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A COMPARISON OF THE PERFORMANCE OF ALTERNATIVE ROAD PRICING SYSTEMS

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Abstract

Current developments in urban road pricing envisage four different systems for charging for road space: point or cordon charging; charging per kms travelled; charging per minute spent travelling; and charging for time spent in congestion. These will have differing impacts on demand, and will lead to differing distributions of traffic in the urban road network.

INTRODUCTION

This paper reports the results of two studies funded by the UK Engineering and Physical Sciences Research Council and related work for the US Transportation Research Board, on the performance of different methods for charging for the use of road space. Most work on road pricing has assumed that charges would be levied at points on the road network, which could be combined to form one or more cordons or screenlines (eg Dawson and Brown 1985). More recently, these charging structures have been criticised as being inflexible, inequitable in imposing the same charge on short and long journeys, and disruptive, in that they can lead to congestion on boundary routes (Oldridge 1990). In response, a number of alternative charging systems have been developed. The studies reported here have considered four charging systems: point or cordon charging; charges related to time spent in an area; charges related to distance travelled in an area; and charges related to time spent in congestion.

THE POTENTIAL OF DIFFERENT CHARGING SYSTEMS

Types of charging system

Virtually all of the studies reported above have assumed that road pricing would operate by imposing charges at points in the road, which could be combined to form cordons or screenlines. This can be done in a simple way, with a single cordon and charging in one direction, as in Singapore (Holland and Watson 1978) and, more recently, in the Norwegian toll rings (Larsen 1988). It is, however, also possible to have a complex series of screenlines and cordons, with charges varying by direction and time of day. The desk studies for Hong Kong included one system with 180 charging points dividing the area into 17 zones and with five different charging periods (Dawson and Brown 1985).

Even such complex structures have been criticised. It has been argued that they are inflexible, since the fixed charging points cannot readily be relocated if conditions change. It has been suggested that they are inequitable, in imposing the same charge on long and short journeys. It is also claimed that they can be disruptive, by adding to congestion on the boundary routes immediately outside the cordon (Oldridge 1990). A recent study in London has also shown that the performance of such systems is very sensitive to the detailed design of the cordon locations and the relative charging levels (DoT 1995).

In response to these criticisms, three other approaches have been developed:

- charges based on time spent travelling;
- charges based on time spent in congestion;
- charges based on distance travelled.

Time-based charging and congestion-based charging have been advocated as being related most directly to vehicles' contributions to congestion; they also avoid the boundary problems of cordon charging. The Cambridge proposal is a particular form of the latter, in which drivers would incur a pre-specified charge every time they took more than a threshold time (provisionally three minutes) to travel a half kilometre. The major concerns with both of these are that the charges would be unpredictable, and that they would encourage unsafe driving. Distance charging would avoid these difficulties, while still overcoming the problems with cordon charging, and is superficially the most attractive method.

The technology for these four charging methods has been reviewed fully elsewhere (Hills et al. 1993). The principal requirements are an in-vehicle unit, a payment and accounting system, a roadside to vehicle communications system, a means of detecting and classifying vehicles and a system for uniquely recording non-compliant vehicles. Cordon pricing can be implemented using a range of in-vehicle unit technologies, some of which are currently available. The other systems require in-vehicle meters, which are still being developed and for which there remain very real technical difficulties. The most serious limitation currently with all systems is enforcement technology, which is likely to be video based, but will be limited to a practical maximum of around 85% by the obscuration of number plates by adjacent vehicles.

The review for TRB

A review recently completed for the US Transportation Research Board (May 1994) used the limited evidence already available to assess the potential of these four charging systems to achieve benefits in terms of congestion relief and environmental protection. It also considered their performance against a range of criteria initially developed by Smeed (MoT 1964) and subsequently extended (May 1992) drawing on a review of technology recently completed for the London Congestion Charging Study (Hills et al. 1993).

