

Measure	Base		Scenario							
	1	2	3	4	5	6	7	8		
	No tolls	First best	Best urban	Constant urban	Best motorway	Constant motorway	Cordon	Cordon & motorway	Access charge	
Total vehicle trips ('000 per day)	110	93	97	96	105	104	100	98	104	
Vehs crossing notional cordon [†] ('000 per day)	38	32	35	35	34	33	21	21	32	
Total veh km ('000 per day)	1798	1531	1657	1608	1677	1674	1594	1531	1720	
Percentage veh km on motorways	59	64	69	72	47	34	59	40	50	
Veh km ('000 per day) on motorways	1059	895	1143	1153	780	567	940	612	852	
Veh km ('000 per day) on urban roads	738	636	514	457	897	1107	654	919	868	
Percentage veh km in Region A	33	32	30	30	36	35	33	35	34	
Veh km ('000 per day) in Region A	588	497	494	475	601	592	529	536	581	
Veh km ('000 per day) in Region B	1210	1034	1163	1133	1076	1082	1065	995	1139	
Total veh hr ('000 per day)	56	39	49	53	50	55	46	45	54	
Percentage veh hr on motorways	42	91	57	55	58	42	74	72	34	
Average trip length (km)	16	17	17	17	16	16	16	16	17	
Average trip duration (min)	31	25	31	33	29	32	28	28	31	
Total cost of delay (k€ per day)	356	216	310	355	293	338	273	257	331	
Total other externality cost (k€ per day)	58	50	54	52	55	55	52	50	56	
Reduction in externalities relative to base ^{††}	0	148	50	7	66	21	89	107	27	
Rank (in terms of externality reduction)		1	5	8	4	7	3	2	6	
Total revenue from tolls (k€ per day)	0	378	210	182	141	92	317	369	96	
Assumed cost of scheme (k€ per day)	0	699	699	699	552	552	552	552	552	
Net benefit relative to base (k€ per day) ^{†††}		-551	-649	-692	-486	-531	-463	-445	-525	
Rank (in terms of net benefit)		6	7	8	3	5	2	1	4	

Notes: [†] between regions A and B (the dotted line in Figure 1); ^{††} [base externalities (incl delay) – scenario externalities (incl delay)]; ^{†††} [base externalities (incl delay) – scenario externalities (incl delay)] - [assumed operating cost].

The revenues from the first best scenario are greater than from any other scenario but those from a cordon scheme, particularly if combined with a motorway charge (i.e. schemes 6 and 7) are also very substantial. Revenues from charges on urban roads exceed those from charges on motorways or on access links and are higher from schemes in which charges vary from link to link (in line with first best charges) than from those for which average charges are applied for a class of links.

When allowance is made for costs of scheme operation, no scheme produces sufficient benefit to cover its costs. This result is not as alarming as it may seem at first sight because the schemes represented here are limited to the peak period (the potential additional revenue from charges at other times of day would be many times greater than the increased costs of operation – particularly in the urban areas). When the cheaper implementation costs of scenarios 4-8 are allowed for, they all outperform the first-best all-links scheme.

The conclusions which we draw from these results are that:

- positive impacts and revenues are higher for schemes which include charges on motorways and on urban roads than for schemes which include charges only on one type of road;
- positive impacts and revenues are highest when link charges reflect the externalities associated with the marginal user of that link - irrespective of whether it is a motorway link or an urban link;
- fixed per-km charges on motorways or on urban roads have much less positive impact than charges which are differentiated to reflect conditions (most notably congestion) on individual links (fixed per km charges on urban roads (only) are particularly ineffective because they cause people to use congested – albeit short – routes);
- the introduction of charges on motorways, but not on urban roads, produces little benefit and causes unwanted diversion to urban roads;
- the introduction of a charge designed to protect the level of service available to strategic motorway traffic succeeds in achieving that goal, but yields little revenue and, because it diverts traffic onto the urban network, has a modest overall impact on delay and other externalities;
- net benefits are reduced by implementation costs and, since these costs are highest for schemes which involve charges on all urban links (and thus require the most sophisticated GNSS equipment), the overall performance of such schemes is depressed relative to that of cheaper schemes – particularly those based on cordons and/or motorway charges; and
- the best performing scheme when implementation costs are taken into account is a cordon charge enhanced by adding a per-km charge for use of motorways outside the cordon.

3. Discussion

3.1. Limitations of our approach

Model simplifications

Any model is a simplification of reality and the simplifications open the door to potential criticism. The model described in Section 2.1 can be criticised in various respects but perhaps most crucially for its use of a single user class and a single time period because it is known that the welfare gains from tolls are underestimated if allowance is not made for heterogeneity of travellers (Verhoef and Small, 2004) or for the dynamics of departure time adjustments (Braid, 1996; De Palma and Lindsey, 2000).

