Optimizing the Benefits of Urban Road User Charging

By Geoffrey Hyman and Les Mayhew

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Abstract

Traffic congestion is a feature of most modern cities but attempts to control it or limit its effects have met with only modest success. There is significant and continuing interest in the concept of charging city vehicle users, although apart from the use of parking charges actual operational schemes are few and far between. In this paper we compare three alternative charging policies using a simplified model of travel demand and supply, which we combine with cost benefit techniques. The charging policies are area-based charging in which users pay to locate in or enter an area, terminal-charging based on supplementary parking fees in residential and non-residential locations and distance-based charging which is a charge related to how far users travel. The model allows for behavioural effects resulting from trip diversion and demand suppression, as well as capacity restraint (speed-flow feedback effects based on limited route capacity). In the case study we parameterize the model using data and geographical dimensions based on London. We show that area based charging delivers the least benefits whilst a hybrid policy based on terminal and distance based charges delivers the most. Because it is of topical interest we compare our results and predictions with the Mayor's strategy for London, which is an area-based scheme. We conclude that the revenue generated using a hybrid policy would be as great as for an area based scheme whilst at the same time delivering substantially greater benefits to road users in terms of travel time and other savings.

Key words: Road user charging, city congestion, route choice model, user benefits, revenues.

Optimizing the Benefits of Urban Road User Charging

Introduction

A version of this paper was presented at the memorial lectures for Martin Mogridge, on 18th December 2000 at University College, London. Those who have studied Martin's work (e.g. Mogridge, 1984, 1985) will know that one of his favourite themes was urban traffic congestion. Several of his papers contain detailed analyses and suggestions on how to improve urban road traffic conditions, primarily but not exclusively through improvements to public transport.

Martin was fond of identifying or quoting universal principles or laws of 'traffic', which he believed were a fundamental consideration in any solution. He also enjoyed pointing out the pitfalls and paradoxes that could arise from application if such laws were ignored, famously noting “that things can actually get worse if you try to improve them in the wrong way”. Our paper contains a similar moral, namely that user charges intended to improve urban road conditions could sometimes cause it to worsen. Specifically, we develop a model to compare the performance of different types and levels of road user charge in terms of their benefits and dis-benefits, the revenues they raise and their effects on traffic.

The interest in user–optimal road user charges stems from the common practice of presenting them as ‘congestion charges’. Congestion charges may be contrasted with toll charges, which are merely intended to pay for privately financed transport facilities, such as bridges and tunnels. Congestion charges however have a more ambitious aim (e.g. Larson, 1995 and 2000). They are expected to relieve congestion by pricing off marginal road users, so that the remaining users experience a reduction in congestion. Clearly if too few users are priced off there will be no congestion relief, whilst if too many are priced off there will not be sufficient remaining users to benefit from the reduced congestion.

It is therefore of interest to investigate user charges that yield the maximum benefits of reduced congestion but this is not a straightforward task especially as far as city traffic is concerned. For example, it turns out that some apparently plausible forms of charging policy may, paradoxically, actually increase congestion. Of course, a direct reduction in road congestion might not always be the sole objective of a road user charge. Others may include environmental improvements e.g. though reduced vehicle emissions or noise, although it is debatable how effective charging policies are in achieving these (for detailed guidance on environmental assessment see Volume 11 of the Design Manual for Roads and Bridges, HMSO 1997).

We consider three basic forms of charge on city traffic. The first is a central *area charge.* This is a charge on all traffic that enters the area within a cordon around the centre. An example is the £5 per day charge for travelling in the central area, as proposed in the *Mayor's strategy for London* and which is similar to schemes operating in Norway and Singapore. We call the second type of charge a central *termination charge*, that is a charge on traffic terminating within the central area. Examples are charges for public parking, or levies imposed on private non–residential parking spaces. Since some sort of parking charge may exist already, the policy we evaluate here is deemed to be additional.

We call the third form of charge a wide area *distance based charge* in which charges are proportional to the road distance actually travelled. This is assumed to apply to an entire urban area not just the central portion. This policy is qualitatively different from the other two in terms of the area it covers and the way in which the charge would be applied. Examples of how it might be collected could be as simple as a local surcharge on fuel sales in addition to normal fuel duties or something more sophisticated like road metering. In principle, the revenues raised from any of these sources could be ring-fenced for transport improvements, but the analysis presented here does not depend on this.

There are also other possible charging variants – for example, a central area charge that includes its surrounding ring road, a cordon charge around the whole urban area, or charges confined to peri–urban routes. Our approach could be adapted to deal these situations and take in refinements including, for example, the problem of siting charging points (Verhoef, 1998 and 2000; Shepherd et al, 2001). The results given in this paper strongly support the need to investigate other charging policies on value for money grounds (DTLR, 2002).

There are major differences in the effects of each of the three policies on different trip movements, which in turn influence the resultant benefits or dis-benefits. Whereas the central area charge affects any vehicle that passes into or through the central area, the termination charge only affects vehicles that are left in the central area after a trip has been completed. Distance charging by contrast applies across the whole city and not simply to the central area and so the behavioural effects are likely to be substantially different.

We begin by outlining the concept of a hybrid charging policy, which essentially involves combinations of policies that optimize user benefits. We then discuss the effects of each charging policy on traffic movements. A simplified approach to modelling route choice is then described, and the effect of each policy is determined. As charges are increased some demand will be suppressed for the simple reasons that marginal users will be priced off roads on to other transport or will decide against making the trip at all, and a method is proposed for incorporating its effects. This is followed by a specification of how traffic levels are represented and how traffic in turn influences the speed of travel.

The next topic we consider is how to measure user benefits arising from each policy within a common framework. Perhaps the most interesting and general result of applying the framework and the assumptions on which it is based is that area charging, of the kind proposed in the Mayor’s Strategy for Greater London (Livingstone, 2001), is the least promising form of charging policy. Our findings show it fails to meet the key goal of reducing congestion in the most effective manner and may not even yield overall decongestion benefits. However, this does not imply that all types of charging policy would necessarily perform badly. Our analysis shows in fact that a hybrid of the other two types of charging policy appears to be much more effective.

Hybrid Charging Policies

Consider 2 types of charging policy A and B. Figure 1 illustrates why a hybrid policy combining A and B may be more beneficial than single policies, when there is a requirement that the combined policy must yield a pre-determined total revenue. Each axis corresponds to the charge level for a single policy and the straight lines the hybrid combinations, yielding a fixed level of revenue. The curves correspond to constant levels of user benefit. If these curves are convex (as illustrated), optimality is achieved where the revenue line is tangent to the user benefit curve. This can be expressed as an equality between the marginal rates of substitution as charge levels vary. In the case study later the required convexity properties are satisfied and the superiority of a hybrid policy is demonstrated.

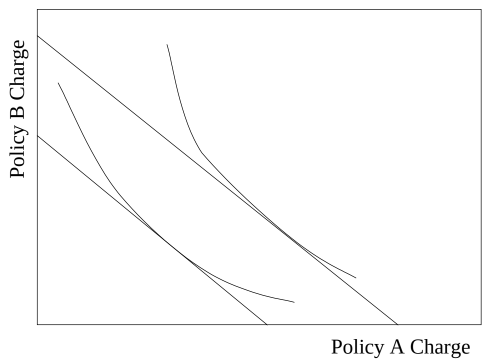

Figure 1: User Optimum Hybrid Policies under a Revenue Constraint

It is important to recognize such solutions can only be constructed under certain conditions e.g. that positive user benefits are produced at ‘positive’ charge levels. Depending on the way in which benefits are accounted, certain types of charge may meet these conditions whilst other may not. Only those policies yielding positive benefits can be included as components in an optimum hybrid policy in which the optimum may be a convex mixture of a wide variety of policies, a mixture of a more restricted set of policies or no policy at all. Specific consideration needs to be given to the effects of charges on travel behaviour, both qualitatively and quantitatively, and this also forms part of the case study.

The reason for introducing a revenue constraint needs further explanation. In general the benefits from raising charges will form an integral part of any scheme appraisal, including benefits arising from local improvements in public transport. However, if we wish to compare alternative charging benefits we need to hold the public transport user benefits at a fixed level. To a first approximation, this can be done by comparing charging methods yielding the same revenue. It should be noted that public transport schemes would need to be sufficiently beneficial to compensate for the aggregate monetary dis-benefits of the charge itself. This requires not only cost–effective public transport improvements but also efficient methods for collecting road user charges.

Basic Modelling Assumptions

Intuitively, all road user-charging policies would be expected to have two main effects: to divert trips onto different routes and to suppress trips. Each policy has a different detailed effect on different types of trips and there are six basic types of traffic movement that we will need to consider:

CC: Trips entirely within the central cordon

CX: Trips from inside the cordon to outside

XC: Trips from outside the cordon to inside

XXR: External trips that cross into cordon then cross back outside

XXO: External trips that route around the edge of the cordon

XXX: External trips that completely avoid the central area

These categories are illustrated in Figure 2.

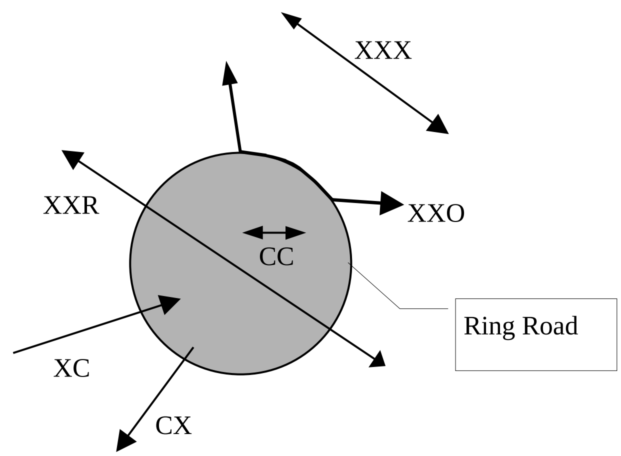

Figure 2: The notation used to describe different categories of trip.

