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ABSTRACT

In this paper the environmental benefits of optimal tolls in eight English towns are estimated. Tolls are simulated using the SATURN model (Simulation and Assignment of Traffic to Urban Road Networks) with associated software to simulate the changes in traffic patterns resulting from cordon tolls. With these results the optimal tolls are computed together with the resulting levels and speeds of traffic in each of our study towns. Changes in vehicle emissions are estimated and reduction in health and global warming costs computed. One of the main results is that any toll designed to reduce traffic congestion would yield positive environmental benefits.

The environmental benefits from road pricing

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Introduction

The British Government has recently decided to allow Local Authorities to levy road charges on vehicles using congested urban centres (House of Commons, 1999) with the incentive that the resulting revenues can be retained by the Authority for dedicated local transport expenditure. In the past the Government has in part justified road taxes as "green taxes", designed to reflect the social costs of damaging emissions, though there appears to be a major mismatch between the tax levels and the amounts that could be justified on environmental grounds (Newbery, 1998). Nevertheless, road transport is responsible for damaging emissions that impact various aspects of human life. The traditional 'polluter pays principle' and the Pigouvian tax approach have encouraged economists to estimate the marginal social costs of transport emissions and hence to identify the optimal corrective "green tax". There are obvious and well-recognised problems of the large measure of uncertainty attached to the estimates and the difficulty of devising a fair, efficient and non-discriminatory system of such taxes, not just on road transport but other politically more sensitive sectors, such as domestic heating.

This paper is addressed to a related but rather different problem. Suppose that a Local Authority chose a system of road pricing to allocate scarce road space efficiently (leaving on one side the temptation such Authorities might have in just using their powers to raise additional tax revenue). In setting the road prices they are almost certain to ignore the environmental consequences of the consequential changes in traffic flows. In this paper we estimate the environmental benefits that would flow from (second-best) optimal congestion tolls.

The most likely choice of road prices in the near future would be cordon tolls, where vehicles are charged for crossing a cordon during certain hours, regardless of their subsequent use of road space within the cordoned area. They have already been tested in Singapore, Oslo, Trondheim and Bergen. Although they do not perfectly reflect the marginal social cost of travelling within the congested area, they are cheaper to install and operate than more sophisticated

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alternatives, easier for the public to understand, and likely to yield higher net benefits than other systems.

Tolls are simulated using the SATURN model (Simulation and Assignment of Traffic to Urban Road Networks), with associated software to simulate the changes in traffic flows resulting from cordon tolls. This allows us to compute the best level for the cordon toll and the resulting levels and speeds of traffic in each of our study towns. We then compute the impact of the change in vehicle emissions on health and global warming for eight towns in England, and estimate their monetary value.

The SATTAX model

SATTAX[1] is a batch file procedure developed at the Institute for Transport Studies at University of Leeds that can be added to SATURN in order to simulate traffic responses to road charging (Milne and Van Vliet, 1993). The program uses the SATURN elastic assignment algorithm, SATEASY to model the response of traffic demand to changes in total trip costs caused by the toll and the associated changes in congestion and hence other travel cost elements. SATURN estimates the 'generalised trip costs', which are the sum of the time cost and the vehicle operating cost of a trip (Van Vliet and Hall, 1997). The generalised cost in pence/pcu (passenger car unit) to travel from origin zone i to destination zone j, GC_{ij}, is given by:

$$GC_{ij} = VOT * time_{ij} + VOC * dist_{ij}$$

where VOT is value of time in pence/pcu-min, $time_{ij}$ is the time taken to complete the trip in minutes, VOC is vehicle operating cost in pence/pcu-km, and $dist_{ij}$ is the distance travelled in km. Time and distance vary according to the route chosen, but in equilibrium no trip-maker can reduce GC_{ij}.

The model has two modes of response: route choice and transfer off the road. Transfer off the road captures:

- Change of departure time to a later or earlier the time period
- Change of mode
- Car pooling, sometimes treated as a change of mode: i.e. from driver to passenger
- Cancellation of some trips, equivalent to a change in trip frequency, given that we are looking at the long-run equilibrium, not the impact on a particular day.