These criteria are:

1. charges should be closely related to the amount of use made of the roads;
2. it should be possible to vary prices for different areas, times of day, week or year and classes of vehicle;
3. prices should be stable and readily ascertainable by road users before they embark upon a journey;
4. payment in advance should be possible although credit facilities may also be permissible;
5. the incidence of the system upon individual road users should be accepted as fair;
6. the method should be simple for road users to understand;
7. any equipment should possess a high degree of reliability;
8. it should be reasonably free from the possibility of fraud and evasion, both deliberate and unintentional;
9. it should be capable of being applied, if necessary, to the whole country and to a vehicle population expected to rise to over 30 million in the UK;
10. the system should allow occasional users and visitors to be equipped rapidly and at low cost;
11. the charge recording system should be designed both to protect individual users' privacy and to enable them to check the balance in their account and the validity of the charges levied; and
12. the system should facilitate integration with other technologies, and particularly those associated with driver information systems.

Distance-based charges were judged to perform well against the twelve operational criteria; their main drawbacks are in terms of enforcement and the ease with which the technology can be tampered with; perceived fairness, in common with all road pricing systems; and ability to equip visitors.

Point or cordon pricing also performs well. It is easier to enforce and more appropriate for visitors than distance-based pricing, but is less directly related to road use; may as a result be perceived as less fair; and is less able to be integrated with other technologies.

Time-based and congestion-specific pricing perform less well. Their major weakness is the lack of predictability of the charges levied, which in turn results in perceived unfairness and difficulties in use.

Overall, it appeared from the review that point or cordon-based and distance-based congestion pricing systems were likely to perform best against the operational criteria and to approach the theoretical optimum in terms of achievable benefits.

THE ASSESSMENT OF NETWORK EFFECTS

The modelling context

Most strategic studies of road pricing have omitted a detailed assessment of the impacts of charging on traffic distribution on road networks. These impacts may expected conceptually to be very different for different charging systems. This issue has been investigated during two studies funded by the UK Engineering and Physical Sciences Research Council and carried out jointly by the Institute for Transport Studies at Leeds University and the Department of Mathematics at York University. The first study has considered the effects of a series of proposed road user charging systems on real urban road networks, using the congested assignment models SATURN and CONTRAM (van Vliet 1982; Taylor 1990). The second study has extended this work to explore the interaction of charging with a number of traffic signal optimization strategies. Results will be discussed in turn, those from the second study being presented later.

The use of two existing traffic network models has enabled a comparison of results from different modelling approaches. SATURN assigns a matrix uniformly for a single time period, achieves equilibrium between simulated network conditions and assignment paths, and is able to represent large urban networks in detail. In addition, the elastic assignment option, SATEASY, allows the broad redistributional effects of charging on travel demand to be reflected without the requirement for interaction with a full strategic model. By contrast, CONTRAM assigns "packets" of vehicles in turn and is thus better able to represent time-dependent conditions.

Modifications have been required to the two models to enable them to reflect the four alternative charging systems. SATURN and CONTRAM estimate drivers' route choices and subsequent congestion levels in terms of "generalised cost", a combination of time and cost. Charging has been implemented through amendments to these generalised cost calculations. The fixed point charges implied by cordons have been represented by time penalties at the appropriate locations on the network. The three 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. The calculation of delay-based charges in the model has been achieved by a factor being applied only to delay time, ie that part of total travel time which exceeds free-flow. This interpretation differs from the congestion metering system proposed in Cambridge (see above). The modelled system imposes charges which are more closely related to congestion on the network, but would prove difficult to replicate in reality with in-vehicle technology. The thresholds inherent in the Cambridge system may have important impacts upon charges levied and driver behaviour, but a faithful representation could only be achieved using a fully microscopic simulation model.

Two principal study locations have been used, Cambridge and York. Both cities possess road networks of appropriate size for analysis, with suitably congested orbital and radial routes. Cambridgeshire County Council and York City Council have had a significant interest in our research and have made their existing SATURN networks and matrices available.

Network effects have been tested under two different assumptions. First, it has been assumed, for both SATURN and CONTRAM, that travel demand patterns remain fixed, so that results reflect solely the rerouteing impacts of charging. Secondly, the SATEASY elastic assignment algorithm has been used with SATURN to represent other responses through a simple cost-demand relationship. For simplicity, an elasticity of -0.5 with respect to generalised cost has been used for most tests. No elastic assignment tests have been conducted with CONTRAM.

