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MODELLING THE NETWORK EFFECTS OF ROAD USER CHARGING: RESULTS FROM A SATURN STUDY

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ABSTRACT

MILNE, D, MAY, AD, VAN VLIET, D (1994). Modelling the network effects of road user charging: results from a SATURN study. *ITS Working Paper* ***411***, Institute for Transport Studies, University of Leeds.

The aim of this research has been to investigate the modelled effects of alternative road user charging systems upon an existing road network using the congested assignment models SATURN and CONTRAM applied to the city of Cambridge.

Four road user charging systems which are being considered for practical application have been tested. These are toll cordons, time-based charging, a congestion charging system similar to that proposed in Cambridge and distance-based charging.

Tests have been conducted using current morning peak travel demand patterns both with a fixed trip matrix, to isolate rerouteing issues and using the SATURN elastic assignment program, SATEASY, in order to address the effects of charging upon the frequency, timing and distribution of trips. Network impacts have been assessed using a series global indicators, in particular effects on vehicle-km, vehicle-hours and the resulting average network speeds. In addition, results have been obtained for total delay times, cordon crossing flows and revenues generated from charging. These results are presented and their implications discussed.

KEY-WORDS:

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MODELLING THE NETWORK EFFECTS OF ROAD USER CHARGING: RESULTS FROM A SATURN STUDY

1.INTRODUCTION

This paper reports the results of a study which has been funded by the Science and Engineering Research Council and which has been carried out jointly by the Institute for Transport Studies at Leeds University and the Department of Mathematics at York University, UK. The aim of the research has been to investigate the effects of a series of proposed road user charging systems at the road network level of detail, using the existing congested assignment models SATURN and CONTRAM. Most other road pricing related modelling work has focused on the strategic distributional impacts of charging upon travel choices, allowing only a simplistic representation of transport networks. This approach provides an overview of the potential benefits of charging but fails to address the impact of alternative road user charging systems on the distribution of traffic and congestion in road networks.

The study has used Cambridge as a base for tests and the work has benefited greatly from the co-operation of Cambridgeshire County Council (CCC). Cambridge was chosen principally because it possesses a road network of appropriate size and structure for assessing the effects of charging. The urban area is sufficiently compact to be handled completely within a congested assignment network model and clear choices exist for drivers between radial and orbital routes. An existing SATURN network of Cambridge and a 1990 morning peak demand matrix, provided by CCC, have been modified to suit the needs of the project.

The use of both SATURN and CONTRAM has enabled a comparison of results from different network modelling approaches. The SATURN elastic assignment option SATEASY has allowed the broad redistributional effects of charging to be reflected without the requirement for interaction with a full strategic model. The packet based assignment of CONTRAM has facilitated a more detailed treatment of the temporal dynamics, which is particularly important for time and congestion related charging structures. This paper, however, solely describes the SATURN results.

2.MODELLING APPROACHES

Four road user charging systems which are being considered for practical application have been tested. These are:
(i)toll cordons
(ii)time related charging, as proposed in Richmond, London (EASAMS, 1991)
(iii)a congestion related charging system similar to that proposed in Cambridge (Oldridge, 1990)
(iv)distance related charging.
A detailed description of these systems has been provided elsewhere (Milne, 1993a).

Congested assignment models such as SATURN and CONTRAM estimate drivers' route choices and subsequent congestion levels in terms of "generalised cost", a combination of time and cost. In the Cambridge models as in many other applications, all vehicles are aggregated to form a single class of road user assumed to respond to average financial values for the time and cost parameters. Alternative road user charging systems may be represented in the models by modifications to the generalised cost calculations in the assignment. The fixed point charges implied by toll cordons have been represented by time penalties at the appropriate locations on the network. The three remaining variable charging systems have been modelled by applying factors to the relevant portions of the cost calculation for individual links prior to their amalgamation to produce trip route costs. Thus, time-based charging requires a factor to be calculated to be applied to travel time and distance-based charging a factor to be applied to travel distance. Further information regarding the methodology used to represent road user charging in SATURN is available elsewhere (Milne, 1993b).