Cordon tolls

Toll cordons are the simplest form of road user charging, probably the cheapest, and have been demonstrated to be feasible in various cities (Milne and Van Vliet, 1993). A fixed toll is levied at specific points on the road network and drivers have to pay

[1] 'SATTAX' is an acronym that follows the same rule as most SATURN batch files that involve running the program. It starts with the 'SAT' prefix, for SATURN, and 'TAX' simply refers to charging.

if they want to travel within the charged area. In the towns studied here, we defined the charged area as the city centre of the town, sometimes delimited by the inner ring road, sometimes by our judgement of the most congested area in that particular town.

Estimating the Optimal toll

We assume a constant elasticity inverse demand function for trips:

$$P(Q) = P_0 * \left(\frac{Q}{Q_0} \right)^{1/\rho}$$

with the elasticity defined as a positive number: $\eta = -\rho$. As there is some uncertainty about the correct (longer-run) value, we span the plausible range with three different demand elasticities: 0.2, 0.4 and 0.7. SATTAX was run for different levels of charges ranging from £0.25 in steps of £0.25 to £5 at intervals of £0.25 to identify the best value for eight English towns: Cambridge, Northampton, Kingston upon Hull, Lincoln, Hereford, Bedford, Norwich and York. The model was run during the morning peak (8.00 to 9.00 am). The optimal toll, defined as the toll for which the social surplus (the difference between the sum of individual utilities[2] of making trips *minus* the sum of individual costs[3]) is maximised, was computed (Santos, Rojey and Newbery, 2000). At this stage environmental externalities do not enter in the cost calculations and are thus ignored.

Methodology

The evaluation of emissions was based on the methodology described in Chapter 7 of the EMIP/CORINAIR Atmospheric Emission Inventory Guidebook (European Environment Agency, 1999). The emissions factors were obtained by applying these formulae to the average speed obtained from SATURN for each trip defined by its origin and destination.

To apply these formulae data on the age distribution of vehicles and the power distribution of the engines is necessary. National averages were used for all towns. The age distribution was derived from Table 5.6 of the National Travel Survey 1993/1995 (Department of the Environment, Transport and the Regions, DETR, 1996). The proportion of vehicles belonging to each European class was deduced from the age of the vehicles. The power distribution was derived from Table 3.3 of the Transport Statistics Great Britain (DETR, 1998) for each period of time. As only a small proportion of vehicles belonged to the classes PRE ECE,

[2] Individual utility is defined as the area under the inverse demand curve. This was calculated for each toll and origin-destination pair *ij*.

[3] Individual costs are unit costs or costs per pcu. They include both private and social costs:

$$c_{ij} = VOT * time_{ij} + (VOC - VAT - duty) * dist_{ij}$$

They vary with the trip *ij*. The values we use for the morning peak are the same for all towns: VOT=23.4 pence per puc-minute, VOC=11.7 pence per pcu-kilometre, VAT=0.82 pence per pcu-kilometre, duty=4.29 pence per pcu-kilometre. They are all averages at 1998 prices.

ECE 15-00, ECE 15-01 and ECE 15-02, these were all considered to be ECE 15-03 vehicles. The percentage shares used are presented in Table 1.

Table 1: Percentage breakdown of norms and engines of vehicles in England

Cylinder Capacity	Vehicle class			
	ECE 15-03	ECE 15-04	91/441/EEC	94/12/EEC
<1400	1.8	10.8	16.7	9.1
1400-2000	1.8	12.3	24.8	14.8
>2000	0.3	2.0	3.6	2.1

Source: Table 5.6 DETR (1996) and Table 3.3 DETR (1998)

The proportions of vehicles types presented in Table 2 are the ones we assumed to hold in each town. They are based on monitoring of traffic flows on the Cambridge radial cordon in 1998.

Table 2: Traffic composition

Vehicle type	Share (%)
Gasoline car	70
Diesel car	15
Light good vehicles	9
Heavy good vehicles	3

Source: Cambridgeshire County Council (2000)

Buses represent only a small proportion of the total. The introduction of the toll would probably lead to an increase in the use of public transport. SATURN however does not model this effect and therefore buses were not taken into account in the analysis. Motorcycles were not included either as their emissions were considered to be negligible.

