COMPARING BENEFITS BETWEEN CORDON AND AREA-BASED ROAD PRICING SCHEMES AND OPTIMISING THE BENEFITS

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ABSTRACT: This paper outlines a procedure for implementing area-based road user charging scheme and then compares the benefits between the usual cordon-based and area-based road pricing schemes. The results are illustrated with a network similar to that for Cambridge, England. It has been found that the benefits from road pricing schemes could be optimised with a combination of the cordon and area-based charging methods, with a particular combination of a toll charge at the cordon together with a discounted fee for residents of the cordoned area resulting in the highest benefits.

INTRODUCTION

The Eddington Transport Study (2006) supported the idea of congestion based charging for relieving traffic congestion in the United Kingdom. It observed that congestion charging methods would stand out above all transport interventions and have substantial potential to contribute to the social welfare. The Government commissioned a road pricing feasibility study back in 2004 which also concluded that well designed congestion schemes could reduce congestion by a substantial 50% compared to the no-charging scenario. Road user charging schemes involve applying a charge for road use based on various methods such as cordon-based, distance-based, time-based and delay-based schemes. May and Milne (2000) compare various such approaches and based on their performance in reducing the congestion, concluded that delay-based charging was the most effective and the cordon-based scheme was the least effective. However, their analysis did not consider the impact on social welfare and equity of different charging schemes, neither did they consider the case of area-based charging.

Analysis of congestion charging methods requires quite significant computational efficiency particularly if involving optimisation methods. Sumalee's work (2004) on cordon design used an optimisation approach based on Genetic Algorithms (GA) to determine the optimal location and toll level around a closed cordon for a network. The GA optimal single cordon generated benefits 80% higher than the best judgmental cordon for a simplified network of Edinburgh. However, GA based methods are known to have a very high computing time and may produce non-unique solutions. As an alternative, a short cut approach was developed, primarily aimed at reducing the computing time significantly, based on an observation that charging on only a few of the highest marginal cost links could result in a high proportion of the system optimum or first best benefits (Shepherd et al 2007). Initial results for Edinburgh and York have shown that the approach can double the benefits compared to a judgemental cordon and more impressively achieved 93% of the GA optimal cordon benefits with only a few model runs in the case of Edinburgh. Further work has confirmed that the approach can also work for SATURN simulation models using total delay per link as the basis for defining the so called high cost – high benefit links (those with highest marginal cost).

Out of all the potential charging methods mentioned earlier, cordon-based charging is the easiest to implement as it simply involves applying a charge on all inbound road links crossing a cordon, usually around a city centre. However, cordon charging fails to charge those trips wholly within the cordon, and inbound charging fails to charge outbound trips, both of which may contribute to congestion. Area charging can address both of these, but raises the question of the need for discounts for residents.

Maruyama and Sumalee (2006) formulate a trip chain equilibrium model and compare the social welfare and equity between cordon-based and area-based charging schemes. While the social welfare computation is based on the usual user benefits from the scheme, the equity computation has been based on an innovative modified Gini coefficient. In their numerical illustration they showed that area-based schemes deliver higher levels of social welfare compared to cordon-based schemes. However, with wider coverage of an area charging scheme, the area-based charging method produced more inequitable results.

This research is aimed at finding a method to implement an area charging scheme for larger real networks and contributes towards improving the understanding of road user charging schemes. This paper describes the implementation of area charging scheme in a SATURN model and compares the efficiency of a cordon charging scheme with an area charging method.

METHODOLOGY

In order to meet the requirements for modelling an area charging scheme, we need to apply a charge on all the vehicles destined to or originated from a designated area of a town/city. In modelling terms, this would mean applying road user charges to various components of the trip matrix including internal-internal, external-internal, internal-external and external-external trips. Ideally, one can apply a charge to each vehicle depending on its origin-destination information, but it would require tracking of route flows using various links potentially through the network thus needing a massive computing effort to implement such a model. An alternative simpler way is to implement a charge on all the inbound links across the cordon in addition to the outbound centroid connectors (i.e., the links emanating from the centroids connecting the real road junctions) within the charged area. However, this method may not be able to distinguish the residents and non-residents of the charged area.