The concept of congestion charging is based upon charges only being incurred in congested conditions. This has been reflected easily in the models with a factor being applied only to delay time, ie that part of total travel time which exceeds free-flow. However, such a calculation may prove difficult to replicate in reality with in-vehicle technology. The congestion metering system proposed in Cambridge relies upon a congestion threshold, expressed in terms of time taken to travel a certain unit of distance to determine whether or not a charge should be levied. The implications of this threshold may have very important impacts upon charges levied and driver behaviour, but a faithful representation of the system could only be achieved using a fully microscopic simulation modelling approach, where costs may be applied separately to individual vehicles rather than to aggregate flows.

A single charging regime has been applied within the Cambridge models for each of the four road user charging systems. The geographical extent of charging has been restricted to the main urban area of Cambridge which lies within a defined outer orbital route, allowing any trips with both origins and destinations outside the city to avoid charges completely.

The precise regimes adopted for the four charging systems have been as follows:

(i)a series of three concentric toll cordons, backed up by six screenlines to discourage rat-running. The outermost cordon falls immediately within the outer orbital route while the innermost cordon falls immediately within an inner orbital route surrounding the city centre. The third cordon falls immediately outside the inner orbital, isolating it as the most congested section of the network, but necessitating the complementary screenlines. All tolls are charged at the same level and in both directions.

(ii)a single charge area with a constant charge rate for the remaining three variable charging systems, containing the complete urban road network within the outer orbital routes.

The complex system chosen for toll cordons provides greater continuity of charging across the study area, and is hence more comparable with the other charging systems than, for example, a single cordon. More geographically complex regimes could be defined for both time and distance based charging with the charge being varied across a series of areas related to the expected congestion level. Congestion based systems, which charge only where delays occur, are inherently self regulating in this respect.

3.TEST SPECIFICATION

Tests have been conducted using current morning peak travel demand patterns, both with a fixed trip matrix, to isolate rerouteing issues, and using the SATURN elastic assignment program, SATEASY, in order to address the effects of charging upon the frequency, timing and distribution of trips.

The elastic assignment algorithm has been employed using simple constant elasticities. In addition to zero elasticity (the fixed matrix), values of -0.5 and -1.0 with respect to generalised cost have been applied (Goodwin, 1992). The analysis of network effects has focused on tests with the -0.5 elasticity value.

A wide range of charging levels has been tested for each regime. Prima facie it was not possible to identify the appropriately equivalent charging levels for the four regimes, but this has been done retrospectively by identifying those charging levels which achieved the same impact on the overall number of trips under elastic assignment.

Network effects have been assessed using a series of indicators, in particular area-wide totals for travel times, travel distances and average network speeds. Other measures which have been defined include area-wide totals for delay, cordon crossing flows and charging revenues. This paper report the results of all these indicators.

4.RESULTS

Results from the tests will be discussed in three sections as follows:-
4.1area-wide totals for travel times, distances, delays and speeds
4.2cordon crossing flows
4.3revenues from charging

4.1TRAVEL TIMES, DISTANCES, DELAYS AND SPEEDS

Results from these tests will be discussed in sequence, as follows:-
(i)impacts of the alternative charging systems upon travel demand as reflected by the SATEASY elastic assignment algorithm
(ii)network effects assuming a fixed trip matrix
(iii)network effects resulting from the modified demand patterns.
Table 1 shows aggregate network speeds separately for the charge area and outer orbital route, both for a fixed matrix and with elastic assignment (with an elasticity of -0,5). Figure 1 contains a series of graphs to illustrate the associated trends in time and distance travelled.

