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AN EMPIRICAL STUDY OF ESTIMATING VEHICLE EMISSIONS UNDER CORDON AND DISTANCE BASED ROAD USER CHARGING IN LEEDS, UK

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Abstract: This paper presents the impact of road user charging (RUC) on vehicle emissions through application of traffic assignment and pollutant emission models. It presents results of an analysis of five RUC schemes on vehicle emissions in Leeds, UK for 2005. The schemes were: a £3 inner ring road cordon charge; a double cordon with a £2 inner ring road and a £1 outer ring road charge; and distance charges of 2, 10 and 20 pence per km levied for travel within the outer cordon. Schemes were compared to a no charge option and results presented here. Emissions are significantly reduced within the inner cordon, whilst beyond the cordon, localised increases and decreases occur. The double cordon exhibits a similar but less marked pattern. Distance charging reduces city-wide emissions by 10% under a 2 p/km charge, 42-49% under a 10 p/km charge and 52-59% under a 20 p/km charge. The higher distance charges reduce emissions within the charge zone, and are also associated with elevated emissions outside the zone, but to a lesser extent than that observed for cordon charging.

Kew words: emissions, road user charging, Leeds.

1. Introduction

In Western Europe road transport has overtaken industrial processes and coal combustion as the main source of atmospheric emissions (EEA, 1998), and for most UK cities, it is the main source of NO2 and PM10 pollution (Carruthers et al., 1998; Stedman, 1998). Thus while air quality management action plans will address a range of sources, it is has been suggested that management of urban road transport will be key to ensuring that air quality objectives are met. The UK National Air Quality Strategy (DETR, 2000) recognises road transport as a principal source of urban atmospheric pollution; hence an objective of the 1999 Transport White Paper was to reduce air pollution through better management of urban road traffic. The 1998 UK government transport white paper 'Breaking the

Logjam' sought to tackle traffic congestion and pollution by giving local government the power to levy charges for road use and workplace parking. A road user charge (RUC) scheme was implemented by the Transport for London in February 2003, via a £5 cordon charge to enter central London. Currently the cordon charge stands at £8. Provisional estimates following a year of operation (TfL, 2004) show reductions in traffic flows, delays and congestion. Other UK cities have expressed interest in road pricing, but with minor exception, none have followed London's lead, in part, due to the uncertainty over the environmental benefits that may result from a RUC.

Evidence for congestion reduction comes mostly from some studies. These indicate that greater benefits accrue from road pricing implemented as part of an integrated approach, with charging reinforcing other strategic measures such as improved public transport provision (May 1992, May et al., 2000). These studies also suggest that charges levied continuously throughout the road network lead to greater travel benefits than those applied to cross cordons and screenlines (May and Milne, 2000; Fridstrom et al., 2000). The air quality impacts of road user charging in urban areas have not been adequately quantified. Although some studies have focussed on emission impacts of charging schemes (e.g. Ubbels et al., 2002; Beamon and Griffin, 1999). The UK government's advisory body on transport has recently recommended that distance based charging be implemented for the UK road network, but did not assess the environmental benefits of the forecast reduction in traffic and congestion. They assumed that such benefits would be positive, but have called for further research to quantify them (CfIT, 2002). This knowledge gap is significant, given that local authorities are seeking to reduce congestion, and at the same time, have legal obligations under the NAQS to ensure compliance with air quality standards. Indeed, environmental enhancement is a key factor in the public acceptability of road user charging (Jaensirisak et al., 2002).

The impact of road user charging on vehicle emissions and urban air quality in Leeds, UK was investigated through application of a chain of dynamic simulation models of traffic flow (SATURN, SATTAX), pollutant emission (ROADFAC) and dispersion (ADMS-Urban), integrated within a geographic information system model (Traffic Emission Modelling and Mapping Suite, TEMMS). Results relating to vehicular emissions under five RUC regimes are presented in this

paper. Leeds is a large (562 km2) metropolitan district with 740,000 residents and has experienced strong economic growth since 1981, second only to London, and forecasts indicate this growth is likely to continue. Car ownership has also risen, by 11% in the last decade, and net in-commuting is predicted to grow 50% in the next (LDA, 2000). Such rapid growth suggests that air quality may be at risk of failing the EU directives. However, this growth also makes Leeds an ideal city to study the emission and air quality implications of alternative road transport 'futures' and management options, as the results can give advance notice of likely outcomes in comparable but less rapidly growing cities.