Cold-start emissions were calculated using the average distance driven in each town before the introduction of the toll and a temperature of 4.7°C, which is the average minimum temperature recorded by Caldecott Weather Station (near Cambridge) between 1961 and 1990 (Meteorological Office, at their web site http://www.met-office.gov.uk/ukclimate/stationaverages/Cald18.html).

Results

Using the method described above, we estimated emissions of eight pollutants for each town and each level of toll. The pollutants we considered are carbon dioxide (CO_2), carbon monoxide (CO), volatile organic compounds (VOC), nitrogen oxide (NO_x), particulate matter (PM), methane (CH_4), nitrous oxide (N_2O) and amonia (CH_3). As an example, we present the emissions (kilograms of pollutant) for Cambridge when the point elasticity of the number of trips with respect to the cost of the trip was assumed to be 0.4 at the actual level of traffic. Emissions were found to vary with the level of tolls introduced. The results are reported on Figure 1. Tolls in £/pcu are shown on the *x*-axes, and the *y*-axes are truncated.

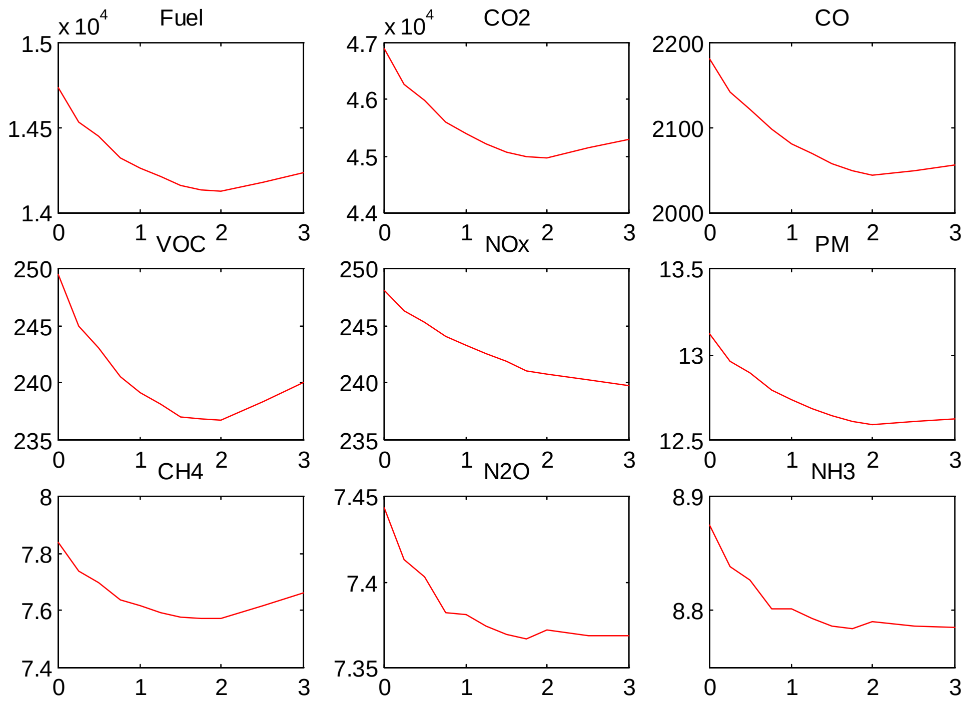

Figure 1: Reduction of emissions for each pollutant at different levels of tolls
Source: Own calculations done with SATTAX outputs and European Environment Agency (2000) and Meteorological Office data. x-axis is the toll in £/pcu.

The curves are all different because the relationship between speed and emissions differs for each pollutant. The reduction in emissions of each pollutant that would be achieved after implementing the optimal toll are presented in Table 3.