It is assumed travellers choose routes minimizing a combination of travel time and operating costs, plus any charges applying on their chosen route. If routes around the charged area were available then some users would be prepared to divert around it rather than pay the charge. In the next sections we study how much traffic would be diverted and on to which route or routes it would divert.

Re-routing is not the only behavioural response to this kind of charging policy, as some trips may either not be made at all or may switch to public transport. We shall, somewhat loosely, refer to this effect as 'trip suppression'. A set of working assumptions concerning which trips would have a tendency to re-route and which would have a tendency to be suppressed, according to the charging policy applied, is indicated in Table 1.

	CC	**CX**	**XC**	**XXR**	**XXO**	**XXX**
Area	Reduced Payment	Reduced Payment	Pay or Suppress	Pay or Reroute	N/A	N/A
Termination	Pay	N/A	Pay or Suppress	Reroute	Reroute	N/A
Distance	Pay or Suppress	Pay or Suppress	Pay or Suppress	Pay or Reroute or Suppress	Pay or Reroute or Suppress	Pay or Suppress

Table 1: Behavioural Responses to Road User Charging Policies

Notice the re-routing response is represented in terms of switching between orbital routes and radial routes through the central area. It has been postulated to apply only to trips between pairs of locations that are both outside the central charging cordon. The reason is fairly obvious, only external-to-external trips have the option to route around and avoid an area-based charge.

In the case of the other charging policies suppression is postulated to apply only to trips from outside to inside the cordon, whereas in the case of distance based charges the suppression applies to all trips. Trips originating in the central area are assumed to receive a discount on area charges so that their travel behaviour would not be changed appreciably. However, this reduction is not assumed for other types or charge.

Our approach is based primarily on the construction of a conceptually simple model of route choice, where travel is assumed to be either on radial or orbital routes. This type of routing model has been extensively studied and its properties are readily examined both analytically and through numerical simulations **(**Hyman and Mayhew L, 2000 and 2001**)**. For trips where there is a choice of route, it is assumed users select the route minimizing a combination of travel time, operating costs and road user charges.

When routes around a charged area are available then, as noted, some users would be prepared to divert around it rather than pay a charge. Any model therefore needs to estimate how much traffic would be diverted and on to which route or routes it would divert. The diversion effect is interesting because it is likely to produce increased congestion on routes that receive extra traffic. Any increase in congestion will need to be offset against decongestion benefits on the route receiving less traffic.

Traffic suppressed by a charging policy represents a loss in economic benefit, which also needs to be offset against the decongestion benefits of the remaining traffic.

(Note that this loss in benefit arises because travellers are assumed to make travel choices yielding the greatest utility, so the charge is a sufficient deterrent for suppressed travellers to switch to choices giving them lower utilities.) The amount of traffic suppressed in this way needs to be quantified and for this we assume a simple ‘elastic demand’ function. Changes in demand associated with congestion relief, diversion and suppression must then be brought together in the overall benefit evaluation.

Re-routing

In a previous paper (Hyman and Mayhew, 2000), the authors developed the concept of a route catchment. This is defined as the area in which it is quicker or cheaper to reach a given destination by a particular class of route than via any other class of route. Of particular interest are simplified routing models in which travel is restricted to orbital and radial directions. As we shall argue, by relating the sizes of route catchments to traffic generations and attractions, levels of traffic on each class of route can be estimated. In particular, when roads are congested, travel speeds depend strongly on the level of prevailing traffic so that there is a two-way interaction between congestion and route choice. The key mechanism for achieving this is the concept of a *switching angle*.

Switching angles

Consider a single circular ring road and a large number of radial routes converging on the centre. When the angular separation between the origin and destination exceeds the *switching angle,* the preferred route is through the centre of the city, whereas for smaller angular separations the ring road is preferred. The resulting sizes of the orbital and radial route catchments determine the traffic on each route.

Assume initially that the charged area is within the ring road. We confine route choice to travel through the cordoned area or travel on the surrounding uncharged ring road, of radius R. Later, we will outline how to include re-routing effects over a much larger area. First, consider a policy that imposed a charge on any traffic travelling in the area enclosed by the ring road but also include a city-wide charge per unit of distance travelled, operating either alone, or in conjunction with the area charge. To calculate switching angles consider trips starting and ending outside the central area. These are trips labelled earlier as XXR.

Let τ denote the central area charge and let κ denote the city-wide charge per unit of distance. Also let υ be the average money value of a unit of travel time savings and let α the average operating cost per unit of distance. The typical travel cost for a radial trip is given by

$$C_R = \upsilon\, t_R + (\alpha+\kappa)\, d_R + \tau$$

Where t_R is the travel time and d_R is the travel distance for such a trip. The travel cost for an orbital trip is given by

$C_O = \upsilon\, t_O + (\alpha+\kappa)\, d_O$

Where t_O is the travel time and d_O is the travel distance for an orbital trip. Let the ring road have a radius of R and let d_x be the average distance travelled on each of the two radial legs a) to and b) from the ring road. We can write:

Routes through the central area: $d_R = 2(R+d_x)$, $t_R = d_R/V_R$

Routes around the ring road: $d_O = R\theta + 2d_x$, $t_O = R\theta/V_O + 2d_x/V_R$

where V_O and V_R are, respectively, the average orbital and radial speeds and θ is the angle traversed around the ring road, measured in radians. The value of the switching angle θ^* is determined by solving for the angle traversed when the travel costs of a radial and an orbital trip are equal. Whence we obtain:

$$\theta^*(\tau)=\mathrm{Min}\,(\pi,\ (2(\alpha + \kappa + \nu/V_R) + \tau/R) / (\alpha + \kappa + \nu/V_O))$$

We can thus estimate the quantity of vehicles using each route as follows:

$T_{XXR}(\tau) = T_{XXC}\,(1-\theta^*(\tau)/\pi)$ (Radial)

$T_{XXO}(\tau) = T_{XXC}\,\theta^*(\tau)/\pi$ (Orbital)

Where T_{XXR} and T_{XXO} refer, respectively, to the number of external-to-external trips per hour using the radial or orbital route and T_{XXC} is the sum of these two types of trip.

Notes

a) The external distance d_x cancels out and so does not affect the value of the switching angle

b) When there are no charges and the radial and orbital speeds are equal then the switching angle is 2 radians (=114 degrees).

c) The switching angle falls as the radial speed rises

d) The switching angle rises as the orbital speed rises

e) The switching angle rises as the area charge rises

f) When the distance based charge gets very large the switching angle approaches 2 radians.

Figure 3a shows how the switching angle varies with size of an area charge (i.e. no distance charge applies). For illustration, operating costs are assumed to be 8 pence per kilometre and the value of travel time 10 pence per minute (£6 per hour) in 1998 prices). The operating cost value represents an average car and includes both fuel costs (resource, duty and VAT) and non–fuel operating costs. Unlike previous versions the cost per kilometre reaches a finite maximum for very low speeds. The value of 8 pence is based on recently published DTLR (2001) figures and applies over a medium range of vehicle speeds. A value closer to 12 pence per kilometre may be more applicable when speeds are lower and 9 pence per kilometre when they are higher. Our value of time assumptions are based on a DETR (1999) study. This study pre–dates latest figures suggesting a value of time of about 15 pence per minute would be more accurate today. Values of time also show small variations during the day and vary between different users. We therefore caution against taking our calculations too literally in this regard although the general conclusions are unaffected.

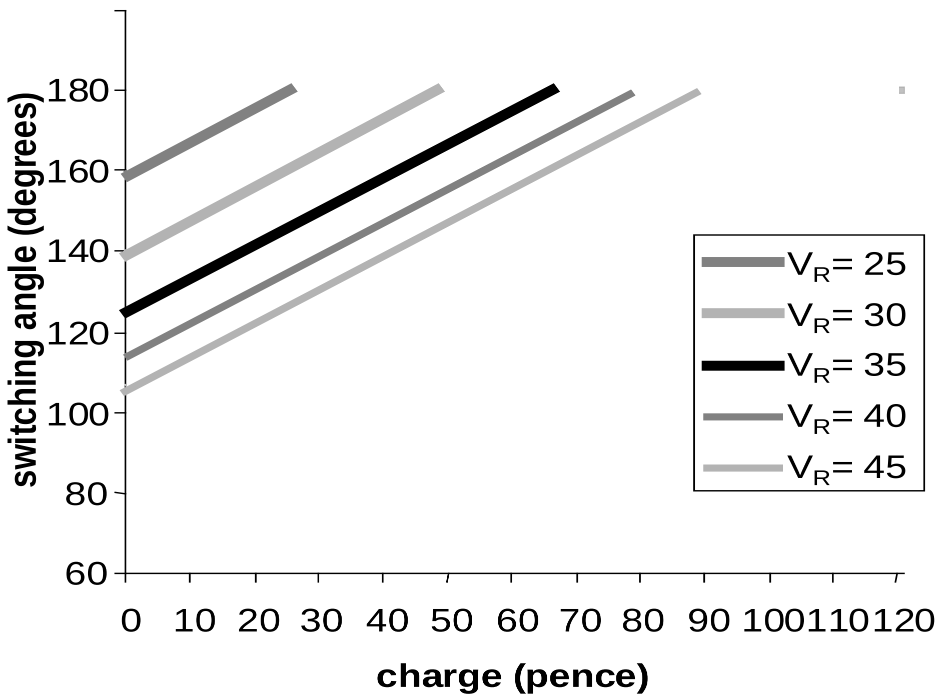

Figure3a: Effect of increasing Area charges on the Switching Angle.