(i)impacts of the alternative charging systems upon travel demand

The shape of the network impact relationships shown by Figure 1 depend considerably upon the scale chosen for the horizontal axes relating to charge levels. The SATEASY elastic assignment algorithm has been used to identify charges which are equivalent in terms of their impact on total trips. The relationship between charge level and the total number of trips is not linear, as lower charge levels induce a slightly greater relative reduction. However, the relationship is very similar between charge systems. The exception is congestion charging, where low charge levels induce a greater relative trip reduction, but there is very little impact at higher charge levels. For each of the four systems charge levels have been identified which result in approximate 5, 10 and 15 per cent reductions to the total number of trips. These are illustrated in Table 2.

The charge levels resulting in a 10 per cent trip reduction have been used to construct the horizontal axes in Figure 1 and are marked by the vertical arrows in the figure.

Table 3 shows the relative reductions to trips by area suggested by elastic assignment for each of the four systems, for the 15 per cent overall reduction level. A number of clear patterns can be seen.
Table 1: Aggregate Network Speeds (kph)

System/Charge Level	Fixed Demand		Elastic Assignment	
	Outer Orbital	Charge Area	Outer Orbital	Charge Area
No Charging	79.5	27.5	79.5	27.5
Toll Cordons:				
20ppc	76.3	27.5	78.3	29.6
45ppc	71.5	26.3	76.0	30.5
100ppc	61.4	26.2	74.4	33.5
Time-Based Charging:				
5ppm	76.8	31.2	78.4	32.7
10.5ppm	73.0	33.0	77.1	35.2
21ppm	66.5	33.5	74.1	36.0
Congestion Charging:				
60ppmd	73.3	34.0	79.0	35.3
180ppmd	72.1	35.0	76.1	36.9
600ppmd	65.2	36.2	75.8	38.1
Distance Based Charging:				
10ppk	72.5	30.5	78.3	31.4
20ppk	67.5	29.8	75.3	32.0
40ppk	60.3	28.0	72.9	31.3

Key:ppc = pence per crossingppm = pence per minute
ppmd = pence per minute delayppk = pence per kilometre

Table 2: Comparison of Charge Levels to Achieve a Given Reduction in Trips

Charging System	Matrix Size Reduction		
	5%	10%	15%
Toll Cordons (pence per crossing)	20	45	100
Time Related (pence per minute)	5	10.5	21
Congestion Related (pence per minute delay)	60	180	600
Distance Related (pence per kilometre)	10	20	40

Table 3: Percentage Reductions to Trips by Area From SATEASY

Key: 1 = City Centre, 2 = Rest of City, 3 = Outside Charge Area

(i)Toll Cordons (100 pence per crossing)				(ii)Time-Based Charging (21 pence per minute)			
From/To	1	2	3	From/To	1	2	3
1	9	32	27	1	35	33	18
2	34	21	20	2	31	34	14
3	26	18	2	3	17	13	2
(iii)Congestion Charging (600 pence per minute delay)				**(iv)Distance-Based Charging (40 pence per kilometre)**			
From/To	1	2	3	From/To	1	2	3
1	33	25	14	1	25	26	20
2	34	32	12	2	26	33	17
3	20	16	2	3	20	15	2

All systems produce a similar small reduction in wholly external trips of approximately 2 per cent. As these trips account for around 10 per cent of the total matrix, the figures for the other cells are typically significantly in excess of the global 15 per cent.

The matrices for toll cordons, time-based and distance-based charging exhibit a symmetry for directionally opposed traffic, despite the fact that the morning peak trip pattern represented results in congestion predominantly on city-bound routes. By imposing charges specifically on congested traffic in the congested direction, congestion related charges may come closer than the other systems to applying the true marginal social costs of journeys, which is the basis of the economic justification for pricing.

Toll cordon charges have a particularly small impact on shorter trips both within the city centre and also between different sectors of the rest of the urban area. This is the result of the discontinuity of charging, which impacts heavily on journeys forced to cross cordons but may actually benefit other urban trips. Inspection of a more disaggregate matrix shows that some short origin-destination movements actually increase as a result of toll charging due to the extra capacity created by diverted trips. Tolls also have the greatest effect on trips from outside the charge area accessing both the city centre and the rest of the urban area.