In general, the link charges can be applied in three different ways – (i) as penalties in time units defined in the input network data file, (ii) as extra data records either in time or money units input through an external data file, (iii) a combination of (i) and (ii). Out of the above, defining the penalties is the easier option. However, there may be restrictions on charging the centroid connectors, because the centroid connectors are not real roads but imaginary links between the real road junctions and the imaginary centroid of a zone. Therefore, in this exercise, it has been decided to use a combination of the two as in (iii), with penalties applied to the cordoned inbound links and extra data records implemented to charge the centroid connectors. There may be some further challenges to face while implementing the charges through extra data records, in that the centroid connector links may need to be coded as turns rather than just as links. This means that we may need to code up all the outbound turns from each centroid within the charged area, which is largely proportional to the size of the area being charged - the bigger the cordoned area, the more the number of turns to be charged.

Road user charging schemes commonly require an elastic demand modelling approach rather than a fixed demand approach thus allowing the transport demand to respond to the pricing. Thus, the overall procedure involves setting up an elastic assignment procedure which, in addition, needs an external file containing information on area charging and the whole iteration terminates when sufficient convergence levels are achieved. At the end of the elastic assignment procedure, user benefits are computed using the 'Rule of Half' method. Finally, the revenue from each chargeable link is computed as the product of the flow assigned and the chargeable rate per vehicle which when summed over all the chargeable links results in the total revenue from the charging scheme. The procedure for setting up an area-based charging exercise can be summarised using the following steps:

- Creating a network data file including the details of road links, zones, centroid connectors, in the usual way;
- Determining trip matrix file, and elastic demand model parameters;
- Creating charge files – cordon charge file and area charge file, which could be combined together depending on the software limitations; and
- Computing the user benefits based on the 'Rule of Half'.

NUMERICAL EXAMPLE

In order to implement and test the methodology described, we have selected network similar to that for Cambridge which has been in use for research concerning cordon charging. The network comprises a 'central area' network which includes the details of the junctions and an 'outer area' network where the delays to traffic occur mainly along the links. Figure 1 shows a smaller inner cordon and a larger outer cordon (adopted from May and Milne 2000), which are being considered for area charging. Typically, in an experiment we select one of the cordons and apply a predefined charge on all inbound links crossing the cordon and also charge the outbound centroid connectors enclosed in the cordoned area. Usually, it would also involve creating a charge file defining the complete set of the links that are being charged and the level of charge. The entire procedure is suitable for batch processing, if all the external input files have been predefined.