To illustrate switching angles, the radius of the ring road is assumed to be 3km, which is the mean radius of London's inner ring, and the orbital speed 40 kph. Each line in figure 3a represents a different value of the radial speed. It can be seen that the switching angle increases with the area charge until it reaches 180 degrees (π radians). At this point all through traffic is diverted out of the centre onto the ring road.

For any given charge the switching angle is highest when the radial speed is low, so only a small area charge would be needed to drive all through traffic from the centre. For larger radial speeds (or lower orbital speeds), a higher area charge would be needed, but the required charge to divert traffic out of the centre does not generally exceed 100 pence in this simplified example. From the switching angle equation, we see the area charge is divided by the radius of the ring road. Hence, if a more extensive area charge (i.e. over a wider radius) were to be applied it would have a smaller impact on re-routing, other things being equal.

Figure 3b shows how the switching angle varies with the distance-based charge (i.e. no area charge applies). This relationship differs from the previous policy since it does not depend on the radius of the ring road. We note most of the lines slope in the opposite direction as the charge increases, implying *reduced* traffic on the ring road. However, the effect is relatively weak as is seen from the moderate gradients. Note also that the switching angle approaches 115 degrees (2 radians) as the distance charge increases, so that the distance travelled by through trips approaches a minimum.

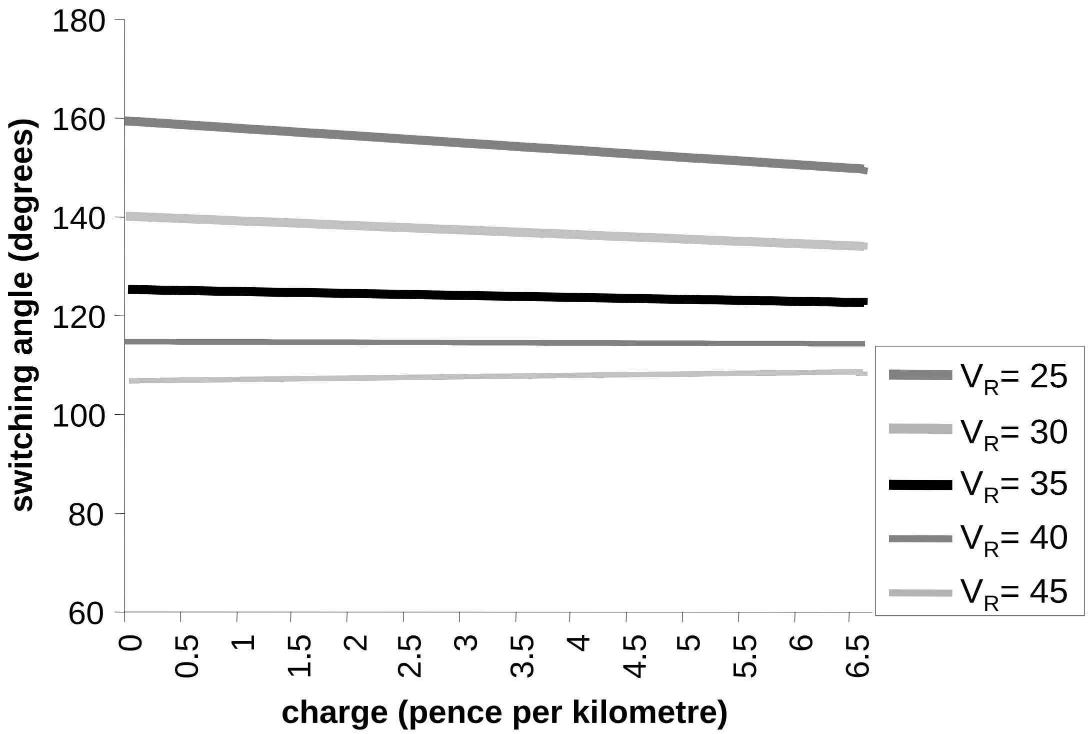

Figure 3b: Effect of increasing Distance charges on the Switching Angle.

Trip Suppression

Turning to trip suppression we now need to include the effects of termination charges explicitly. We ignore the effect of vehicle occupancy, although in practice some forms of charge will increase ride sharing. We simply assume that trip suppression includes any such changes.

Let μ denote the charge for all trips terminating in the central area in conjunction with the distance charge κ and the cordon charge τ. The termination charge is assumed to suppress two classes of trips - those travelling from outside to inside the central area and those travelling within the central area. Trips from outside to inside the central area are affected by all three forms of charge, whereas trips within the central area are affected only by the termination charge.

The distance-based charge is assumed to affect all trips, except those entirely within the central area, as their length is assumed to be too short to have any effect. Let d* denote the mean trip length of all such trips. Centrally oriented trips between locations outside the central area have a choice between travelling through the centre or around the ring road. This choice as we have previously argued will be influenced by the area charge. If this is significant they will divert to the ring road rather than pay the charge, so they are only suppressed by the distance charge in this instance. We adopt an exponential functional form with a suppression rate of λ per unit charge in which the suppression rate is assumed to be independent of the level or type of charge. Trip numbers are expressed as functions of one or more charge levels, with zero denoting the absence of a charge.

We therefore have the following suppression relations:

Trips within the central area:

$$T_{CC}(\mu) = T_{CC}(0)\, e^{-\lambda\mu}$$

Trips from inside to outside the central area:

$$T_{CX}(\kappa) = T_{CX}(0)\, e^{-\lambda d^{*}\kappa}$$

Trips from outside to inside the central area:

$$T_{XC}(\tau, \mu, \kappa) = T_{XC}(0,0,0)\, e^{-\lambda(\tau+\mu+d^{*}\kappa)}$$

Centrally oriented trips from outside to outside the central area:

$$T_{XXC}(\kappa) = T_{XXC}(0)\, e^{-\lambda d^{*}\kappa}$$

Trips that completely avoid the central area:

$$T_{XXX}(\kappa) = T_{XXX}(0)\, e^{-\lambda d^{*}\kappa}$$

Traffic levels

An indicator of the success or otherwise of charging policies will be their impact on traffic levels. We express traffic levels in terms of trip kilometres and evaluate them by multiplying the number of trips of each type by their corresponding mean distances. We therefore need to determine how these distances are calculated for each type of trip shown in Figure 2.

First, we will deal with all the trips that impinge in some way on the central area either entering it or using the orbital, then we will deal with of traffic resulting from trips, T_{XXX}, that avoid the central area all together. Let d_x denote the mean external radial distance travelled to reach the ring road from origins or to destinations outside it. The angles traversed around the ring road are assumed to be uniformly distributed between zero and the switching angle. Hence the average angle traversed around it is equal to one half of the switching angle.

So, when both origin and destination are outside the ring road we obtain,

$d_{XXR} = 2(R+d_x)$

which is the distance travelled all on radial routes, and

$d_{XXO} = 2d_x + R\theta^*/2$,

where the first term is the distance on radials and the second is the average distance travelled on the ring road. Note the switching angle is divided by two because is represented the *largest* angular separation for orbital trips, so that the *average* angle is one half of this.

Now consider trips with either an origin or a destination within the ring road or both (i.e. T_{CX}, T_{XC} and T_{CC}). We assume that, to reach these origins or destinations, they will travel to or from the centre, plus a mean distance of d_C from or to the centre to reach the trip end, both legs being on radial routes. When the other trip end is outside the ring road one of these legs will be of length R. Hence the total distances for each movement is given by:

$d_{CX} = d_C + R + d_x$ $\qquad$ $d_{XC} = d_x + R + d_C$ $\qquad$ $d_{CC} = 2\, d_C$

Finally let d_{XXX} denote the mean distance travelled by trips that completely avoid the central area. This provides all the data we need to compute the required measures of traffic. For centrally oriented traffic on radial links we have:

$$Q_R = d_{CC}T_{CC} + d_{CX}T_{CX} + d_{XC}T_{XC} + d_{XXR}T_{XXR} + 2d_X T_{XXO}$$

For centrally oriented traffic on the inner ring road:

$$Q_O = (R\theta^* / 2)T_{XXO}$$

Finally, for traffic completely avoiding the central area we have:

$$Q_X = d_{XXX}T_{XXX}$$

The Effect of Traffic Levels on Travel Speeds

In general both traffic diversion and traffic suppression will cause traffic speeds to alter. Over a limited range this effect can be approximated by simple linear relationships of the type.

Radial: $V_R = A_R - B_R Q_R$

Orbital: $V_O = A_O - B_O Q_O$

External: $V_X = A_X - B_X Q_X$

We assume radial speeds are only affected by radial traffic, orbital speeds by orbital traffic, and speeds well away from the central area only by traffic completely avoiding the central area. Although an approximation, this model permits the suppression of centrally oriented traffic to produce radial speed improvements outside the central area. Reductions in radial traffic may help to cut journey times not only for non–central radial traffic, but may result in a small increase in orbital capacity. This is more likely to occur if traffic signals in radial–orbital intersections can be adjusted to extend the orbital phases. It is of interest to note that Phang and Toh (1997) found that, in Singapore, high area charges resulted in substantial decreases in speeds on peripheral ring roads. This finding appears to be well established and is fully consistent with both the assumptions and conclusions of our case study. For each route, speed reduces with each extra unit of traffic using it, at a rate given by parameter B. When flow Q approaches zero the speed, V approaches A, which may be taken to represent a notional 'free flow speed'. However, a fixed linear relationship of the type presented here would be inaccurate if it were applied to both congested and free flow conditions, so parameter values A and B need to be based on suitable ranges for the radial, orbital and external speeds.