Table 3: Reduction in emissions at the optimal level of toll (%)

Town	Elasticity	Optimal toll (£ to cross the cordon)	Fuel Consumption	Emissions							
				CO_2	CO	VOC	NO_x	PM	CH_4	N_2O	NH_3
Cambridge	0.2	0.75	-1.4	-1.4	-2.3	-1.8	-1.0	-1.4	-1.1	-0.3	-0.3
	0.4	1	-3.2	-3.2	-4.6	-4.1	-1.9	-2.9	-2.8	-0.8	-0.8
	0.7	1.5	-5.7	-7.7	-7.7	-7.2	-3.4	-5.1	-5.2	-1.9	-1.9
Northampton	0.2	3	-1.6	-1.6	-3.3	-2.6	-1.6	-1.7	-0.5	-0.5	-0.5
	0.4	3	-3.2	-3.2	-5.2	-4.4	-2.7	-3.2	-2.0	-1.5	-1.5
	0.7	3.5	-5.9	-5.9	-8.6	-7.6	-4.6	-5.7	-4.3	-2.7	-2.7
Kingston upon Hull	0.2	2.5	-4.6	-4.6	-5.7	-5.6	-2.5	-4.1	-4.3	-1.6	-1.6
	0.4	3	-7.2	-7.2	-8.9	-8.7	-4.2	-6.5	-6.9	-3.0	-3.0
	0.7	3.5	-9.7	-9.7	-11.6	-11.5	-6.0	-8.8	-9.5	-4.8	-4.8
Hereford	0.2	3.5	-10.4	-10.4	-14.5	-13.6	-4.3	-8.9	-9.7	-1.5	-1.5
	0.4	1.75	-11.6	-11.6	-15.6	-14.7	-5.3	-10.0	-10.9	-2.6	-2.6
	0.7	1.5	-14.2	-14.2	-18.2	-17.4	-7.5	-12.5	-13.6	-4.8	-4.8
Lincoln	0.2	0.25	-4.0	-4.0	-5.3	-4.6	-3.4	-3.9	-3.3	-2.6	-2.6
	0.4	0.5	-2.0	-2.0	-3.0	-2.5	-1.8	-2.0	-1.6	-1.2	-1.2
	0.7	1	-2.7	-2.7	-3.7	-3.3	-2.1	-2.6	-2.3	-1.4	-1.4
Bedford	0.2	0.5	-2.7	-2.7	-4.0	-3.5	-1.8	-2.5	-1.2	-2.2	-1.2
	0.4	0.25	-2.0	-2.0	-2.4	-2.3	-1.4	-1.9	-1.9	-1.1	-1.1
	0.7	1.5	-12.9	-12.9	-14.3	-14.1	-10.3	-12.3	-13.0	-9.3	-9.3
Norwich	0.2	0.5	-2.0	-2.0	-2.8	-2.7	-0.4	-1.5	-1.9	0.0	0.0
	0.4	0.5	-2.0	-2.0	-2.8	-2.7	-0.4	-1.5	-1.9	0.0	0.0
	0.7	0.75	-3.4	-3.4	-4.6	-4.5	-1.2	-2.8	-3.4	-0.7	-0.7
York	0.2	0.75	-2.0	-2.0	-3.5	-3.1	-0.6	-1.7	-1.7	0.3	0.3
	0.4	0.75	-2.6	-2.6	-4.1	-3.9	-1.0	-2.2	-2.3	-0.1	-0.1
	0.7	1.5	-5.0	-5.0	-6.8	-6.9	-2.2	-4.2	-4.8	-1.2	-1.2

Source: Own calculations done with SATTAX outputs and European Environment Agency (2000) and Meteorological Office data

Costs of pollution

The health costs of these emissions were estimated using the values reported by McCubbin and Delucchi (1999). The values used are presented in Table 4.

Table 4: Health cost in pounds per kilogram of motor vehicle emission at 1998 prices

	Emissions					
	CO	NO_x	SO_2	PM	VOC	$VOC+NO_x$[a]
Low	0.0074	1.18	10.20	7.14	0.096	0.015
High	0.074	17.32	139.1	67.5	1.08	0.104

Source: McCubbin and Delucchi (1999)
Note: CO: carbon monoxide, NO_x: nitrogen oxides, SO_2: sulphur dioxide, PM: particulate matter, VOC: volatile organic compounds
[a]Deluchi shows the cost of VOCs and NO_x combined because these pollutants contribute jointly to ozone production.