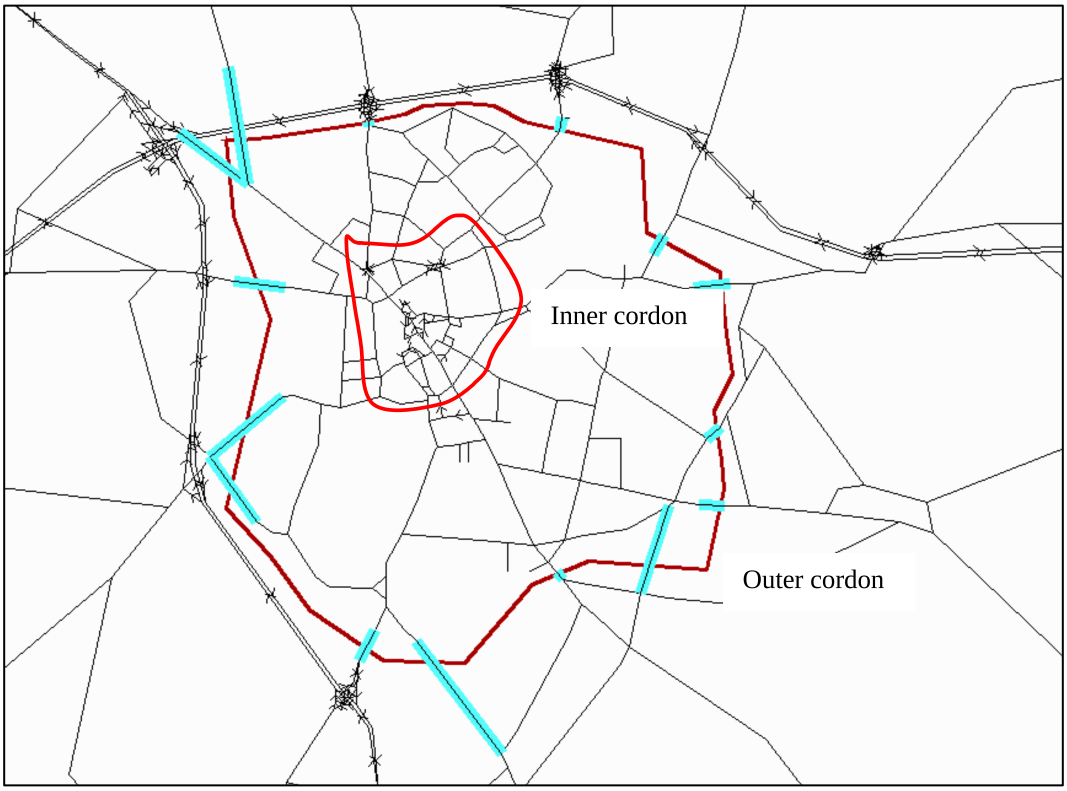

Figure 1 Cambridge Network: Inner and Outer Cordons

Comparison of User Benefits

The elastic assignment procedure was run with charges varying from 0p to 400p in 25p increments and the user benefits and revenues from the scheme were computed. The net benefits were converted to monetary units and were compared between the cordon charging and area charging methods. Figure 2 shows that the area charging results in higher benefits at lower charge rates. This is because the area charging method applies to a larger proportion of the trip makers and includes the internal-external and the internal-internal component of the trip matrix. However, at higher toll rates of £1 and above, the user disbenefits gradually outweigh the toll revenue and the net benefits from the charging scheme become negative.

Figure 3 presents the results in the case of the outer cordon. It may be noted that in both the cases, identical charge has been applied both on cordoned links and centroid connectors. However, this is not a limitation of the modelling procedure and different sets of charge rates can be applied at cordon and inner areas.