These relationships induce a dependency of speeds on the level of the charge, through their effect on traffic levels, and so on. An equilibrium between speeds and traffic demand has to be established for each assumed level of the charge. At equilibrium, speeds must be consistent with the traffic levels they produce (arising from trip diversion and suppression), whilst traffic levels must be consistent with the speeds they produce (arising from supply side constraints). This condition must apply to all types of movement. The key variable driving this equilibrium is the switching angle, which in turn depends on the type of charge.

To converge to equilibrium we initialize the model with speeds for both radial and orbital routes, and then calculate the resulting traffic demand on both. We then insert these traffic levels into the speed equations to determine revised speeds and solve for a consistent solution. Given the simplicity of our model, it was easy to do this using the facilities built into a standard spreadsheet package. The resultant equilibrium speeds are then used in the final outputs.

Benefits arising from Road User Charges

We now bring the elements of the model together into a single evaluation framework using cost-benefit analysis. The main benefits or dis-benefits expected to arise from road user charges, can be categorized as follows:

a) Benefits of lower road user travel times as congestion is reduced

b) Benefits from reductions in vehicle operating costs

c) Benefits of lower accidents

d) Dis-benefits to trips suppressed by the charges

e) Direct monetary dis-benefits to those paying the charges

f) The benefits obtained from the revenues raised from charging

g) The environmental benefits of lower traffic levels

h) Wider economic impacts, including those on property values and employment

To set our approach in the context of a more general approach to transport scheme appraisal, we consider each of the above items in turn. ‘Cost/benefit analysis’ is defined (HM Treasury 1997) as: "A term used to describe analysis which seeks to quantify in money terms as many of the costs and benefits of a proposal as possible, including items for which the market does not provide a satisfactory measure of economic value. The expression is sometimes confined to these costs and benefits alone and sometimes used to describe an analysis of all the welfare costs and benefits."

Note that it is standard practice when assessing UK transport to require an economic appraisal of items a, b, c, d and e (Department of the Environment, Transport and the Regions, 2000). We shall overlook item (c), the direct appraisal of benefits due to lower accidents, for the simple reason it is beyond the scope of the current investigation. However, an indirect and approximate assessment is obtained by a comparison of general traffic levels before and after the introduction of the charging scheme in question (see also Newbury 1988; Dickerson et al 1998).

The inclusion of item (d) is implicit in current practice, but is sometimes unrecognized. It arises for the same reason that induced traffic effects need to be included in the appraisal of schemes - that there is a change in user benefit whenever new trips are generated or whenever existing ones are suppressed. (Note: to the extent that some suppressed travellers may switch to an improved public transport mode, any compensating benefits they receive is included under item (f).)

Since road users bear the direct costs of any charges paid (e) their amount needs to be included as a disbenefit to road users. However, we will simplify this requirement by assuming the total revenue is ‘hypothecated’, that is it is ring fenced for spending on for example public transport improvements. This is not unreasonable since, in the London case, one of the reasons for introducing charges is precisely for this purpose. The key question therefore is what level of benefits (f) would be obtained by these investments to set against the dis-benefit to road users arising from the charge.

It seems obvious not all transport improvements will generate the same levels of benefits. Ideally, the majority of transport investment projects would yield benefits of value in excess of their cost, but this cannot be guaranteed and would depend very much on the projects involved. In absence of appraisal data on the projects that might be conceivably financed in this way the simplest assumption one can make is ‘benefit neutrality’. This means that any benefits generated by these projects are of the same value as the revenue collected. That is (e) will equal (f). This includes not only the benefits to previous users of public transport but any transfers from private to public transport resulting from the charges. The neutrality assumption hence provides a possible basis for appraising charging options without explicit consideration to the benefits obtained from the transport projects in which revenues are invested.

Two reasons qualify this assumption in practice. On the one hand, the investment projects should have a benefit to cost ratio in excess of unity, so that they generate benefits in excess of their cost. On the other hand, there may be appreciable cost of implementing any road user-charging scheme, with both initial set-up and recurrent operating costs. As any excess benefits from transport schemes is partially cancelled by costs of implementation, the neutrality assumption has a degree of credibility, but it is only an approximation. Also the neutrality assumption does not include any benefits or dis-benefits resulting from improved or worsened bus speeds or from changes in rail overcrowding levels.

There is, however, another way to address this issue which is to argue a given revenue stream generates equal 'net transport user benefits', irrespective of the revenue collection method. We can therefore restrict attention to policies or combinations of policies, which produce the minimum levels of dis-benefit overall while yielding a given revenue stream. We will therefore incorporate this approach accordingly.

It is clear there is more than one way in which any of the policies being evaluated could be introduced in operational terms, with for example varying degrees of technical sophistication. In an extreme case, it is possible the initial set-up and recurrent costs may exceed any user benefits the scheme may produce. As our case study is designed to focus on user benefits we will defer consideration of the costs of implementing alternative charging schemes until we compare our results with those available for one specific scheme.

Proceeding now to other appraisal issues we need to consider environmental benefits (g), particularly for example the effects on air quality and noise. It is of interest to note it is not currently standard UK practice to value these in economic terms, so it is inappropriate to trade them off against user benefits if we stick strictly to these conventions. The best qualitative indications of environmental effects we can provide are therefore the reductions in traffic levels the policies produce. For further details on environmental appraisal see DETR (2000).

Charging policies will also be expected to have wider, mostly long term economic effects (h), but it is accepted that these will generally be diffuse and inter-related. In order to assess them properly we would need to model property, land and labour markets and the way they interact with the transport system. The inclusion of such effects is clearly of some interest, but is beyond the scope of our analysis. The SACTRA committee (DTLR, 2000) examined links between transport and the economy. It was found that the empirical evidence is weak and disputed, and that conclusions are strongly dependent on local circumstances. Still and Simmonds (2000) have reviewed evidence on the influence of parking restraint policies of the behaviour of local businesses, but they also were only able to draw tentative policy implications.

Finally, we should make mention of various distributional issues. These arise because some users will benefit from changes in policy more than others. Business activities, for example, tend to be more concentrated in and around the central area than non-business activities, so charging policies with a strong central area focus would affect business disproportionately. Conversely, more dispersed charging regimes would be expected to have a greater effect on residents. In general businesses would be more likely to support a centrally focussed policy *provided they yield benefits*, whereas residents would be more likely to support a dispersed policy (although clearly much would depend on the details of the scheme) Our analysis is not designed to address this level of detail and so would need to be the subject of further research and investigation. To summarize the implications of the discussion in this section, our measure of user benefit will therefore be restricted to items (a), (b) and (d) in the list above.

Changes in User Benefit arising from Trip Suppression

We have already made the point that our results are based on the monetary value of benefits. To calculate travel time benefits net hourly savings in travel time arising from the policy are simply multiplied by the assumed value of time. This applies to all of the different types of movement given in Figure 2. Similarly, the net reductions in distance travelled are multiplied by the operating cost per unit distance and the results are aggregated over all types of movement. As a further approximation, the hourly benefits are then annualized by factoring them over 12 hours and 260 days per year.

The calculation of the dis-benefits of trip suppression is a slightly separate issue. The problem is to recognize that some road users will be deterred by the charging policy. Some of these will transfer to other modes such as public transport; some may change their destination or re-time their trip, whilst others will decide not to travel at all. We shall confine our attention to a simplified treatment in which all such effects are assumed to be represented by variable demand functions that depend on the level of road user charge, as given earlier. If the charge is sufficiently small we can approximate the change in demand by a linear function of the charge level. Now consider a charge that increases gradually from zero and order travellers in the sequence they will be suppressed. The first user to be suppressed experiences a negligible loss, whilst the last user to be suppressed experiences a loss equal to the full level of the charge. The average loss of all of the suppressed users is therefore equal to one half the level of charge. In the case study that follows all suppression effects will be based on this rule of thumb.

The Case study: Parameters and dimensional characteristics

We now turn to the case study in which we give results for a hypothetical city with dimensional and traffic characteristics similar to those for Greater London (an area of approximately 2000 sq. kms the area contained within the M25 outer orbital road). The central area is assumed to be surrounded by an inner ring road whose radius corresponds more or less to roads delineating the proposed area charge in London. For further realism we use trip data derived from the 1991 London Area Traffic Survey (DETR, 1991). The assumed level of trip movements is intended to represent average hourly flows over a 12-hour period and the traffic speeds those in the off peak.

The geometric parameters used in the case study are given in Table 2. We assume the area and termination charge policies both apply to the central area, represented by a disc of radius R (3 kms) surrounded by a circular inner ring 25 kms in radius.

	R	**d_X**	**d_C**	**d***
Distances (kms)	3	5	2	15

Table 2: Geometric Parameters used in the Case Study.