Estimates of the cost of global warming due to CO_2 emissions span a very wide range. Maddison *et al* (1996) use the shadow price of controlling the last unit of CO_2 emitted. They estimate it at £ 4.6/tonne of carbon (tC) at 1998 prices. The Royal Commission on Environmental Pollution (1994) gives the value as £68.5/tC, also at 1998 prices (though this appears to have been strongly influenced by the proposed EU carbon-energy tax of $10/barrel of oil and may not have much scientific basis). These figures were used in the present study as low and high estimates respectively.

According to McCubbin and Delucchi (1999), road traffic generates pollution not only through motor vehicles emissions but also through upstream emissions and road dust emission. To take this effect into account, we multiplied the cost of the motor emissions by the ratio of total cost (including motor, upstream and road dust emissions) over motor emissions cost for each pollutant. The estimated monetary value of the reduction in emissions is presented in Table 5. The low estimates of the total environmental cost are about 7% of the high estimates (showing the considerable uncertainty attached to the figures). The table shows that, even when using the highest estimate for pollution costs, the increase in social surplus that would follow a reduction in emissions is small (typically less than 10%) compared to the increase in social surplus that would follow a reduction in congestion and travel times.

Table 5: Reduction in environmental costs in £ thousand and increase in annual social surplus in £ million at 1998 prices

Town	Elasticity	Estimate	Effect: Health	Effect: Global Warming	Effect: Total	Increase in annual social surplus (£ million)
Cambridge	0.2	Low	1.5	0.8	2.3	0.45
		High	23.2	11.6	34.9	
	0.4	Low	3.0	1.8	4.8	0.91
		High	46.4	26.0	72.3	
	0.7	Low	5.2	3.1	8.3	1.27
		High	80.6	45.6	126.2	
Northampton	0.2	Low	2.7	1.3	4.0	2.37
		High	39.9	19.5	59.4	
	0.4	Low	4.7	2.5	7.2	3.31
		High	70.5	37.9	108.3	
	0.7	Low	8.1	4.7	12.8	4.85
		High	122.3	69.7	192.0	
Kingston upon Hull	0.2	Low	5.9	4.2	10.1	3.24
		High	90.0	62.2	152.2	
	0.4	Low	9.6	6.6	16.2	4.46
		High	146.1	98.6	244.7	
	0.7	Low	13.2	8.9	22.1	5.14
		High	201.5	132.2	333.6	
Hereford	0.2	Low	2.1	1.5	3.6	0.53
		High	31.1	22.3	53.4	
	0.4	Low	2.4	1.7	4.1	0.77
		High	36.1	24.8	60.9	
	0.7	Low	3.1	2.0	5.1	0.85
		High	46.5	30.2	76.7	
Lincoln	0.2	Low	2.4	1.3	3.7	0.44
		High	37.0	18.7	55.7	
	0.4	Low	1.3	0.6	1.9	0.52
		High	19.3	9.6	28.9	
	0.7	Low	1.5	0.9	2.4	0.54
		High	23.8	12.9	36.7	
Bedford	0.2	Low	0.8	0.5	1.3	0.52
		High	12.4	7.1	19.5	
	0.4	Low	0.6	0.4	1.0	0.11
		High	9.4	5.3	14.7	
	0.7	Low	4.2	2.3	6.5	0.35
		High	64.3	34.5	98.8	
Norwich	0.2	Low	1.5	1.5	3.0	0.90
		High	22.4	21.6	44.1	
	0.4	Low	1.5	1.5	3.0	0.92
		High	22.4	21.6	44.1	
	0.7	Low	3.2	2.6	5.8	1.29
		High	48.3	38.3	86.6	
York	0.2	Low	1.2	0.8	2.0	0.72
		High	17.6	12.6	30.2	
	0.4	Low	1.6	1.1	2.7	0.84
		High	24.3	16.3	41.0	
	0.7	Low	3.2	2.1	5.3	0.87
		High	48.8	31.0	79.7	

Source: Table 4 and values by McCubbin and Delucchi (1999), Maddison *et al* (1996) and Santos, Rojey and Newbery (2000).