Time and congestion related charges induce the most marked reduction in wholly internal trips, while distance based charging leads to the most even impact on all trips with an internal origin or destination. The exception to this is trips internal to outer urban area, which are affected as much by distance-based charging as under time and congestion charging. This suggests that these trips may make up a higher proportion of trip kilometres travelled within Cambridge than the other cells.

(ii)network effects assuming a fixed trip matrix

In general, the pure rerouteing responses to road user charging have been consistent with expectations. Charging has encouraged traffic to reroute onto orbital roads and away from the charge area, in order to reduce the amount of charge paid. As charge levels increase, the distance travelled within the charge area falls and that on the outer orbital route rises. The overall effect of this is to increase the total distance travelled. Referring to Figure 1, charge levels of 45 pence per crossing for toll cordons and 10.5 pence per minute for time-based charging result in an approximate 5 per cent increase in total distance travelled. Comparable charge levels of 180 pence per minute delay for congestion charging and 20 pence per kilometre for distance-based charging lead to an approximate 11 per cent increase.

The impacts of charging upon aggregate travel times and speeds are more complex and vary by charging system. All four systems produce some improvements to network conditions at low charge levels. However, for both toll cordons and distance-based charging there is evidence that network conditions may deteriorate as the charge level rises. Speeds within the charge area rise initially, but begin to fall beyond charge levels of 10 pence per crossing for toll cordons and 10 pence per kilometre for distance based charging. The diversion effects of both time and distance based charging result in the total time spent travelling on the outer orbital route increasing with charge rates to exceed that within the whole of the modelled urban road network of Cambridge. It is also these systems which have the most dramatic effect upon the outer orbital speed, indicating significant increases in delay.

Congestion charging produces the greatest increases in average network speed within the charge area (see Table 1), from 27.5 kph without charging to 35 kph at a charge level of 180 pence per minute delay. This compares with speeds of 26.3 kph for toll cordons at a charge level of 45 pence per crossing, 29.8 kph for distance-based charging at 20 pence per kilometre and 33 kph for time-based charging at 10.5 pence per minute. However, there is very little reduction to distances travelled in the city, as traffic which is displaced beyond the urban area is immediately replaced by further rerouteing within. This suggests that congestion charging, as represented and responded to in the model, may induce a gradual spatial spread of moving traffic rather than a strong incentive to avoid the designated charge areas. Above a charge level of 500 pence per minute delay total travel time and distance within the charge area actually starts to increase, such is the pressure to avoid congestion.

The impacts of charging with a fixed demand pattern upon total delay times are illustrated in Table 4. Reductions to delay time within the charge area, and particularly the city centre, relative to the uncharged situations, are produced by all four systems at all charge levels. However, for both toll cordons and distance-based charging, increasing charge levels result in increasing delays within the

Table 4: Total Delay Time by Area for the Fixed Demand

System/Charge Level	Total Delay Time (PCU Hrs/Hr)		
	Outer Orbital Route	Charge Area	City Centre
No Charging	197	1094	368
Toll Cordons:			
20ppc	285	960	331
45ppc	489	1085	309
100ppc	832	1075	225
Time-Based Charging:			
5ppm	280	624	172
10.5ppm	384	417	103
21ppm	626	370	70
Congestion Charging:			
60ppmd	289	376	116
180ppmd	417	264	64
600ppmd	701	201	47
Distance-Based Charging:			
10ppk	474	567	87
20ppk	666	578	79
40ppk	1017	719	82

Table 5: Total Delay Time by Area for Elastic Assignment

System/Charge Level	Total Delay Time (PCU Hrs/Hr)		
	Outer Orbital Route	Charge Area	City Centre
No Charging	197	1094	368
Toll Cordons:			
20ppc	239	683	236
45ppc	298	545	119
100ppc	340	282	56
Time-Based Charging:			
5ppm	238	439	118
10.5ppm	279	244	59
21ppm	370	179	31
Congestion Charging:			
60ppmd	216	243	68
180ppmd	290	133	33
600ppmd	304	68	15
Distance-Based Charging:			
10ppk	241	487	131
20ppk	323	367	66
40ppk	404	341	44