The distance-based charge meanwhile is applied to the entire hypothetical city, which we assume for the moment to be of unspecified radius. The parameters describing the behavioural responses of re-routing and trip suppression are given in Table 3. The assumed value of λ=0.002 means that a £1 charge would suppress about 18% of the trips that could not reroute to avoid it. This value was chosen in order to reproduce an overall level of traffic reduction which was broadly consistent with that reported in the Mayor's strategy. Table 4 gives the number of trips per hour assumed for each of the five movement types, prior to the introduction of a charging policy. The figures are derived from the 1991 LATS Vehicle Combined Trip File (DETR 1991) and include cars, motorcycles, vans, lorries, coaches and minibuses. Note that trips completely avoiding the central area (T_{XXX}) dominate all other movements. This is followed by a much smaller number of trips terminating in the charged area but originating from outside (T_{XC}) and trips originating inside but terminating outside (T_{CX}). Meanwhile, trips within the charged area itself (T_{CC}) and centrally oriented through traffic (T_{XXC}) represent an even small number of total movements.

Value of time ν Pence/min	**Operating Cost α Pence/km**	**Suppression rate λ /Pence**
10	8	0.002

Table 3: Behavioural Parameters

	T_{CC}	T_{CX}	T_{XC}	T_{XXC}	T_{XXX}
Hourly Road Trips (000s)	10	22	26	9	467

Table 4: Hourly Road Trips before the Charging Policy

These figures correspond to an existing situation in which there are already substantial parking charges in the central area, so any termination charges would be additional. Table 5 gives the values of the model parameters used to determine the relationship between traffic levels and average speeds. Slope parameters are expressed in speed per unit of traffic, whereas traffic is expressed in thousands of vehicle km of traffic produced in an average hour during a typical working day. To put these figures in context base levels of centrally oriented traffic (radial +orbital) is around 2 million trip-km/hr whilst base traffic completely avoiding the central area is of the order of 7million trip-km/hr. Given this, the parameters were chosen to exhibit realistic levels for observed speeds speeds and variations in these speeds. As the linear relations are approximations to curves that are concave at low flows, the intercept parameters would generally exceed the prevailing free–flow speeds.

A_R **km/hr**	**A_O** **km/hr**	**A_X** **km/hr**	**B_R**	**B_O**	**B_X**
91	99	60	0.050	0.066	0.0013

Table 5: Speed Parameters (R=Radial, O=Orbital, X=External)

Presenting the results of the Case Study

Often road user charging policies are shown as yielding direct benefits to road users, so we will first examine the user benefits obtained from each type of charging policy, at different charging levels. It will be observed that, depending on the type and level of the charging regime, the production of positive user benefits cannot be guaranteed and it turns out that this is a key means of discriminating between alternatives.

For reasons given previously, we will require our charging policy to generate a fixed level of revenue, which will be appropriated to finance an unspecified set of projects. The question we address is which charging policies or combinations of policies would yield the required level of revenue and give the maximum benefit to road users. For any single charging policy and revenue target there will generally be only a very limited range of charge levels that yield the required revenue These may sometimes be regarded as excessive and indeed very far from the types of policy that maximize user benefits. We overcome this possibility by investigating *hybrid policies*, which are policies designed to combine different types of charging mechanism into one overall policy that maximizes benefits for any desired level of revenue. Provided component charging policies have sufficiently different characteristics, this provides a substantially greater scope and therefore flexibility than any single policy alone.

A three-stage procedure is adopted:

Stage 1: The model is first run over a wide range of different charge levels for each individual policy. Resulting user benefits and revenues are examined and the types and levels of charging policies narrowed down to those generating revenue of the required amount and yielding high levels of benefit.

Stage 2: A second set of model runs simulates the revenues obtained from more promising cases. These runs are conducted over a more restricted range of charge levels, based on the findings from stage 1 with respect to levels of user benefit. Regression models are then fitted to predict revenues using the data obtained from the simulations. A hybrid revenue model is then constructed combining the results from each of the preferred charging policies.

There are two hybrid variants: the *'one–at–a–time'* method which simulates each policy separately, estimates separate regression models, and then combines the models to calibrate the hybrid revenue model. The '*all-together'* method simulates the revenue impacts of the hybrid policy and calibrates the hybrid revenue model directly from these results. *One-at-a-time* is the most transparent, but may be prone to error if there are strong interactions between the effects of the component policies. The *all–together* method could be used to incorporate policy interactions in the hybrid revenue model but would require a suitable and careful calibration. In fact, it turns out that, provided policy levels are varied over a narrow enough range, the *one–at–a–time* approach gives sufficient accuracy for policy optimization purposes.

Stage 3: The revenue model is then 'inverted' with the objective of constructing a suitable range of alternative charge levels for individual components of the hybrid policy, subject to the revenue constraint. Specific model runs are conducted for each of the synthesized charge level combinations in the hybrid policy to confirm they yield the required revenue and are optimal. This leads to the identification and selection of a preferred hybrid policy.

Results

Stage 1: User Benefits

a) *Area charges*

Let us begin with the area charging policy. Figure 4a shows the impact of raising the area charge from zero to £3. The vertical axis shows the user benefits in millions of pounds per annum and the horizontal axis the level of the charge. Four separate curves are shown, corresponding to the benefits or dis-benefits incurred by trips using exclusively radial routes, trips using the ring road, suppressed trips and the combined total of all three. Note the radial trip category, by definition, includes trips that are solely within the central area.

A key finding is that the total user benefit is negative at all positive area charge levels. Whilst there are some user benefits arising from reduced congestion these are confined to radial routes. This benefit is outweighed by dis-benefits to all other types of trip.

At low charge levels the main dis-benefits are to ring road users, due to the increased congestion on the ring from traffic that has been diverted from travelling through the centre. Notice that once the area charge exceeds £1 all such traffic has already been diverted onto the ring road and so the dis-benefits to trips on the ring road do not increase further. Once the area charge reaches £2 the dis-benefits to suppressed travellers exceeds that resulting from additional congestion on the ring road. We therefore find that the user benefit for the totality of trips remains negative at all positive charge levels.

Our key conclusion is that the optimum level of area charge is in fact zero. In view of its poor performance, it would not be sensible to retain area charging in the subsequent analysis of optimal user charges. However, the possible wider area effects of a central area charging policy remains of some interest and so will be discussed later.

b) *Termination charges*

Figure 4b, drawn to the same scale as Figure 4a, shows the effect of raising the termination charge from zero to £3. As for the previous case, four separate curves are shown, corresponding to trips using exclusively radial routes, trips using the ring road, suppressed trips and the total of all of these trips. As is seen the user benefit for the totality of trips is now positive for termination charges below £2, with a maximum benefit of just under £13m p.a. when the charge is equal to £1. Both radial trips and trips using the ring road also experience user benefits, but this is partially outweighed by dis-benefits to suppressed trips.

The benefits to both radial trips and trips using the ring road arise partly from reduced travel times and implicitly fewer ‘stop-starts’ but also by a reduction in operating costs since travel distances are slightly decreased. The reduction in distances results from the different influences of the termination charge on radial and orbital speeds. Before the charge orbital speeds were larger than radial, so the switching angle exceeded 2 radians. The termination charge mainly increased radial speeds, so that the switching angle moved closer to its distance minimizing value of 2 radians.

The dis-benefits to suppressed trips, due to the termination charge, is identical to that arising from an equivalent area charge of the same magnitude. Since positive user benefits appear to be feasible at realistic levels of termination charge, this policy is retained for inclusion in the analysis of user-optimal charges.

c) *Distance charges*

Figure 4c shows the user benefits arising when the distance-based charge applied over the range zero to 4 pence per kilometre. Unlike area and termination charges, five separate curves are needed to include trips completely avoiding the city centre and inner ring road. These are indicated by the XXX curve. As is seen, the user benefit for the totality of trips is positive for all distance charges in the plotted range, with a maximum benefit of about £25 million p.a., corresponding to a distance charge of 2.5 p/km. Note that for total benefits to become negative, the distance charge would need to exceed 5p/km.