If the model had included more than one class of driver with different values of time (VoT) it could have captured the benefit which high VoT drivers might derive from reduced congestion on links which, due to the imposition of high charges, low VoT drivers were seeking to avoid. A shift of high VoT drivers onto high cost links, and of low VoT drivers onto slower or longer routes, would clearly have implications for equity and the distribution of benefits. More importantly, given our focus on the relative performance of the different charging scenarios, its impact on the overall performance of the network might be different in different scenarios. The effect will depend crucially on factors such as the relative sizes of the different user classes and on whether their trip patterns differ systematically in terms of their use of motorways and of links with different degrees of congestion. On balance, one might expect that the inclusion of different user classes with different VoTs would increase the benefits to be gained from motorway tolling more than those to be gained from urban charging⁷, but this assumption needs to be tested.

If the model had included a dynamic representation of departure time adjustments, it would have been possible to explore the effect of introducing different levels of charge at different times of day and thus to investigate a much wider range of scenarios for the co-introduction of changes on motorways and on urban roads. To the extent that urban areas tend to have more off-peak congestion than motorways, one might expect that extension of the analyses to include off-peak periods would add more to the justification for urban charges than to that for motorway tolls⁸. However, this assumption needs to be tested because a realistic, dynamic, representation of departure time adjustment would show that some of the traffic seeking to avoid a peak charge would shift to the preceding period and thus contribute to the build up of the peak – and the seriousness of this phenomenon would depend on how the trip departure profile of users of motorways differs from that of users of urban links.

If the model had included a representation of mode choice (rather than simply using a constant elasticity to adjust the trip matrix in response to any change in the generalised costs of car travel), it would have allowed for the fact that there are generally more modal alternatives in urban areas. It would thus have allowed charges on urban links to

⁷ Since all journeys start and end on “urban” links, no group could be priced-off the urban links and so, of the two types of link, it is clear that motorways are the only candidate to become the high-price-high-speed links which high VoT drivers would be prepared to pay for.

⁸ Off-peak charges would help to offset the costs of operating the charging system.

have more impact on demand than those on motorways. The economic case for charges on urban links would therefore have been enhanced.

Definition of benefit

The indicator of benefit included in Table 1 makes no allowance for loss of consumer surplus caused by trip suppression, for loss of fuel tax revenue, or for any long term impacts on land use and the economy, and makes no assumptions about the uses to which the revenue might be put.

Inclusion of an allowance for loss of consumer surplus would reduce the attractiveness of scenarios 1, 2, and 3 relative to 4, 5, and 8 (1, 2 and 3 having greater reductions in trip making than 4, 5 and 8) but would probably have no significant effect on the overall rankings. Inclusion of an allowance for loss of fuel tax revenue⁹ would reduce the attractiveness of scenarios 1 and 7 relative to scenario 8 (1 and 7 being the ones with greatest reductions in trip kilometres and scenario 8 being that with the least reduction) but, again, would not be expected to alter the rankings (e.g. the fuel tax accruing from scenario 7 might be about 19 k€ per day less than in scenario 8 and would leave scenario 7 well ahead of scenario 8 in terms of benefit).

Table 1 reports any reduction in vehicle trip numbers but, in the absence of any disaggregation of the elasticity parameter we are not in a position to indicate what proportion of the “missing” trips can be assumed to have moved into other time periods, or on to other modes, or to have ceased to occur. City authorities are likely to be concerned that any trip suppression might harm the local economy. A full economic appraisal of a charging scheme would clearly need to know the extent of time shift, mode shift and trip suppression, because they have very different implications for the overall benefit (for example; diversion of trips to public transport may have implications for subsidies and producer surplus, while trip suppression will affect consumer surplus and the performance of the local economy). Work by Bonsall et al (2007) suggested that the loss of consumer surplus associated with suppressed trips could significantly erode the overall benefit of road user charging.

It is difficult to speculate on the effect of including long term impacts on land use and the economy because the impacts would depend crucially on how the revenues were spent but, on balance one might imagine the long term benefit to be greatest for those schemes which show the greatest revenues and benefits in the short term.

Our indicator of benefit includes an allowance for changes in environmental externalities but they are assumed to be simply proportional to the vehicle kilometres on specified types of road. In practice they will vary with traffic composition and speed.

The indicator of net benefit seeks to allow for the costs of scheme operation but, although the costs are based on an authoritative report, they remain speculative and any error could affect the relative levels of net benefit calculated for each scenario.

Net effect?

The net effect of the simplifications in the model and the limitations of the benefit measure discussed above are difficult to estimate without more detailed analysis but, on

⁹ Note that revenue from fuel tax, like that from charges, is a transfer and only affects net benefit if trips are suppressed or if it is assumed that returns from expenditure of the revenue are lower (or higher) than those that would be achieved by the individual motorist.

balance, it seems likely that the model used for this work has under-represented the true performance of the urban charging regimes relative to that of the motorway charging regimes.