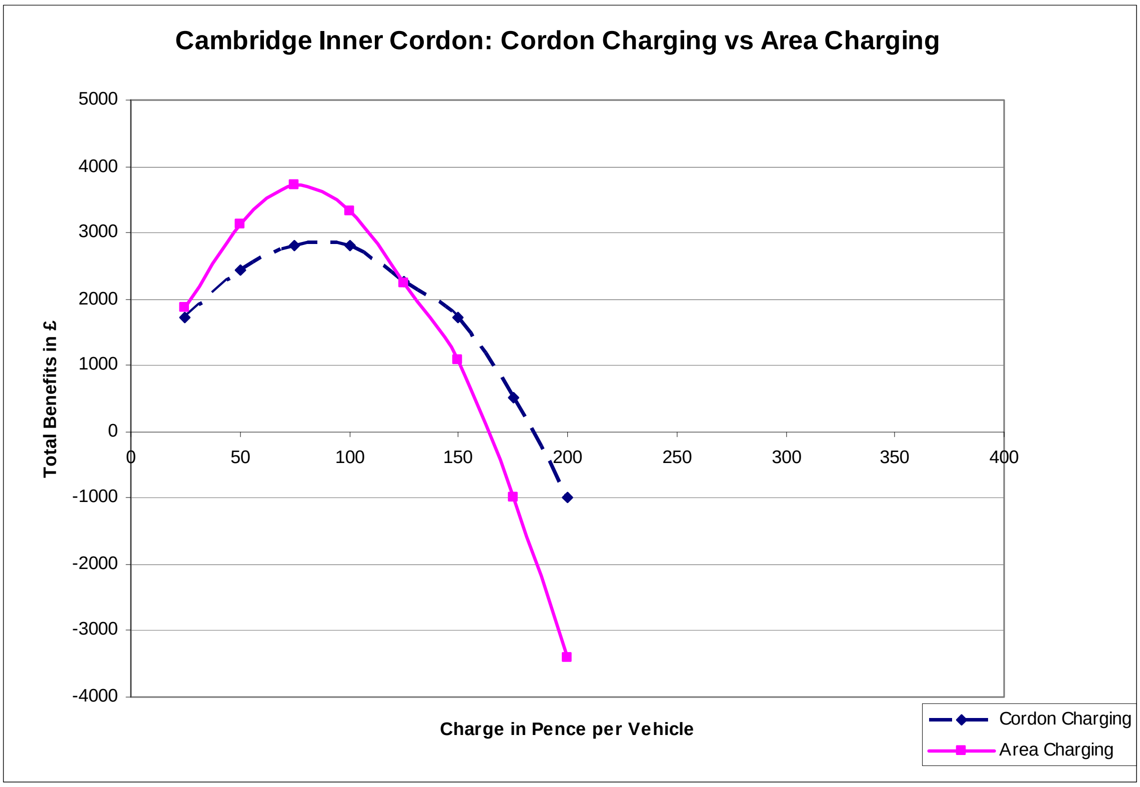

Figure 2 Inner Cordon: Total Benefits by Cordon and Area Charging Methods

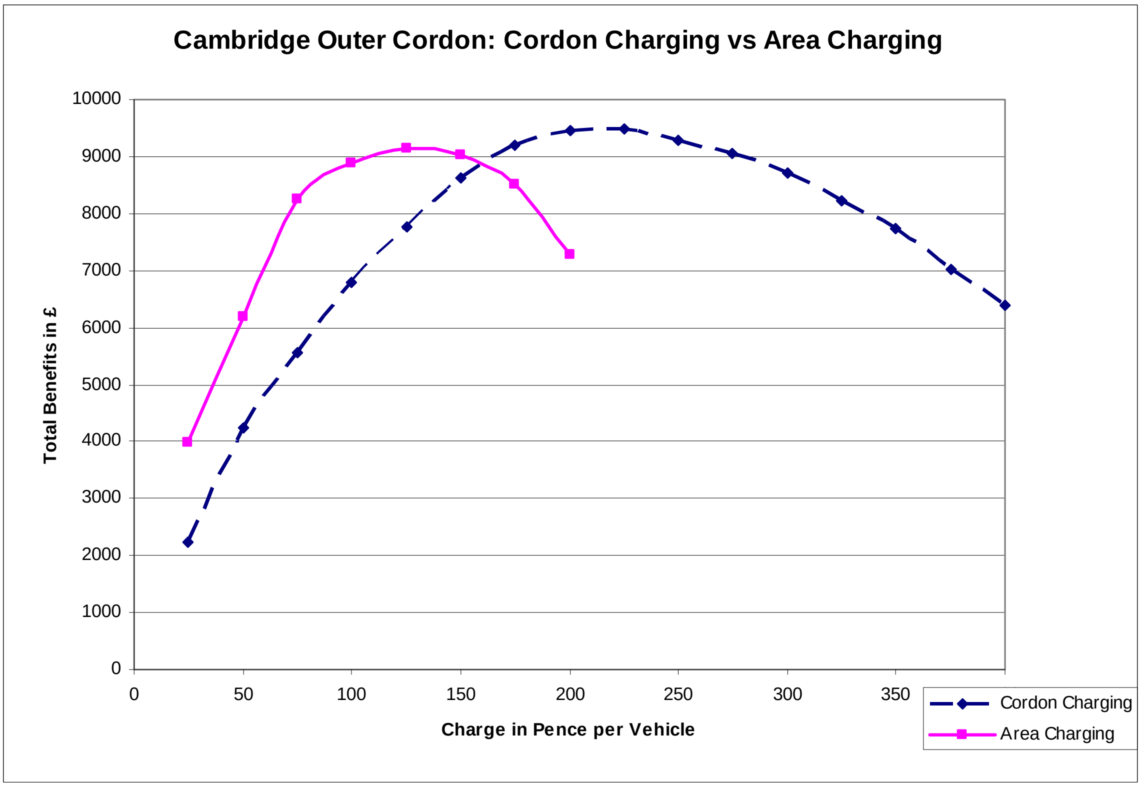

Figure 3 Outer Cordon: Total Benefits by Cordon and Area Charging Methods

Figure 3 shows that the total benefits from area charging are higher than for cordon charging for charge rates up to £1.50 with peak benefits at £1.25. Cordon charging would need significantly higher charges to achieve similar benefits. Cordon charging results in a peak benefit of £9475 at a charge rate of £2.25. As a test of charging differential rates, a one-off run of the model charging £2.25 at the cordon and 50p inside the cordoned area resulted in a benefit of £12230 (not shown in Figure 3). This result implies that differential charging may be more suitable in maximising the overall benefits from the scheme and may support the case for discounts to the residents of the cordoned area.

Optimal Benefits from Road Pricing Scheme

The analysis presented in the previous section assumes that the area-based scheme charge a similar fee for the cordon and the centroid connectors. However, there may be a case for differential charging at the cordon and within the area, based on equity considerations. In addition, it would also be interesting to see which combinations of cordon/area fee would result in highest social benefits. To do this, a charging grid has been set up in steps of 25p with area and cordon charges defining the two sides of the grid. Several model runs were conducted for each combination of charge levels and user benefits were computed, from which a surface of user benefits was generated as shown in Figure 4.