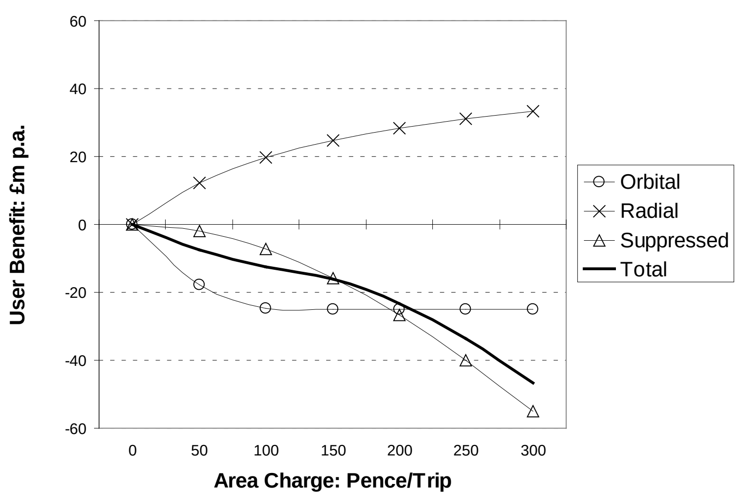

Figure 4a: User Benefits of Area Charges

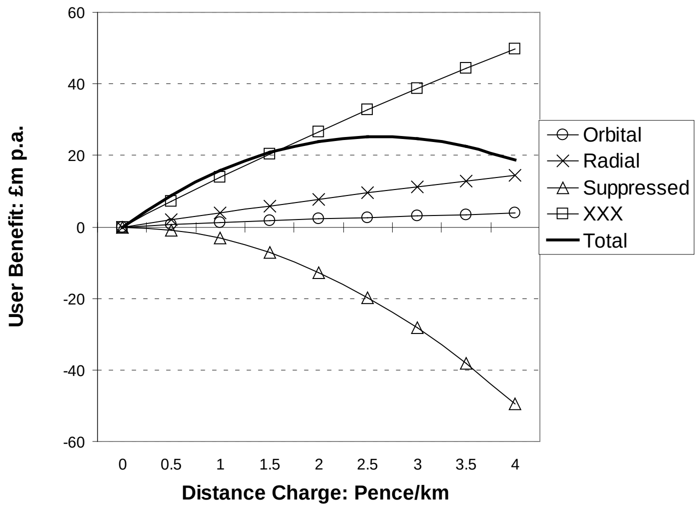

Figure 4b: User Benefits of Termination Charges

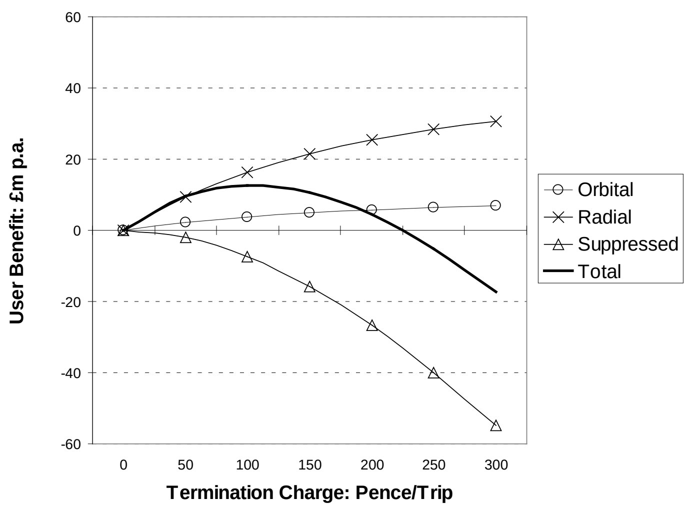

Figure 4c: User Benefits of Distance Charges

Radial trips, those using the ring road and those that completely avoid the central area, all experience user benefits and the only type experiencing dis-benefits are suppressed trips. The benefits to both radial trips and trips using the ring road arise from a combination of reduced travel time and reduced vehicle operating costs. Since positive user benefits arise over a wide range of charging levels, this policy is also retained for inclusion in the analysis of user-optimal charges.

Stage 2: Estimation of the Revenue Model

For the reasons given estimation of the revenue model is restricted to termination and distance charges. The values obtained that were closest to the optimum hybrid policy were in the range 50p to 150p for termination charges and 0.2p/km to 1p/km for distance charges. Note the maximum distance charge is set less than the optimum distance charge of 2.5p/km to be compatible with range required to meet the revenue constraints. The model was used to simulate the revenues arising from each of these policies over the indicated ranges. The following logarithmic regression models were fitted to the simulated results (standard errors are shown in brackets):

Termination charges: $$Ln(\mathrm{Re}venue) = 0.4292 + 0.8452\,Ln(\mu) \quad R^2 = 0.999$$
(0.1033) (0.0228)

Distance charges: $$Ln(\mathrm{Re}venue) = 5.643 + 0.9959\,Ln(\kappa) \quad R^2 = 1.000$$
(0.0005) (0.0005)

These models are only accurate in the vicinity of the range of charges over which they are fitted and more general functional forms may be required over extended ranges. It can be noted that the coefficient for the termination charge is significantly below unity, so there are diminishing returns from higher levels of this charge. At low charge levels the area charge yields slightly higher revenues than the termination charge, but at higher levels their revenues are identical as all through traffic is diverted out of the centre and hence does not pay the area charge, which falls exclusively on terminating trips.

The correlation coefficients for both models are, to all intents and purposes, equal to one because the simulated data lie on smooth curves. Assuming the revenues from termination and distance charges are largely independent we can add the predicted revenues for each policy, giving the following revenue model:

$$\mathrm{Re}venue = 1.536\mu^{0.845} + 282.4\kappa^{0.9959}$$

Stage 3: Application of the Revenue Model

Since the hybrid policy only has to deal with two charge levels it is particularly straightforward to set up the next stage of analysis. First we fix the revenue at the required level, and vary the termination charge in small increments over ranges lying within the ranges used in step 2 for fitting the regression models. The revenue model obtained in step 2 is mathematically inverted to obtain the required distance charge, for the specified revenue and termination charge:

$$\kappa = \left(\frac{Revenue - 1.536\mu^{0.845}}{282.4} \right)^{1/0.9959}$$

We make two alternative revenue assumptions: either £200 million per annum or £300 million per annum. These amounts are based on figures contained in the Mayor's Transport Strategy for Greater London (Livingstone, 2001). In addition a sensitivity test was conducted in which there was a 25% reduction in the dis-benefit experienced by suppressed trips. This may be taken to represent a scenario in which there is a sufficient improvement in public transport, arising from the policy, so that previous road users who transfer to public transport experience a negligible loss in benefit. The value of 25% was judged to be maximum number of potential mode switchers that were expected to fall into this category.

Table 6 shows the key results obtained for a user–optimum hybrid charging policy. It may be confirmed that the required revenues are obtained without the need to fine–tune the charge levels. This confirms the validity of the revenue model derived in stage 2. We find that the optimum user benefit is obtained when the termination charge is just over 80 pence, and is largely insensitive to the level of the required revenue. For revenue of £200m p.a. the optimum distance charge is equivalent to 0.49 pence per kilometre. At normal rates of fuel consumption this is equivalent to about 5 pence per litre of fuel. To put this in perspective we note that, since submitting this paper, the average price of fuel in London has fallen by slightly more than this amount, but a spread of as much as 15p per litre can be found. Total urban traffic is reduced by 1.8% and traffic in the central area by 3%. For revenue of £300m p.a. the optimum distance charge rises to about 0.8 pence per kilometre, equivalent to a fuel cost of about 9 pence per litre. Total urban traffic is reduced by 2.7% and traffic in the central area by around 3.5%.

Termination Charge Pence/Trip	**Distance Charge Pence/Km**	**Annual Revenue £m p.a.**	**User Benefit £m p.a.**	**Total % Traffic Reduction**	**Central % Traffic Reduction**
Revenue £200m p.a.					
90	0.463	200	19.9	1.8	3.3
80	**0.486**	200	**20.0**	1.8	3.0
70	0.510	200	19.8	1.8	2.7
Revenue £300m p.a.					
100	0.795	299	24.3	2.7	3.8
90	**0.818**	300	**24.5**	2.7	3.6
80	**0.841**	299	**24.5**	2.7	3.3
70	0.865	299	24.3	2.7	3.0

Table 6: User Optimum Hybrid Charging Policy

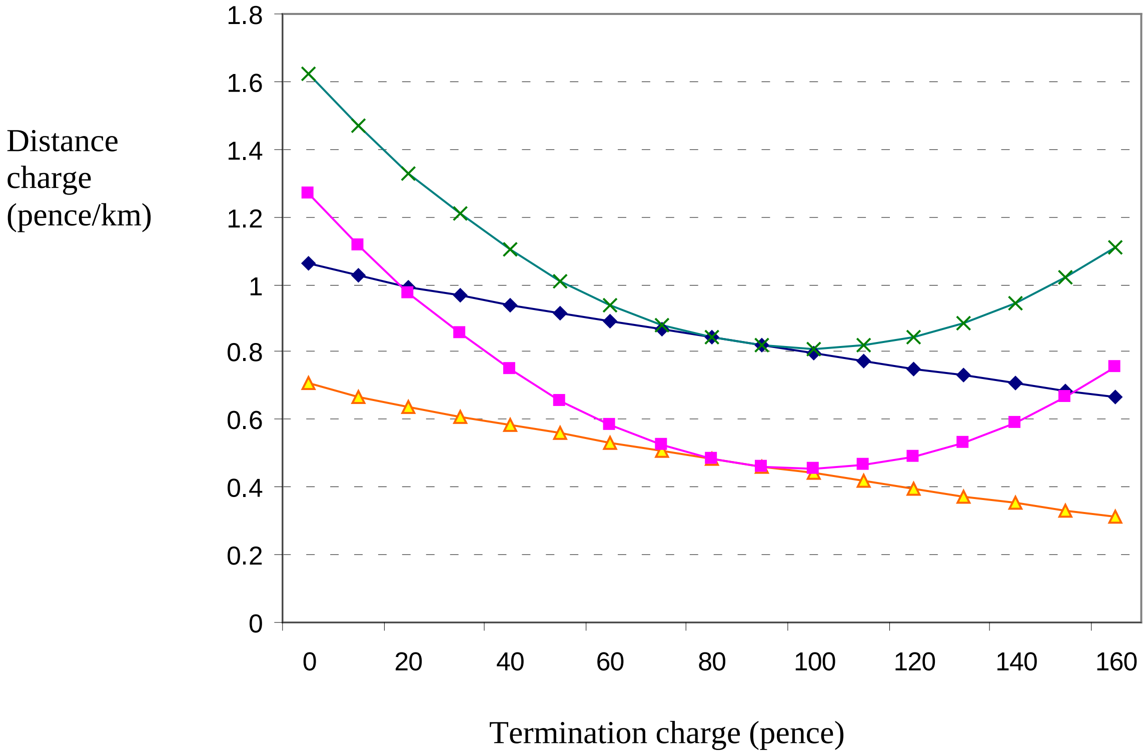

Figure 5: User Optimum Hybrid Policies, showing convex benefit isoquants tangential revenue curves. The horizontal axis is the termination charge in pence. The vertical axis is the distance charge in pence per km.