3.2. Practical considerations

A number of studies have explored the performance of networks in which certain classes of link are left un-tolled or in which different objectives are being used to set the tolls on different classes of link (for example, if different authorities or toll-concessionaires have control over different parts of a network). Although most of this work has been based on simple networks with a very small number of links, on generalised representations of networks or without any explicit network representation (e.g. Verhoef et al, 1996; De Palma and Lindsey, 2000; Verhoef, 2002; Proost and Sen, 2006; Ubbels and Verhoef, 2008), it is possible to draw a conclusion which is relevant to metropolitan networks. Namely, that, while social welfare is likely to be maximised by having charges set by one government agency responsible for the entire network, competition between government agencies attempting to maximise the welfare of their separate constituencies is likely to yield less welfare than that might come from a monopolistic profit optimiser or from effective competition between profit optimisers. An example of competition between toll operators having a potentially adverse effect on overall societal goals can be seen in the Paris region where concessionaires offer return tickets and regular user discounts (marketed as “*Liber-t Weekend*” and “*Activ-t*”) which may increase overall demand not only on the concessionaire’s motorway, but also on the roads leading to and from that motorway (for a fuller description of the incentives offered by toll concessionaires in the Paris region, see Section 10.3.1 of Bielefeldt et al, 2008).

Theoretical modelling clearly suggests that one cannot expect to maximise welfare unless charges can be implemented on all links in a network. However, it is in practice easier, technically, politically and administratively, to impose tolls on motorways than on general purpose roads. It is technically easier because physical limitations on access and egress allow use of cheaper charging technologies and more effective enforcement. It is politically easier because the public are more accepting of charges on high quality, “special”, roads (particularly if they are new) the use of which is discretionary, than on general purpose roads which they cannot avoid using. It is administratively easier because motorway administrators, unlike local highway authorities, generally have no specific responsibility to riparian owners and can concentrate exclusively on transport objectives.

It is quite common for the administration of motorways in a conurbation to be separated from that of other roads in the area. In such cases it is likely that the owners, managers and/or franchisees of the different networks will have different objectives. Typically, the motorway manager will want to maximise revenue (initially to cover the costs of the infrastructure and subsequently to generate profit) or maintain strategic connections, while the urban roads manager will want to manage congestion and/or promote the local economy. It should also be noted that charging schemes on different types of road might be best implemented using different technologies; for example, the technology required to implement a simple motorway toll is likely to be much cheaper than that required for a scheme covering urban roads. These different objectives and

requirements will often lead different scheme sponsors to favour charging regimes and technologies which might be incompatible with those favoured by other sponsors.

It is perhaps interesting to note that the most prominent example of successful co-introduction of charges on urban roads and nearby expressways is found in Singapore - a country famed for the strength of its central planning. Singapore's original charging scheme was limited to the city centre but was extended to include the expressways and, when this caused some diversion onto arterial roads and charges were introduced on these roads too (though at lower levels). The current system, as described by Santos (2005), uses a common technology (stored-value smart cards from which charges are deducted at charge points) combined with a charge regime in which charges vary by location, type of vehicle and time of day. Charge levels are reviewed every three months with the goal of maintaining average speeds on expressways and arterials within a target range. The differentiation by location allows charges to be set to reflect the different roles of different roads and appears to give the authorities the ability to manage demand throughout the urban network (including the expressways) in pursuance of their overall objective - to optimise the use and performance of the overall network.

Although it may be theoretically desirable to co-ordinate the introduction of charges on all classes of road, it is very common to find motorways and other roads under the control of different agencies and for these agencies to have different objectives. However, this need not mean that they cannot cooperate on technical and design issues. For example, in Trondheim, a single agency has been formed to administer tolls on roads owned by different authorities, a single unified toll structure has been devised and a single pass can be used to pay tolls on any of the roads (see chapter 2 of Bielefeldt et al, 2008).

Although institutional barriers may exist (e.g. if different authorities, with different powers and objectives, are responsible for the different types of road), the scale of potential benefits may be sufficient spur to seek to overcome them. A coordinated approach which treats the overall network as a single entity will have greater chance of achieving agreed prioritisation of objectives, and only by adopting a coordinated approach is it likely to be possible to achieve complicated, multi-faceted, objectives such as regional development or social equity.

An issue which was not captured in the theoretical work referred to above is the fact that competition among profit-oriented concessionaires may result in schemes which may cause some confusion among motorists. For example, competition among concessionaires in the Paris region (as described in Section 10.3.1 of Bielefeldt et al, 2008) has resulted in adjacent schemes adopting different definitions of the peak period and different classifications of vehicles. Any scheme characterised by highly differentiated charges and/or a non-intuitive relationship between the charges on urban roads and motorways might not be easily understood by road users. This could be a significant problem if it prevented people from understanding the intended price signal (because their behaviour would not reflect the signal) or if it led them to put pressure on the political authorities to abandon the scheme.