2. METHODOLOGY

2.1 Traffic and emission modelling

TEMMS uses network link-based data on vehicle flow and speed as an input to produce link based emissions in a format suitable for entry to an atmospheric dispersion model (Namdeo et al., 2002). Namdeo et al., 2002 discuss the performance of component models of TEMMS and conclude that the model performance is acceptable for use in statutory air quality modelling. TEMMS has so far been exclusively applied in conjunction with SATURN, a widely used interactive simulation and assignment model (Van Vliet, 1982), although any source of link flow data can be used. SATURN provides estimates of traffic flows and travel conditions (e.g. travel times, delays and average speeds) for spatial road networks. It utilises two primary models: an assignment model, in which drivers choose routes through the network according to Wardrop User Equilibrium principles, based on generalised costs implied by link and turn-specific cost-flow relationships; and a simulation model, in which the cost-flow relationships for the assignment are modified, based on more sophisticated representation of the interaction of traffic flows at junctions. These models are applied in an iterative manner until the critical outputs satisfy a series of stability criteria. Input requirements comprise numerical representations of : (i) travel demand, in the form of a spatial trip matrix; and (ii) network supply, including network topology, link cost-flow relationships, junction layout and, where appropriate, traffic signal settings. The Leeds SATURN application provides a detailed representation of morning peak hour road travel throughout the developed urban area, out to and

beyond the main strategic orbital routes. The network includes 10 250 links and 1 314 intersections, while the trip matrix covers approximately 85 000 journeys between 370 spatial zones.

Using its integral emission model ROADFAC, TEMMS calculates link-based emissions of NO_x, CO, CO_2, SO_2, PM_{10}, $PM_{2.5}$, VOC's, benzene and 1-3 butadiene. In addition to the link flow and speed data (from SATURN), ROADFAC requires data on fleet composition and speed dependent emission factors, both of which are drawn from MEET (EC, 1999). The fleet is described according to vehicle type, gross weight, engine capacity and type, fuel type and emission control technology used, giving 72 sub-classes with characteristic emission rates. Speed dependent emission factors for each vehicle class are developed from chassis dynamometer tests simulating observed drive cycles of differing mean trip speeds. Additional emissions from acceleration and queuing at junctions are therefore included, but these emissions are allocated evenly to the whole link, and not apportioned using a junction weighting. ROADFAC uses CORINAIR methods to estimate the additional emissions resulting from cold start motoring (Eggleston *et al*., 1991). For each link, a composite emission factor is determined from the fleet data, vehicle-class emission factors, and mean speed of the link. Total link emissions are the product of this composite factor and link flow. Speed and flow data from SATURN relate to a short period only (e.g. AM peak), hence to calculate emissions through 24 hours, time variant emission correction factors must be applied to the modelled short period emission. These correction factors are developed from time variant data, using observed vehicle count and speed data collected hourly throughout the week, and for a range of road types. Emissions from sources other than vehicles were derived from the local government stationary source emission inventory for the 416 regulated point source emissions in the city.

2.2 Development of road user charging transport and emission scenarios

The possible impacts of road user charging on emission and air quality were assessed using cordon and distance charging. Cordon charging was selected as it is proven technologically (London, Singapore, Norway), and hence of most interest to local authorities. However, May and Milne (2000) found that cordon

pricing was the least effective regime in terms of network performance (generalised cost, trip time and distance, total trips) under road pricing. They added that this is very sensitive to cordon location and concluded that, given concerns over added driver risk taken and the uncertain charge per trip associated with time and congestion charging, future road pricing work could usefully focus on distance based charging.

RUC tests in this study were conducted on the 2005 'Do-Min' network, using SATTAX (Milne and Van Vliet, 1993) module of SATURN that uses the SATEASY elastic assignment algorithm to model trip demand in response to generalised cost. Trips in SATURN are expressed as passenger car units (PCU). SATTAX uses demand flows, not actual flows. Cordon charging is represented by adding the crossing toll to the generalised cost for that link, and distance charging by adding a fixed km cost for all links that fall within the charge area. The model response is then to transfer trips off the network (switch mode, travel at other times or not at all) and to modify route choice. Table 1 gives the details of the tests and associated trip suppression.