A single charging regime has been applied for each of the four systems. Charging has been restricted to the main urban area of the city, which lies within a defined orbital route, allowing any trips with both origins and destinations outside the city to avoid charges completely. For time, distance and congestion related charging, a single charge area with a constant charge rate was assumed, covering the complete urban area within the orbital route. For cordon charges, the SATURN tests imposed a series of three concentric cordons and six screenlines. This provided continuity of charging across thè study area and thus aids comparison with the other systems. For CONTRAM, a single cordon was used, located inside the outer orbital route.

Tests have been conducted using current morning peak travel demand patterns. During the first study traffic signal settings remained fixed to their existing plans, regardless of changing flows on the network. For the combination of pricing and signal control, two demand profiles were considered. The basic demand profile is a one-hour inelastic rectangular demand derived from a SATURN model of York. To consider more realistic demand profiles we spread this over five 20-minute time slices, increased the demand rate in the middle time-slice, and reduced the demand rate in the two outer time-slices. We tested delay-based charging with (i) fixed signal settings, (ii) a natural equisaturation policy and (iii) the P0 policy introduced by Smith (1979).

Study results with fixed signal settings

Results from the tests are most appropriately discussed in three stages, as follows:

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

(ii) network effects assuming fixed travel demand patterns;

(iii) network effects with demand response.

Impacts of the alternative charging systems upon travel demand

The relationships between charge level and total number of trips, obtained from SATEASY with an elasticity of -0.5, are given in Table 1.

Three of the charging systems exhibit similar relationships, with the charge required to achieve a 15 per cent reduction being approximately four times that required to achieve a 5 per cent reduction. However, for congestion charging, the relationship increases more rapidly, since charging applies solely to those parts of trips experiencing congestion. These 'low' 'medium' and 'high' charge levels have been used below to compare the impacts of the different charging systems on network performance.

Table 1 Comparison of charge levels to achieve a given reduction in trips

Charging system (units)	Location	Matrix Size Reduction		
		5%	10%	15%
Cordons (pence per crossing)	Cambridge	0	45	100
	York	9	20	35
Distance (pence per kilometre)	Cambridge	10	20	40
	York	3.9	8.3	14.2
Time (pence per minute)	Cambridge	5	10.5	21
	York	2.3	5	8
Congestion (pence per minute delay)	Cambridge	60	180	600
	York	18	50	100

If the impact of charging on travel demand is further broken down by area, a number of significant differences emerge between the four systems. Table 2 illustrates these differences for Cambridge, for the charge levels which produce a 15 per cent overall reduction in trips.

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 total demand, the figures for the other cells are typically significantly in excess of the global 15 per cent.

The matrices for 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. However, congestion charging has a markedly greater impact on inbound travel. 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.

Table 2 Percentage reductions to trips by area for Cambridge

(i) 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

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

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 encourage other urban trips. Inspection of a more disaggregate matrix shows that some short origin-destination movements actually increase as a result of cordon charging due to the extra capacity created by diverted trips. Cordon charges 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 the 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.

Network effects assuming fixed travel demand patterns

In general, the pure rerouteing responses to charging have been consistent with expectations. Traffic has been encouraged to reroute onto orbital roads and away from the charged area, in order to reduce the amount of charge paid, but this has increased the total distance travelled. For Cambridge, at medium charge levels, cordons and time-based charging result in an approximate 5 per cent increase in total distance travelled, while distance and congestion related systems produce an approximate 11 per cent increase. Total travel times and distances decrease within the charged area but increase on the outer orbital route. While speeds improve, the overall impact is a disbenefit to network conditions for all systems at all but the lowest charge levels, with travel time improvements in the charged area being offset by large delays outside.

Tables 3 and 4 show the resulting impacts on speeds for Cambridge and York, for the charge area and the outer orbital route separately. Cordon charges produce falling speeds for both the charge area and the outer orbital in both cities. Distance-based charges result in a small increase in speed within the charge area in Cambridge at low charge levels, but this is not maintained as the charge level rises. No similar increase is found in York and the speed on the outer orbital falls significantly in both cities. Time and congestion related charging produce consistent increases to speed in the charge area in both cities. In Cambridge this is achieved alongside generally smaller reductions to speed on the outer orbital. In York, the speed reductions on the outer orbital are greater than for cordon and distance-based charging, especially in the case of congestion-related charges. This effect may be the result of a lack of any route choice beyond the outer orbital route in the York SATURN model.