Change in traffic patterns

Results from SATTAX show that when a cordon toll scheme is introduced, two changes take place:

- The cordon results in a **decrease in the total number of trips**, which is beneficial, as long as the marginal benefit of adding one more vehicle is smaller than its marginal social cost. Increasing the toll raises the cost of all trips crossing the cordon and therefore it reduces the total number of vehicles on the network. As a consequence, congestion, average travel time, emissions and total costs are all reduced.
- The cordon results in a **shift of the traffic from the centre of the town to the surrounding areas.** Peripheral areas are generally less congested than the centre. This does not have a direct effect on total emissions but it may have some effect on the harm produced. The less concentrated the emissions, the less the external cost will be. However, this effect has not been quantified in this study.

Conclusions

The range of variation of environmental cost estimates of road transport emissions vary within a wide range. As a consequence the estimates of the reduction in external costs also vary within a wide range (low to high estimates). What is clear is that any toll designed to reduce traffic congestion, particularly at peak times, would yield the positive by-product of environmental benefits. Although congestion tolling may encourage more and/or longer trips (Richardson and Bae, 1998), simulations done with SATURN and its batch file procedure SATTAX show that in all cases there would be an environmental benefit, at least in what health and global warming concerns.

Given the great uncertainty in the estimation of the damage and the certainty in that some benefit would be gained from congestion tolls, the idea of introducing congestion tolls instead of green taxes may well be an alternative.

If environmental taxes are to be both politically attractive and economically effective, they must be clearly distinguished from other taxes or charges, set at levels determined by acceptable methods of computing the cost of the damage done, and applied uniformly to all sources of the same damage. (Newbery and Santos, 1999). Meanwhile some of the benefits may be realised with the simple introduction of a cordon toll.

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References

Cambridgeshire County Council (2000), *Cambridgeshire Provisional Transport Plan 2000-2005*, Cambridge.

Department of the Environment, Transport and the Regions (1996), *Transport Statistics Report: National Travel Survey 1993/95*, HMSO: London, July.

Department of the Environment, Transport and the Regions (1998), *Transport Statistics Great Britain 1998,* The Stationary Office, London, September.

European Environment Agency (2000), EMIP/CORINAIR *Atmospheric Emission Inventory Guidebook* (European Environment Agency, Second Edition, http://binary.eea.eu.int:80/g/group07.pdf

House of Commons (1999), The Transport Bill, accessed from http://www.parliament.the-stationeryoffice.co.uk/pa/cm199900/cmbills/008/1000008.htm on December 20 1999.

Maddison, D., Pearce, D., Johansson, O, Calthrop, E., Litman, T., and E. Verhoef (1996), *Blueprint 5: The True Costs of Road Transport*, London: Earthscan.

McCubbin, D. and M. Delucchi (1999), 'The Health Costs of Motor-Vehicle-Related Air Pollution', *Journal of Transport Economics and Policy,* Vol. 33, Part 3, pp. 253-86, September.

Meteorological Office, *UK Climate 1961-1990 Station Averages*, http://www.met-office.gov.uk/ukclimate/averages_sites.html

Milne, D. and D. Van Vliet (1993), 'Implementing Road User Charging in SATURN' *ITS Working Paper 410,* Institute for Transport Studies, University of Leeds, Leeds, December.

Newbery, D. (1998), *Fair payment from road-users: A review of the evidence on social and environmental costs,* Report published by Automobile Association, February.

Newbery, D. and G. Santos (1999), 'Road Taxes, Road User Charges and Earmarking', *Fiscal Studies*, 20(2), pp. 103-132, June.

Richardson, H. W. and C-H. C. Bae (1998), 'The Equity Impacts of Road Congestion Pricing'. *In* Button and Verhoef (1998).

Royal Commission on Environmental Pollution (1994), *Transport and the Environment,* 18th Report, London: HMSO.

Santos, G., Rojey, L. and D. Newbery (2000), The Economics of Cordon Tolls, Department of Applied Economics, Cambridge, *Mimeo,* October.