The inner cordon charge was set to £3, deemed politically acceptable by the local government, but below the £5 toll levied in London (current toll is £8). A second test splits this fee over two cordons, which increases trip suppression as more trips are affected by the outer cordon. Using real monetary values in SATEASY, a revenue of £97,000 for 470,000 PCU kms travelled is generated. From this a 20p/km toll is derived that is consistent with tests elsewhere (May and Milne, 2000) but gives a trip suppression likely to be far from the economic optimum, even if externality effects were valued highly. Additional distance charges were thus set at half the 20p/km charge, and at an order of magnitude lower, the latter giving a trip suppression similar to the initial inner cordon charge. All charges were levied according to PCU's with no attempt to differentiate by vehicle type.

3. RESULTS AND DISCUSSION

Emission rates in g/km/s from road links in the network are plotted to show the spatial variation in link-based emissions. Figure 1 shows NO_x emissions from roads for the 2005 Do-Min Base scenario. High emission roads in the City Centre and motorways in South and SE clearly stand-out in this emission map. Grid emissions were calculated by combining emissions from all road links within

grids of 1km x 1km size. The study area was 30 x 25 km thus resulting in 750 grid cells. RUC scenarios were compared with the base scenarios to estimate the percent changes in grid emissions. For example, Figure 2 shows the NOx emission response to a 2p/km charge at grid-levels. Table 2 shows variation in total emissions of major pollutants under each RUC scenario. It also gives the changes in emissions compared to the Base Case. It is clear from the table that 20p charge results in the greatest reduction in emissions (ranging from 52 to 59 percent) whereas single cordon scenario results in emission reduction of 3 to 5%. Double cordon charging results in around 18% reduction compared with 10% in the 2p charge scenario.

Road pricing using a £3 inner cordon charge suppresses trip demand, improves trip speeds and reduces total vehicle kilometres travelled on the network (Table 1). It is notable that the mean trip length also increases, by 4-5% depending upon the network configuration, suggesting that some drivers re-route to avoid the toll, and that more shorter trips are suppressed. This effect is less marked with the double cordon, which has the same charge to enter the city centre as the inner cordon. The much wider double cordon intercepts more trips and gives fewer opportunities to avoid the charge zone cost effectively. All re-routing effects tend to lengthen routes, while the outer cordon suppress predominantly longer trips, and the inner cordon more short trips. Overall, cordon charging suppresses total vehicle kilometres, reduces emissions and improves air quality. Inspection of the SATURN network flow maps indicates that introduction of a cordon charge increases flows on some links outside the charge zone, despite a reduction in the total number of trips made. Thus cordon charging does present the risk that trips and emissions are redistributed to the extent that exceedances of air quality standards may occur. With the single cordon, for example, emissions within the CBD (Central Business District) fall by up to 50% in places (km grid squares), but increase by > 25% in areas outside the cordon. The scale of redistribution is less marked with the double cordon, due to a greater overall level of trip suppression and the sharing of re-routing impacts between the inner and outer cordons.

The 10 p/km and 20 p/km distance charges improve mean link but the trip suppression rates (Table 1) are very high, and are unlikely to be economically optimal, even were all the externalities accounted for. However, the 2 p/km distance charge is notable as the only road user charge scenario in which trips

become shorter. The trip suppression for the 2p/km charge is comparable to that of the single cordon scenario, where trips are longer. This reduction in mean trip length may be a result of greater suppression of longer trips, or drivers taking more direct routes in a less congested network, or simply that distance charging encourages drivers to take shorter routes, regardless of the level of congestion. Increases in mean trip length under the higher distance charges are attributed to a greater proportion of trips that avoid the charge zone altogether. Note that emission gains from reduction in mean trip distance or total distance travelled could, in principle, be offset by greater trip speeds. However, the speed-emission relationship is U-shaped, with high emission at low and high speed, and a minimum at c. 65 km/h for 2005. In urban networks, mean link speeds are generally low (c. 25 km/h in the case of the Leeds network), hence even under a high trip suppression, speeds increases will not lead to elevated emissions, at least for the fleet as a whole (SATURN does not generate speeds for different vehicle classes with different speed-emission relationships). Indeed, in congested networks, relatively small increases in vehicle speed should have a significant beneficial impact by reducing emissions. Depending upon the pollutant, distance charging reduces total road traffic emissions by c.10 % under a 2 p/km charge, 42-49 % under a 10 p/km charge, and 52-59 % under a 20 p/km charge, illustrating a diminishing marginal return in emission abatement with the distance charge.