Table 3 Percentage change from base in average network speeds with fixed travel demand: Cambridge

Charge Level*		Low	Medium	High
Charging system	Area			
Cordons	charge area	0	-4.1	-4.7
	outer orbital	-4.0	-10.1	-22.8
Distance	charge area	10.9	8.4	1.8
	outer orbital	-8.8	-15.1	-24.2
Time	charge area	13.5	20.0	21.8
	outer orbital	-3.4	-8.2	-16.4
Congestion	charge area	23.6	27.3	31.6
	outer orbital	-7.8	-9.3	-18.0

*See Table 1

Table 4 Percentage change from base in average network speeds with fixed travel demand: York

Charge Level*		Low	Medium	High
Charging system	Area			
Cordons	charge area	-3.1	-5.8	-8.5
	outer orbital	-2.3	-4.1	-7.6
Distance	charge area	-1.9	0	-3.1
	outer orbital	-4.4	-10.3	-14.5
Time	charge area	3.9	10.4	11.2
	outer orbital	-10.4	-16.4	-22.4
Congestion	charge area	18.5	26.3	27.4
	outer orbital	-32.7	-50.4	-61.5

*See Table 1

Network effects with demand response

The network performance of road user charging improves considerably once the impact of charging upon demand is included. The overall impact suggests improvements to network conditions with charging, as benefits within the charge area now more than offset the disbenefits modelled on the outer orbital. All systems would be expected to increase the distance travelled by individual drivers while reducing their travel time. For Cambridge, with an elasticity of -0.5 at medium charge levels, a 10 per cent reduction in total journeys is associated with a 4 per cent reduction in the total distance travelled for cordons, distance and time-related charges and no reduction for congestion related charging. Corresponding reductions for travel time are 17 per cent for cordons, 22 per cent for distance and congestion and 25 per cent for time. Tables 5 and 6 show the impacts on speeds for both cities.

All systems increase speeds within the charge area and produce greater increases than under the assumption of fixed travel demand. The greatest increases to speeds within the charge area are produced by time and congestion-related charges in both Cambridge and York. Given the greater distance travelled per trip for congestion charging, speed benefits may be due in part to encouraging traffic to use longer, faster routes to avoid junction delays. The least beneficial system in terms of speed appears to be distance-based charging, which actually results in a small reduction in speed within the charge area in Cambridge between the medium and high charge levels. This is undoubtedly the result of distance-related charges favouring the shortest routes as charge levels rise, even where these are more congested. All systems reduce speeds on the outer orbital, but to a significantly lesser extent than with the constraint of fixed demand. In particular, the speed reductions on the outer orbital resulting from time and congestion related charging are smaller than for the other systems in Cambridge, and the specific problem identified for congestion-related charging under fixed demand in York is avoided.

Table 5 Percentage change from base in average network speeds with demand response: Cambridge

Charge Level*		Low	Medium	High
Charging system	Area			
Cordons	charge area	7.6	10.9	21.8
	outer orbital	-1.5	-4.4	-6.4
Distance	charge area	14.2	16.4	13.8
	outer orbital	-1.5	-5.3	-8.3
Time	charge area	18.9	28.0	30.9
	outer orbital	-1.4	-3.0	-6.8
Congestion	charge area	28.4	34.2	38.5
	outer orbital	=0.6	4.3	-4.7

*See Table 1

Table 6 Percentage change from base in average network speeds with demand response: York

Charge Level*		Low	Medium	High
Charging system	Area			
Cordons	charge area	1.2	0.8	1.9
	outer orbital	-0.4	-0.1	-1.2
Distance	charge area	4.3	3.1	5.8
	outer orbital	-3.0	-4.1	-3.8
Time	charge area	9.7	18.3	26.1
	outer orbital	-2.8	-5.7	-7.1
Congestion	charge area	23.3	35.8	41.6
	outer orbital	-3.2	-9.1	-10.3

*See Table 1

Overall, time-based and congestion-based charging perform significantly better than cordons and distance-based charging. In Cambridge they achieve almost double the improvement in speed; in York they are five to ten times as effective.