These results from the surface plot give a maximum benefit of about £12,350 with a cordon fee of £2.25 and an area charge of 75pence. This increased cordon only benefit by 30% compared to a cordon fee and area charge both set at £2.25, and clearly supports the case for discounts to the outbound trips of the residents. However, it is important to note that the present model does not apply discounts to the inbound residents and the future work needs to develop a method to identify the inbound resident trips so that appropriate discounts could be applied without the risk of charging them twice.

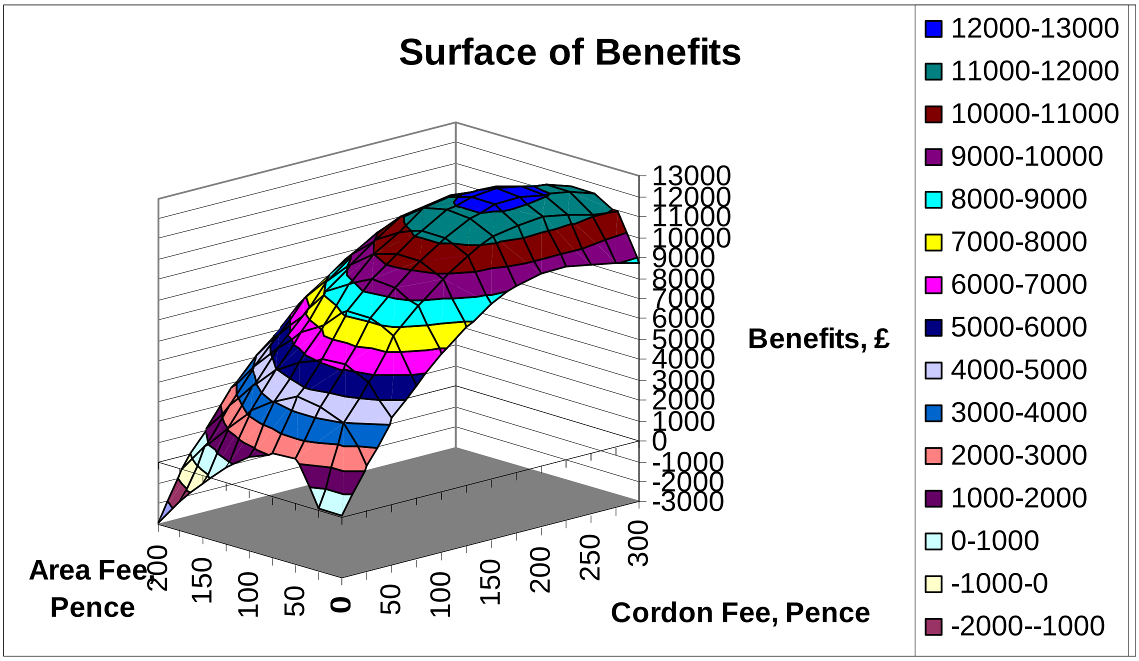

Figure 4 Surface Plot of Benefits for Cambridge-like Outer Cordon

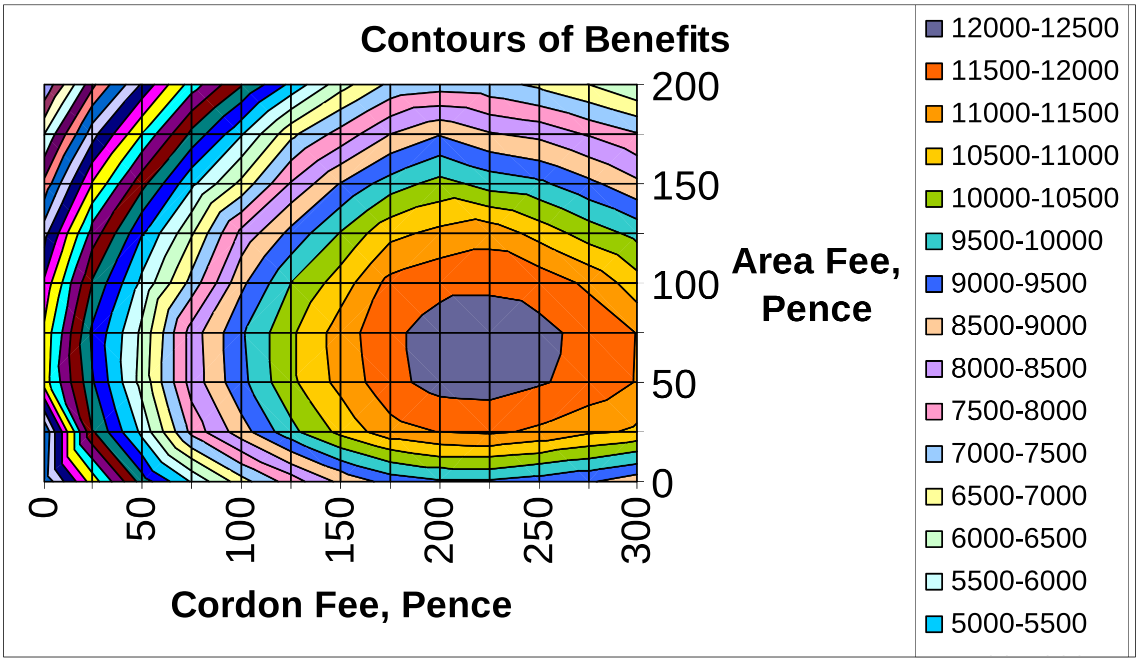

Figure 5 Contour Plot of Benefits for Cambridge-like Outer Cordon

CONCLUSIONS AND FURTHER RESEARCH

This paper has compared the efficiency of area-based and cordon-based charging schemes. The main elements of this work include (i) setting up an area-charging scheme for large real networks with a particular contribution by applying the area charge to zonal centroid connectors within the area being cordoned and (ii) investigation of the optimal benefits from the charging scheme following a grid search method. This approach has made it possible to analyse the impact of offering discounts to the outbound residents of the cordoned area and identifying an optimal fee combination for the residents and non-residents. The main conclusions from this work are listed below:

- Firstly, setting up a modelling exercise involving an area charging scheme has been made simpler in that applying the charge at the zonal centroid connector level is relatively easier compared to other potential ways of charging, for example, tracking vehicles belonging to each O-D pair.
- While the cordon-only charge method resulted in highest benefits of £9475 at a charge level of £2.25, the area-only fee produced a highest benefit of £2250 at a fee of 50p. However, a combination of cordon and area charge outperforms the cordon only and area-only charging schemes. We get the highest social benefit of £12,350 at fee levels of £2.25 and £0.75 for the cordon and area charge respectively. This result can be used to support the area charging scheme projecting the discounted fee of a third for the outbound residents compared to the non-residents, but clearly needs the analysis to extend further to include inbound resident trips.