Key:ppc = pence per crossingppm = pence per minute
ppmd = pence per minute delayppk = pence per kilometre

full charge area, as the benefits gained by a low charge are eroded. This is consistent with the results for network speeds shown in Table 1. All four systems result in considerable increases to delays on the outer orbital route. A comparison of charge levels which produce an approximate 10 per cent reduction in trips in SATEASY shows that, with fixed demand, time and congestion related charges result in an approximate 100 per cent increase in delays on the outer ring, while toll cordons and distance charging result in approximate increases of 150 and 250 per cent respectively.

(iii)network effects resulting from the modified demand patterns

Taking account of the demand response impacts of road user charging results in a significant improvement to the modelled network effects, illustrated by Figure 1. In general, significantly greater reductions to travel time within the charge area are modelled, with complementary smaller increases to travel times on the outer orbital route. The overall impact suggests improvements to network conditions with charging, as benefits within the charge area more than offset the disbenefits modelled on the outer orbital. Aggregating results for the charge area and the outer orbital diversion route shows a small overall reduction to the total distance travelled of approximately 4 per cent for tolls, time and distance related charging at charge levels which reduce total trips by 10 per cent. The corresponding reduction to all travel times are 17 per cent for toll cordons, 25 per cent for time and 22 per cent for distance-based charging. Congestion charging produces no change to total distance travelled and a 22 per cent reduction to total time.

Table 1 shows that all four systems lead to significant improvements to network speeds within the charge area, with only quite small disbenefits to speeds on the outer orbital routes. The best performance in terms of speed is produced by time and congestion related charges. Time-based charging results in an increase in speed within the charge area from 27.5 kph without charging to 32.5 kph at a charge level of 10.5 pence per minute, while congestion charging produces a speed of 36.9 kph at 180 pence per minute delay. However, the latter may be partly due to encouraging traffic to use longer, faster routes to avoid junction delays. The corresponding charge area speeds resulting from toll cordons and distance-based charging are 30.5 kph at 45 pence per crossing and 32 kph at 20 pence per kilometre, respectively.

The least beneficial system in terms of speeds appears to be distance based charging which actually results in a small reduction in speeds within the charge area between medium and high charge levels, while also producing the greatest decrease in outer orbital speeds. This is undoubtably the result of distance-based charges weighing route choice in favour of the shortest routes rather than avoiding time losses in the slower areas of the network.

The trends in total delay time with road user charging and elastic assignment, shown by Table 5, are generally consistent with the results for travel times, distances and speeds. In comparison to the fixed demand situation, charging with elastic assignment leads to greater reductions in delay time within the charge area and smaller increases on the outer orbital route, for all four systems. The best performance is again achieved by congestion charging, which produces the greatest decreases to urban delays and also compares favourably to the other systems in terms of delay increases on the outer orbital. At the high charge level of 600 pence per minute delay, delays within the charge area have almost been priced to elimination.

Table 6: Cordon Crossing Flows for the Fixed Demand Matrix (PCUs/Hr)

System/Charge Level	Outer Cordon		Inner Cordon	
	Inbound	Outbound	Inbound	Outbound
No Charging	14,621	5,520	11,363	7,315
Toll Cordons:				
20ppc	13,736	4,644	9,640	5,560
45ppc	13,645	4,528	8,732	4,729
100ppc	13,664	4,542	8,158	4,291
Time-Based Charging:				
5ppm	14,334	5,256	10,298	6,260
10.5ppm	14,185	5,086	9,577	5,530
21ppm	14,385	5,226	9,008	5,043
Congestion Charging:				
60ppmd	15,051	5,943	10,231	6,297
180ppmd	15,204	5,999	9,700	5,808
600ppmd	15,496	6,237	9,467	5,561
Distance-Based Charging:				
10ppk	14,123	4,994	9,230	5,200
20ppk	14,274	5,134	8,972	4,936
40ppk	14,623	5,450	8,592	4,575