Figure 5 shows the revenue and benefit curves as a function of the termination and distance charges. These are based on the same results as given in Table 6, but a more extensive range of charge levels has been plotted in order to aid visualization. It can be observed that the benefit curves bend back as the termination charge has a local optimum in the vicinity of 100 pence. These curves were constructed by fitting a quadratic function of the charge to the model outputs. This took the form

$$UserBenefit = 4.17 + 0.197\mu - 0.00099\mu^2 + 12.94\kappa$$

Table 7 shows the results of the sensitivity test whose motivation was previously described in which the dis-benefit to suppressed trips is reduced by 25%. The required revenues are still obtained, confirming the continued applicability of the revenue model. The optimum user benefit is now obtained when the termination charge is 100 pence, and remains insensitive to the revenue level. For a revenue of £200m p.a. the optimum distance charge is 0.44 pence per kilometre, equivalent to just under 5 pence per litre of fuel. Total urban traffic is reduced by 1.8% and traffic in the central area by 3.6%.

At revenues of £300m p.a. the optimum distance charge, for the sensitivity test, is about 0.78 pence per kilometre, equivalent to a fuel cost of about 8.5 pence per litre. Total urban traffic is reduced by 2.7% and traffic in the central area by around 4%.

Termination Charge Pence/Trip	Distance Charge Pence/Km	Annual Revenue £m p.a.	User Benefit £m p.a.	Total % Traffic Reduction	Central % Traffic Reduction
Revenue £200m p.a.					
110	0.418	200	21.6	1.9	3.9
100	**0.440**	200	**21.7**	1.8	3.6
90	0.463	200	21.6	1.8	3.3
Revenue £300m p.a.					
120	0.750	299	26.3	2.7	4.4
110	**0.772**	299	**26.6**	2.7	4.1
100	**0.795**	299	**26.6**	2.7	3.8
90	0.818	300	26.5	2.7	3.6

Table 7: Sensitivity Test of User Optimum Hybrid Charging Policy

Wider area effects

The re-routing effects discussed thus far are restricted to a choice between radial travel through the city centre and travel around a single inner ring road. In reality the impacts of road user charging on the choice of route would be much more complex and may be dispersed over a much wider area. How might this influence our results? To shed light on this question we have narrowed the issues down to three topics each of which is related to the availability of further orbital routes, their radius and capacity. Topic 1 is concerned with the effects of a low central area charge on these routes, topic 2 examines the effects of higher central area charges, and topic 3 looks at the effects of the preferred hybrid charging policy on the same routes. We shall treat topic 1 in some detail as it also provides considerable insight into the other topics and provides a good geographical illustration of the general issues involved.

Topic 1: Wider spatial impact of central area-based charge

Suppose we extend the area to include additional ring roads and retain previous assumptions about radial travel. With a central area charge the reduced speed on the inner ring road may divert some traffic onto the outer rings, so generating a ‘ripple effect’. We illustrate how the magnitude of such effects can be assessed, considering not only the choice between radial and orbital routes but also the choice between alternative orbital routes. By measuring the sizes of route catchments, with and without a central area charge, we show how and whether traffic will be diverted onto outer orbital routes.

Mathematical techniques to model multiple orbital routes were set out in Hyman and Mayhew (2000), but these need to be extended to allow route choice to depend not only on travel time but also on vehicle operating costs and road user charges. Route catchment maps may be constructed by fixing one end of a trip and colouring all other locations according to the cheapest route for reaching it. In general the catchment patterns shown on these maps shift slowly as the fixed location is moved, but key changes occur when the fixed location crosses an orbital route.

Our illustration is based on a similar hypothetical city to that adopted in the case study, but now with three ring roads, corresponding to rings in London. Thus, Ring 1 has a radius of 3kms, Ring 2 a radius of 12kms and Ring 3 a radius of 25kms. We assume that the speeds before and after an area charge of 70 pence are as given in Table 8.

	Radial	**Ring 1**	**Ring 2**	**Ring 3**
Before	30	40	30	95
After	32	35	30	95

Table 8: Speed Assumptions (kph) for low Area charges

We consider two typical fixed locations to illustrate the catchment maps. One of them is between rings 1 and 2 and the other between rings 2 and 3, two locations that are representative of the middle to outer suburbs (urban symmetry can be assumed). Each route catchment is shaded according to the route to which it belongs. So, for example, the area shaded light grey represents the radial catchment. It means that for users located within it the minimum cost route to their destination is through the city centre. The results before and after the application of the charge are shown in Figure 6 (A-D).

In either of the fixed locations, there is little or no impact on the route catchments for rings 2 and 3 whereas the impact on the ring one catchment is substantial due to the reduction in size of the radial catchment (caused by changes in switching angles). Notice also that in (B) and (D) the outer-most orbital features as an alternative route but not in (A) and (C) where the fixed location is closer to the city centre. In either case we conclude that the effect of the area charge is confined to the immediate vicinity of the charged area, although it is noteworthy in (D) that all externally generated trips now use ring 3. In general, however, we conclude the area charge has only a minimal ripple effect at the given speeds. The key parameter affecting this conclusion is the reduction in speed on ring 1 from 40 to 35 kph, after the imposition of the central area charge. A charge of 70 pence is sufficient to divert almost all through trips onto ring1, so this would not change significantly at higher area charges.

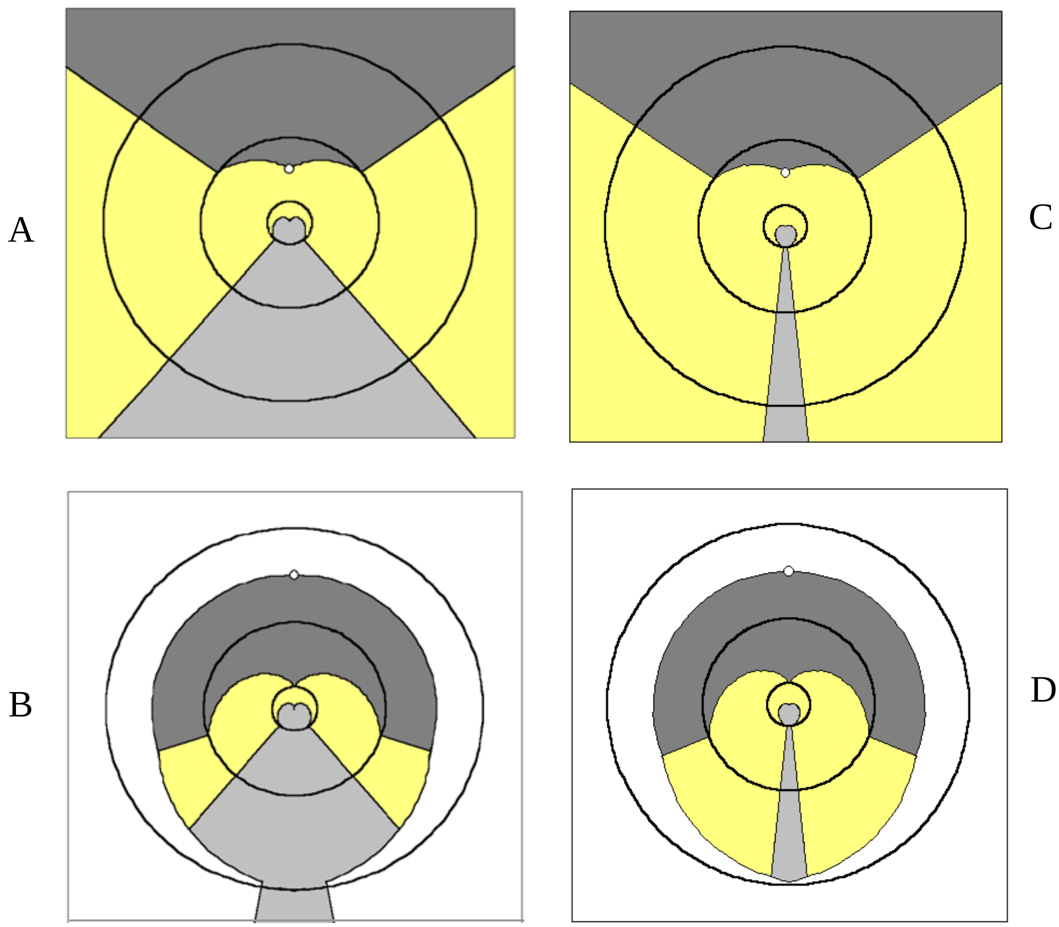

Figure 6: Route catchment maps for two fixed locations.(a) At 7.5 kms, no charge; (b) At 18.5 kms, no charge; (c) At 7.5 kms, charge 70p; (d) At 18.5 kms, charge of 70p.

Given the much greater distance of the outer rings, there would need to be a substantially greater speed reduction on ring 1 before they would become alternative routes. For example, if the speed on ring 1 was reduced to below 6 kph then the cost of traversing any given angle around either of the outer rings would then be less than on ring 1. As this limit is approached there would be an increasing number of trips diverting to the outer rings as a consequence. However, the results from our case study do not indicate that area charges would result in speed reductions on ring 1 of such magnitude.

Topic 2: The effect of higher central area charges

At higher area charge levels than 70 p the principal influence is on the suppression of trips into the central area, leading to slightly higher radial speeds, but with no further impact on ring one speeds. From Figure 5 it can be inferred that this would have no direct effect on the catchment area for ring 2, but may slightly reduce the levels of traffic using ring 3. However, our analysis suggests this effect is not likely to be substantial and would not affect the conclusions from the case study application.