4. CONCLUSIONS

Road user charging can deliver improved air quality by constraining trip demand and reducing emissions. Although emissions are speed dependent, the dominant factor behind emission reduction is a reduction in the total PCU-km travelled on the road network. All road user charging scenarios investigated for Leeds result in a reduction in emissions. Emissions are significantly reduced within the inner cordon, whilst beyond the cordon, localised increases and decreases occur. The double cordon exhibits a similar but less marked pattern. Distance charging reduces city-wide emissions by 10% under a 2 p/km charge, 42-49% under a 10 p/km charge and 52-59% under a 20 p/km charge. The higher distance charges reduce emissions within the charge zone, and are also associated with elevated emissions outside the zone, but to a lesser extent than that observed for cordon charging. This research has shown that traffic restraint due to road user charging

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can deliver substantial greenhouse gas reduction benefits, and is able to reverse projected increases in CO_2 emission that would occur under a 'do-nothing' strategy.

Though road user charging could prove to be a very effective air quality management tool, its successful use is context specific, being dependent upon (i) the source apportionment of the application city; and (ii) the prevailing air quality, both in terms of its spatial distribution, and the proximity of concentrations to permitted standards.

Acknowledgements

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Figure 1: NOx emission from roads under a zero user charge (2005 Do-Min/Base Scenario)
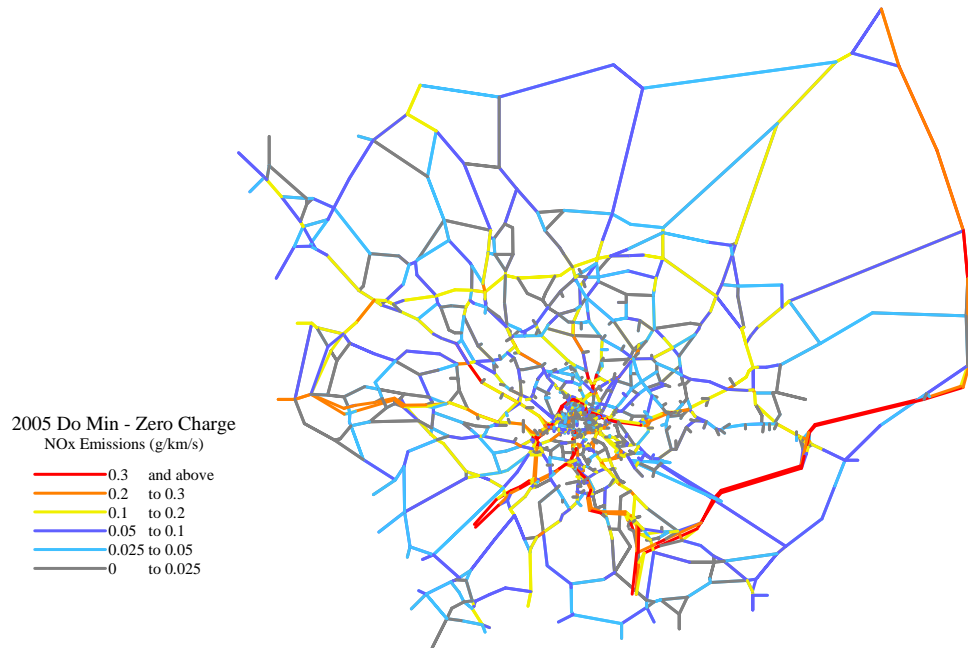