Table 7: Cordon Crossing Flows for the SATEASY Demand Matrices (PCUs/Hr)

System/Charge Level	Outer Cordon		Inner Cordon	
	Inbound	Outbound	Inbound	Outbound
No Charging	14,621	5,520	11,363	7,315
Toll Cordons:				
20ppc	12,910	4,336	8,801	5,035
45ppc	11,977	3,920	7,062	3,716
100ppc	10,890	3,550	5,541	2,741
Time-Based Charging:				
5ppm	13,759	4,986	9,652	5,782
10.5ppm	12,978	4,569	8,387	4,795
21ppm	12,189	4,346	6,861	3,674
Congestion Charging:				
60ppmd	14,074	5,424	9,594	5,973
180ppmd	13,237	5,082	8,447	5,156
600ppmd	12,022	4,680	7,076	4,272
Distance-Based Charging:				
10ppk	13,386	4,687	9,647	5,763
20ppk	12,605	4,351	8,330	4,770
40ppk	11,759	4,101	6,765	3,624

Key:ppc = pence per crossingppm = pence per minute
ppmd = pence per minute delayppk = pence per kilometre

4.2 CORDON CROSSING FLOWS

Tables 6 and 7 illustrate the impacts of the alternative charging systems and charge levels upon traffic flows across two cordons, for fixed and elastic demand patters respectively. The two cordons defined for this purpose are:

i)an outer cordon, falling immediately within the outer orbital route. This identifies all traffic entering and leaving the urban area and corresponds to the outermost cordon defined in Section 2, which has been used to define the charge area.

ii)an inner cordon, falling immediately outside the inner orbital route. This identifies all traffic entering and leaving the most congested central area of the Cambridge road network and corresponds to the intermediate cordon defined for the tolling regime.

The impacts of charging with fixed demand upon the outer cordon are quite complex. The cordon crossing flows represent the net effects of charging leading to reductions in wholly divertible traffic entering the urban area while causing increased rerouteing of urban traffic to the orbital to reduce the charge paid. The only significant reduction to cordon flows results from, tolls, which may actively discourage urban traffic from diverting to the orbital route in many instances. Three of the four systems (tolls, time and distance charging) produce some reductions to cordon crossings at low and/or medium charge levels, but show a tendency for crossings to increase as charges rise. Congestion charging produces increasing outer cordon crossings at all charge levels, supporting previous evidence that the system produces the greatest overall diversionary impact.

However, with demand response, all four systems produce reductions to outer cordon crossing flows which increase with rising charge levels. The greatest reductions result from tolling, but the magnitude of the impact is similar for all four systems.

Increasing reductions to inner cordon crossings are produced by rising charge levels for all four systems, both with and without demand response. The flow reductions are greatest for the toll cordon system for both sets of tests and are generally greater after elastic assignment. These results are consistent with expectations.

4.3REVENUE GENERATED BY CHARGING

Table 8 illustrates the revenue generated by the alternative charging systems, for different charge levels and for both fixed and elastic demand.

In general the results are as expected. Increasing charge levels produce greater revenue and the sums produced with a fixed trip matrix are greater than those with elastic assignment. In addition, the revenues resulting from elastic assignment show a significantly reduced rate of increase at high charge levels. The magnitude of revenues compares very closely for three of the four systems with fixed demand and for all systems after elastic assignment. The exception is congestion charging, which produces significantly greater totals with the fixed matrix.