- Generally, for smaller cordons the area fee can be equal to the cordon fee but the charge to residents may be lower than an optimal cordon only fee thus giving greater benefits with greater acceptability – due to more people paying a lower fee with greater welfare improvement. For larger cordons an improvement in

performance can be achieved by adding a small area fee to residents within the cordon – this could be seen as a discount compared to the full area fee approach.

There are a number of ways to extend the analysis presented in this paper. Firstly, an optimisation method such as that involving GA could be employed to find the optimal combination of the charge levels and cordon locations. Secondly, the equity question pertaining to the distribution of benefits amongst the population could be analysed thus leading to the identification of the area that benefits the most. With such an approach, perhaps we can design a charging scheme targeting the population from deprived areas to benefit the most from a scheme. Finally, there are modelling challenges that still need addressing, for example, how to represent the problem that an area fee that allows more than one pass through a cordon per day and also how to model the trips with multiple destinations such as a trip chain without being charged at each destination.

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REFERENCES

Eddington, Sir Rod (2006) The Eddington Transport Study, *HMSO*, London

Maruyama, T. and A.Sumalee (2007) Efficiency and equity comparison of cordon- and area-based road pricing schemes using a trip chain equilibrium model, *Transportation Research* Part A, **41**, 655-671

May, A.D. and D.S.Milne (2000) Effects of alternative road pricing schemes on network performance, *Transportation Research* Part A, **34(6)**, 407-436

Shepherd S.P. Koh, A. and May A.D., (2007) "How to design effective road pricing cordons" Proceedings of the World Conference on Transport Research, Berkeley USA

Sumalee, A. (2004) Optimal road user charging cordon design: a heuristic optimisation approach, *Computer-Aided Civil and Infrastructure Engineering*, **19,** 377-392