Topic 3: Impact of the preferred hybrid charging policy

We saw that the conclusion from the body of the case study was that benefits are optimized using a hybrid policy rather than any single one. As far as wider area effects of the hybrid policy are concerned, the principal effect of the preferred hybrid charging policy would be to increase speeds on radial routes, primarily via the effect of the termination charge on suppressing trips into the central area. Significantly, however, it appears to have no appreciable direct effect on orbital speeds. The distance component of the charge might, in principle at least, divert traffic away from ring 3 onto shorter routes. However, at a typical distance charge of 0.5p/km this effect is not strong enough to increase congestion in the outer suburbs or to affect our central conclusions.

Comparison between the Case Study and the Mayor's Strategy

Livingstone (2001) describes the net revenue expected to be generated by the proposed central area-charging scheme:

"The scheme would generate net revenues of between £170m and £210m per year (central estimate £190m) which, by law, must be spent on improving transport within Greater London for ten years from the introduction of the scheme."…"The Government has promised that these revenues will be additional to transport grant and the Mayor will press for maximum transparency in future grant allocations to London so that this can be confirmed."

On set and recurrent costs the document states:

"In round terms, the cost of developing and introducing a scheme is estimated to be £50m. The cost of associated traffic management and transport measures is estimated to be up to £150m. Annual scheme operating costs are estimated to be of the order of £50m per year."

If we add the central estimate of revenue of £190m to the annual operating cost of £50m p.a., we obtain implied gross revenue of £240m p.a. (The initial set-up costs amount to £200m, which slightly exceeds the net revenue from a single year of operation, but this is presumably a one-off cost.) In our case study we examined schemes in which the gross revenue raised was between £200m and £300m p.a., so these revenue levels are broadly consistent with the Mayor's strategy.

Our optimum level of user benefits was between £20m and £27m p.a. This was obtained for a charging policy based on a mixture of central termination and wide area distance based charges, whilst the central area charging policy gave negative user benefits. The optimum charging policy therefore appears to yield road user benefits that are around half of the annual cost of operating the proposed charging scheme.

A possible indication of the level of user benefits claimed for the Mayor's strategy is given in the following extract:

"In total, this would represent an annual economic saving in terms of reduced delays, more reliable journeys and reduced fuel consumption of about £50m–£90m for car users…"

Our own analysis does not reproduce a comparable level of user benefits, either from a central area-charging scheme or from an optimised hybrid charging strategy. This could possibly arise from differences between the broad brush approach we have taken with the more detailed approach taken in the studies cited in the Mayor's strategy or from the fact that our analysis is based entirely on historical car trip levels and takes no account of growth in these numbers. Another possible factor may be that dis-benefits to suppressed trips are not accounted for in the analysis quoted in the Mayor's strategy. However there is insufficient detail given in Livingstone (2000) to check this.

Other reasons for the differences may include assumptions about the effects of traffic reduction on speeds, on the value of travel time savings or on the type and extent of the behavioural responses of road users to the charge. Another source of difference in our estimates of user benefits may be that the benefits quoted in the Mayor's strategy excludes some of the dis-benefits outside the charged area. To test this we can restrict our attention to radial traffic. We then obtain a user benefit of £37m p.a., which approaches the lower end of the range quoted for the Mayor's strategy. However such an estimate of benefits excludes disbenefts of £25m p.a. to orbital traffic (outside the central area) and dis-benefits of £128m to suppressed trips.

For a £5 area charge our case study model indicated that central area traffic would reduce by 11.4%, which appears consistent with the 10-15% range quoted in the Mayor's strategy. However, only one quarter of this reduction is due to diverted traffic, the remainder being suppressed trips, which would also be reduced by a termination charge.

For a £5 area charge our case study model gave a total traffic reduction of 2.6% over the whole of London, which is again broadly consistent with the 3% reduction quoted in the Mayor's strategy. These comparisons are consistent with the view that the primary differences in our benefit estimates arises not in the modelling of behavioural response, but from differences in the ways in which road user benefits are compiled and presented.

A more complete audit of the specific sources of the differences in our estimates of user benefits is outside the scope of this paper. However, our main interest in such an audit would be to check the validity of the differences in the effects of different types of charging policy.

More substantially, we have found that there are robust and consistent differences in the user benefits obtained from area based charging, termination charging and distance based charging policies. One of the reasons cited in the Mayor's proposal to support a central area charging policy is:

"…it would be more effective in reducing through traffic than other measures, for example, parking controls can reduce terminating traffic, but can increase through traffic – a particular problem for central London…"

Our results indicate that a central area termination charge yields actually *more* user benefits than an area based charge. This is precisely because a termination charge, unlike a central area charge does *not* impose dis-benefits to through traffic. Moreover, by imposing a charge as high as £5 per day, through traffic would be largely diverted out of the central area and would not be contributing to revenue. The financial burden of the proposed charging policy would therefore be borne primarily by terminating trips.

The 'problem of through traffic' appears to be actually made worse by the type of charging policy proposed in the Mayor's strategy, when judged in terms of conventional measures of user benefit. This is, perhaps, a prime example of the type of paradox that Martin Mogridge was fond of quoting. The policy implication is that a central area parking levy is a better way of addressing the problems of traffic congestion in and around central London than a policy whose main effect is to divert through traffic, provided that the parking levy is not excessive in magnitude.

The Mayor's rationale quoted above also raises some interesting issues of the geographical equity of alternative types of road user charging policy. The meaning of the term 'through traffic' depends very much on one's geographical perspective, as all traffic travels through other areas in order to reach their destinations. The central area is not the only part of London that experiences traffic congestion. Is it reasonable to reduce congestion in central London whilst increasing it in inner London? Some detrimental effects in inner London are implicitly recognised in Livingstone (2000), but they are perhaps downplayed a little:

"Residents with cars living adjacent to the charging area could find their travel choices affected and would have an incentive to avoid travelling by car into the charging area. This may be difficult for unplanned trips, or for trips by car that some residents may consider essential, such as to schools or health facilities within the charging area."

A much more widely dispersed charging policy appears to be a better way of raising the revenue required for improvements in public transport, particularly when combined with a central area parking levy. It could be regarded as a challenge to devise ways of implementing such policies that are efficient, fair and command widespread support. If such a challenge cannot be met the alternative may be simply to fall back on more conventional funding sources for investment in transport projects.

Finally let us briefly look at the claims made for the safety & environmental benefits of the Mayor's strategy. No benefits are claimed for air quality and noise reductions. Lower traffic levels result in a claimed 2–3% reductions in casualties, a 3% reduction in greenhouse gases and a 2% drop in fuel consumption.

These claims are broadly consistent with the 2.6% traffic reduction found in our case study for a £5 area charge. However other types of charging policy appear to give similar traffic reduction levels, with our optimum hybrid policy yielding a typical traffic reduction in excess of 2%. It is therefore reasonable to expect that the area charging proposals in the Mayor's strategy would not yield significantly greater safety or air quality benefits than alternative charging strategies.

Livingstone (2001) gives no monetary figures on the user benefits arising from the expenditure of the revenue raised by the proposed area-charging scheme. We are therefore unable to comment on the efficiency with which the net revenues raised from these charges can be utilized.

The overall effects of the proposed area charging policy are summed up in Livingstone (2001) as follows:

"London would gain. There would be a substantial net economic benefit across London from charging, plus substantial net revenues to be spent on transport within London."

Pending an analysis of possible wider economic benefits, our research provides a basis for questioning this claim. However our findings are based on a highly simplified model which was primarily designed to illustrate the broad differences between alternative charging regimes, and to illustrate the methods by a check on the reasonableness and robustness of the charging proposals for London. We have only compared our findings to those quoted in the Mayor's strategy. An extensive review of other studies of London congestion charging is beyond the scope of this paper.

Conclusions

The problem of traffic congestion now afflicts most major cities. Reducing or controlling it has become a major preoccupation of urban authorities. In this paper we have compared three different road user-charging policies for controlling congestion in cities - area charging, distance charging and terminal charging.

We specified the effects of each different charging policies on spatially different types of trip, developing simple models for the effects of road user charges on the choice of route and on the suppression of trips. We showed how traffic levels are calculated and how traffic congestion influences the speeds experienced for each type of trip. We then discussed how to measure the user benefits arising from each of the different charging policies. The analysis was applied in a case study that identified hybrid road charging policies that optimized user benefits, subject to a constraint on the revenue raised from charging. The robustness of the simplified model in the context of wider area impacts was also examined.

The case study illustrated that central area charging in London, as proposed in (Livingstone, 2001), does not seem to be the ideal form of charging policy and may even fail to yield overall road user benefits. Indeed, other types of charging policy, such as a combination of termination and distance based charging appear to be much more promising. These conclusions are based on a simplified representation of travel choices using a geometric model for traffic routing but are robust under various parameter assumptions. We have made no attempt to assess the implementation costs of alternative policies, and so are not in a position to dismiss alternative conclusions if one policy, say, were to cost significantly more than another in this respect. These charging options are not the only ones possible, and others are worthy of further investigation. For example, lower charges spread out over a wider area combined with a more intelligent collection and enforcement mechanism may prove to be a particularly promising option. Other options include charges on limited access orbital routes or localized charging in sections of London where effective diversionary routes can be provided. More generally, much greater discrimination of charging levels to meet the conditions prevailing in different parts of London, combined with a rigorous assessment of all the implementation issues, appears to be required.

Martin Mogridge often presented urban public transport improvements as a solution to the problems of road congestion. However it is beginning to look like some level of road congestion is here to stay, but any alleviation to it would require a package of complementary measures. The best packages appear to be those that combine both wide area and local policies. Some forms of road user charging could form part of such a package, but extreme caution is required in order to ensure that they to not exacerbate the problem of congestion. Informed public debate about alternatives may help to assist in identifying better policies.

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