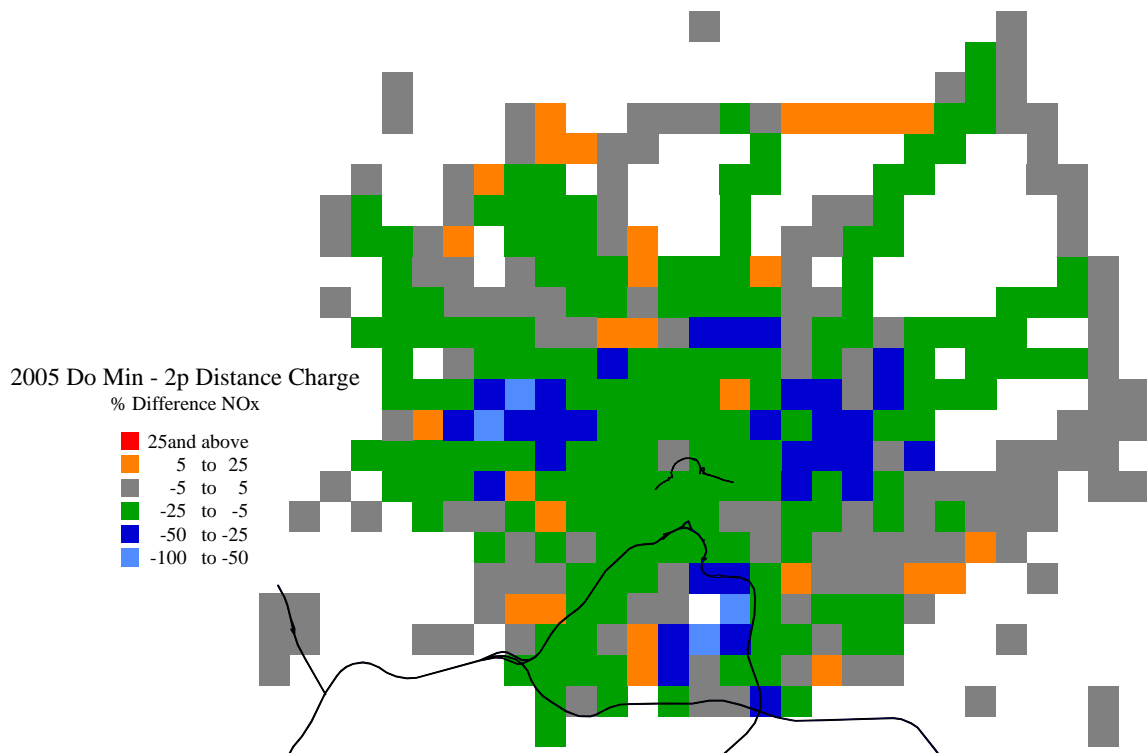Figure 2: Total NOx emission response to a 2p/km charge

Table 1: Road user charge scenarios, trip and total distance travelled suppression

Road user charging scenario	%change in network performance parameter over Base Scenario		
	% Reduction in trips (and v/kms)	Mean Link Speed	Mean Trip Length
City centre (inner orbital) cordon : £3	7.0 (2.0)	+0.39	+5.46
Double cordon : £2 inner and £1 outer	18.5 (17.2)	+3.86	+1.89
Distance charge : 2p/km	8.8 (11.1)	+6.16	-2.57
Distance charge : 10p/km	47.0 (46.1)	+31.66	+1.10
Distance charge : 20p/km	62.5 (55.7)	+42.86	+18.14

Table 2: Change in total road emissions (%) under alternative RUC scenarios

	RUC Scenarios					
	Base	2p	10p	20p	DC	SC
	Emissions, 10^3 kg per year (% Change from the Base Scenario)					
CO_2	930953	839007 (-10)	508863 (-45)	415909 (-55)	755714 (-19)	892341 (-4)
CO	16527	14854 (-10)	9140 (-45)	7596 (-54)	13506 (-18)	15793 (-4)
NOx	2104	1920 (-9)	1218 (-42)	1017 (-52)	1735 (-18)	2032 (-3)
SO_2	32	29 (-9)	18 (-43)	15 (-53)	26 (-18)	31 (-4)
PM_{10}	122	111 (-9)	68 (-44)	56 (-54)	100 (-19)	117 (-4)
Benzene	89	81 (-9)	51 (-42)	43 (-52)	74 (-18)	86 (-4)
1,3-Butadiene	17	16 (-9)	9 (-49)	7 (-59)	14 (-20)	17 (-5)