THE COMBINED EFFECTS OF CHARGING AND SIGNAL CONTROL

Comparisons of charging structures with signals fixed

While the second EPSRC study concentrated primarily on combinations of charging and signal control, it initially checked on the results of the earlier study. Figure 1 shows the results for the rectangular demand profile. It confirms that delay-based charging gives the lowest travel time on the whole network, although the two-way cordon produces excellent results for low charge rates. Figure 2 presents similar results for the bell-shaped demand profile. It confirms the superiority of delay-based charging, but here the percentage gains are much less. It also suggests that time-based charging is nearly as good as delay-based charging.

Comparisons of signal control strategies with delay-based charging

Following these results, further testing concentrated on delay-based charging. Figure 3, with rectangular demand, suggests that, of our three alternatives, control policy P_0 is likely to give the best result, for the whole network, at all charge levels. P_0, combined with delay-based charging, achieves almost a 25% reduction in total journey time at the optimum charge level, as compared to around 10% for fixed signal controls. In Figure 4, with the bell-shaped profile, P_0 gives the best results for all except one charge level. However the percentage gains are less with the bell-shaped demand. The results are generally much more variable throughout the range. P_0, with delay-based charging, achieves around a 13% reduction in total journey time at the optimal charging level, as compared to around 7% for fixed signal controls. The differences between the two demand profiles suggest that absolute results need to be treated with caution. However, both results confirm the superiority of P_0 combined with delay-based charging.

CHARGING RESULTS WITH SIGNAL CONTROLS FIXED

(Here "TOLLS" refers to "CORDON" charging)

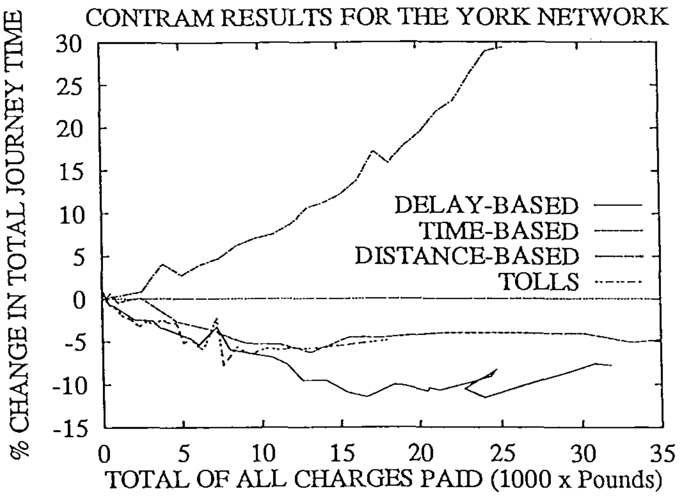

Figure 1 **Charging results with signal controls fixed: Total travel time on the whole network: original rectangular demand**

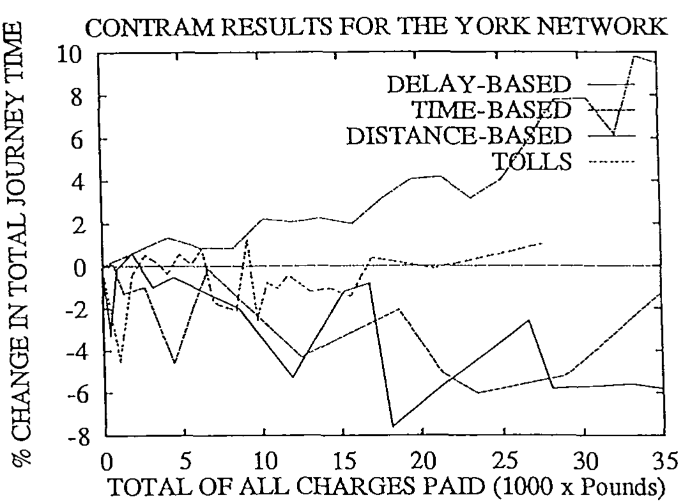

Figure 2 **Charging results with signal controls fixed: Total travel time on the whole network: bell-shaped demand**