Failure to coordinate details such as start and finish times, vehicle classifications and exemptions might create perverse incentives and so generate unwanted responses (e.g. if, in order to maximise revenue, the motorway authority started the morning peak surcharge period earlier than that on urban roads, early morning traffic might switch to the urban roads - exacerbating the build up of the urban peak; or if, given the objective of reducing production of greenhouse gasses, motorway charges were based on engine

emissions, the most polluting vehicles would be the most likely to switch to the urban roads - with unwanted implications for urban air quality).

4 Conclusions

4.1. Policy implications

The degree of interaction between urban roads and adjacent motorways will naturally depend on the location and frequency of motorway access and egress points, the density of the urban network and the degree of spare capacity on parallel links in each network. Obviously, the greater the degree of interaction the more important it is to consider the potential cross-impacts.

Previous modelling work, reinforced by the new work described in this paper, has shown that charges imposed on one category of roads in a typical metropolitan network can have profound consequences for traffic on other categories of road in that network. Considerable problems are likely to occur if charges on urban roads are designed without regard to their potential impact on any adjacent motorways or if charges on motorways passing through metropolitan areas are designed without regard to their potential impact on the roads in those areas or on the local economy.

Some diversion of traffic from one network to the other is an inevitable consequence of introducing charges. Although some diversion may be desirable in order to achieve a better match of demand to capacity or to prioritise particular types of traffic, excessive diversion can cause serious problems. Diversion of traffic from motorways to other roads can be particularly serious, because it leads to increased accident risk and environmental externalities.

Where motorways and other roads come under different political or administrative jurisdictions, it is particularly important to ensure effective coordination and cooperation. Cooperation on technical and procedural issues, and over detailed definitional points such as start and finish times, vehicle classifications and exemptions, is desirable even if the two road authorities have different objectives. In the absence of such cooperation the resulting complexity will tend to increase costs for system operators and end users and may cause particular resentment among the latter.

Although it has not been proven by detailed modelling, it appears unlikely that a scheme designed to maintain free-flow on the motorways or maximise revenue for the motorway manager would simultaneously minimise congestion and other externalities within the urban area. It follows that, in order to maximise overall benefits, a degree of prioritisation or compromise is required.

It seems likely that net benefit to society and the economy might be maximised by combining a charge on the urban roads with charges designed to provide a high level of service for traffic using motorways and other strategic links. The urban charge might be levied on traffic crossing specified cordons or using roads within a specified area, while the strategic-link-protection charge might involve specific charges for using motorway access or egress links or dynamic charges just sufficient to preserve free flow conditions.

Although benefits are likely to be obtained by introducing a charge regime which draws no distinction between motorways and other roads, that does not mean that all

roads should carry the same charge; different roads have different characteristics and roles and an optimal design may imply charges which tend to be higher on one type of road than on another – but this is an output of the design process not an input to it.

Although it is likely to be easier to gain political support for introducing charges on motorways than on other types of road, the benefits from so doing are generally lower than can be obtained by introducing charges on congested urban roads. It seems clear that the un-coordinated introduction of charges on motorways and other types of road in metropolitan areas could seriously compromise the efficiency of the overall network and the effectiveness of such charges that are introduced. The most serious problems are likely to occur if charges are imposed on only one type of road (with the other type left free at point of use) but problems can also occur when both types are charged if the charges are not co-ordinated.

4.2. The need for further work

We identify a need for more detailed modelling – particularly to include a representation of different user classes with different values of time and elasticities, a representation of the complex consequences of any re-timing of trips from the peak into adjacent periods (including the impact on the build-up and decay of congestion), and a fuller representation of mode choice. It is recognised that the first two issues, in particular, are not amenable to a simple solution.

We identify a need for more detailed evaluation and would advocate an approach involving sensitivity analysis to allow for uncertainties in costs and benefits. The treatment of some impacts – notably loss of fuel tax revenue and of consumer surplus – are controversial and so should be separately identified in any evaluation. Impacts on employment, retail activity, property rents, economic output or efficiency are difficult to predict but could be based on an assessment of the effect that the scheme is likely to have on the costs of doing business in the city or region and of changes in the perceived attractiveness of the area. This requires a calculation of changes in the transport costs (including any expected congestion relief) experienced by commuters, shoppers, and suppliers, of changes in local environmental conditions, and of changes in business sentiment – with the latter two being particularly difficult to quantify.

The potential social impacts of a road charging scheme are a matter of particular concern to government and require thought to be given to the incidence of costs and benefits among the affected population. Our suggested use of a model incorporating different classes of user is consistent with this aim.

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