The reason for this is not immediately clear, but may be explained by the fact that congestion charges are incurred during only a small portion of a journey and typically may be concentrated within limited areas of the network. Thus, a large proportion of the revenue may be provided by a small proportion of trips which travel in the most congested areas. In the morning peak one might expect these to be principally the trip travelling to the city centre. In the fixed demand case these trips are forced to travel to their destination and may have paid very high prices because, despite rerouteing, the city centre road network is not able to accommodate the full demand volume of traffic without significant congestion. Once demand response is introduced, the emphasis of congestion charging has been shown, by Table 3, to be reductions in journeys travelling inbound to the city centre and revenue levels fall to become comparable with the other systems. A further related issue is that the ratio of delay time to total travel time within the charge area for the uncharged situation is approximately 0.29, but a comparison of the relative charge levels required to produce similar reductions in trips for time and congestion related systems shows that much higher relative unit charge levels are required, when pricing congestion. This illustrates the fact that congestion related charges need to be higher to achieve a given impact on travelling, as they are affecting a small and decreasing element of journeys as charge levels rise.

One anomaly in Table 8 is that at the lowest charge level the revenue generated by distance-based charging is greater after elastic assignment. Initially this appears to be completely contrary to expectations, but is confirmed by evidence regarding total travel distances. Figure 1 shows that distance travelled within the charge area decreases more rapidly at low charge levels for the fixed matrix than under elastic assignment. This is probably caused by the interaction of time and distance as components of generalised cost which may be particularly sensitive with demand response.

Table 8: Total Revenue from Charging (£)

	Fixed Demand	Elastic Assignment
No Charging		0
Toll Cordons		
20ppc		8,131
45ppc	18,154	14,883
100ppc	37,354	26,718
Time-Based Charging		
5ppm	9,045	7,932
10.5ppm	16,530	13,411
21ppm	30,407	21,263
Congestion Charging		
60ppmd	13,532	8,749
180ppmd	28,543	14,400
600ppmd	72,203	24,311
Distance-Based Charging		
10ppk	7,982	8,300
20ppk	15,348	14,060
40ppk	29,588	22,739

Key:ppc = pence per crossingppm = pence per minute
ppmd = pence per minute delayppk = pence per kilometre

5.CONCLUSIONS

This study has used the network model SATURN to represent the network effects of four urban road user charging regimes, both with a fixed matrix and when the impacts of charging upon demand patterns are taken into account.

Under the fixed matrix, both cordon and distance-based charges achieve small increases in speed within the charge area at very low charge levels, but reduce speeds at medium and higher charges. Congestion and time-based charges perform best, producing increases in speeds in the charge area at all charge levels tested. Greater increases in speed within the charge area resulting from congestion charges are offset by larger reductions to outer orbital speed when compared with time-based charges.

With demand response, the four systems impact on demand patterns in very different ways, with cordons failing to affect short urban trips and only congestion charging focusing on the most congested routes. In general, all systems increase distance travelled by users while reducing travel time. Charges which reduce trips by 10 per cent reduce total distance travelled by 4 per cent for three systems and generate no reductions for congestion charging. The corresponding reductions in total travel times are 17 per cent for toll cordons, 22 per cent for distance and congestion charging and 25 per cent for time-based charging. The greatest benefits in terms of speeds have been found for time and congestion related charges. However, the latter may produce artificially high speeds due to a greater diversionary impact.

All four systems result in decreases to traffic accessing the central urban road network, both with and without demand response. For charge levels which reduce trips by 10 per cent and fixed demand, trips travelling into the central area in the morning peak reduce by approximately 15 per cent with time and congestion charging and 22 per cent for tolls and distance charging. After elastic assignment the figures rise to an approximate 26 per cent decrease resulting from three systems and a 38 per cent decrease with toll cordons.

The revenue generated by charging is similar for three of the four systems with fixed demand, where medium charge levels are modelled to generate around £16,500 in the morning peak for tolls, time and distance systems. Congestion charging focuses revenue collection on only a small part of most journeys, which decreases as charge levels rise, and may be concentrated in limited areas of the network. It produces a greater revenue estimate in the fixed demand situation of approximately £28,500. Once demand response is included the four systems produce very similar revenue levels, with medium charges leading to sums of around £14,000, an approximate 15 per cent reduction compared with those generated by the fixed demand.

A further SERC funded research project, about to commence, will seek to build on this work by investigating the combination of urban road user charging with a series of traffic signal strategies (Smith et al, 1993).

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