CHARGING/CONTROL RESULTS

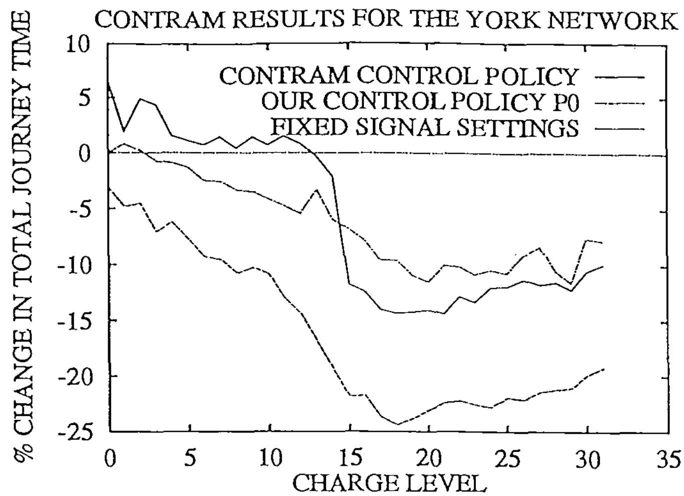

Figure 3 **Charging/control results: Total travel time on the whole network: original rectangular demand**

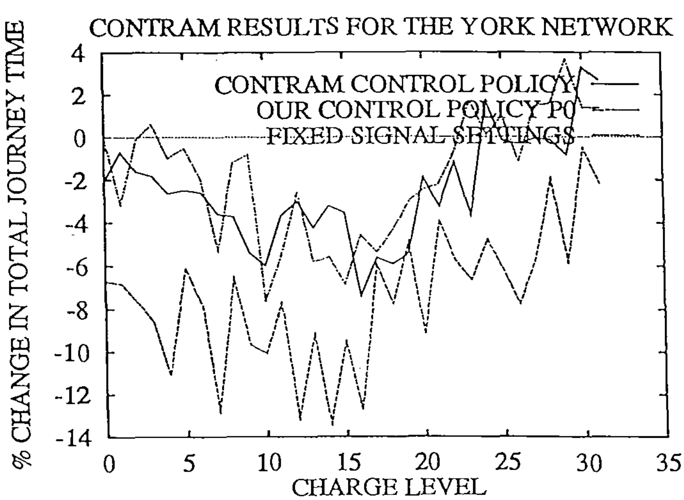

Figure 4 **Charging/control results: Total travel time on the whole network: bell-shaped demand**

CONCLUSIONS

As in many developed countries, there has been a resurgence of interest in the UK in road pricing. While earlier studies assumed that cordon charging would be used, the possibility now exists for charging directly in relation to distance travelled, time spent, or time spent in congestion. A study for the US Transportation Research Board assessed these against Smeed's criteria for the design of road pricing systems, and concluded that cordon pricing and distance-based pricing would be more effective, since they would ensure that drivers knew the charge level in advance, and avoid any encouragement of unsafe driving to reduce the charge paid.

However, subsequent research has shown that, provided that drivers respond in the same way to a given charge levied by any of the systems, charging for time, and for time spent in congestion, are likely to be at least twice as effective as cordon and distance-based charging in reducing congestion. The reason for this is clear: these two systems, and particularly congestion charging, charge directly for the problem being caused. Further research into drivers' response to real-time charging systems is thus urgently needed and has recently been initiated (May et al. 1995).

Subsequent research has shown that congestion charging can achieve even greater benefits when combined with the natural signal control algorithm, P0. Results presented here suggest that this combination could roughly double the travel time savings achieved by congestion charging and fixed signal settings, even without any reduction in total travel. This result arises because the signal settings are able to reinforce the rerouteing effects of charging. This offers a possible way of making road pricing more acceptable, since it should be possible to achieve the same benefits at much lower charge levels, and with less need to reduce overall car use.

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