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THE AIR QUALITY IMPACT OF CORDON AND DISTANCE BASED ROAD USER CHARGING: AN EMPIRICAL STUDY OF LEEDS, UK

Gordon Mitchell [1, 2] , Anil Namdeo [2] and David Milne [2]

1. School of Geography and 2. Institute for Transport Studies,

The University of Leeds, Leeds, LS2 9JT, UK

g.mitchell@leeds.ac.uk

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Abstract

Traffic assignment, pollutant emission and dispersion models were applied to a major UK city so as to assess the air quality impacts of five road pricing schemes. Schemes were evaluated with reference to: exceedence of air quality standards for six pollutants; greenhouse gas emission; redistribution of pollution, an environmental justice concern; and road network performance as traffic speed and trip distance. Results were compared to alternatives of do nothing, network development and clean fuel promotion. The air quality benefits of a modest distance based charge are highlighted. However, whilst road pricing shows potential as an air quality management tool, its value and suitability are strongly sensitive to prior air quality and emission source apportionment in the application city.

Keywords: Air quality management, urban, road pricing, traffic emission, dispersion modelling

1 Introduction

Exceedence of air quality standards is common for European cities (EEA, 1998). This is a significant threat to public health, with an estimated 24 000 premature deaths per annum attributed to poor air quality in the UK alone (DoH, 1998). The EC air quality framework directive (96/62/EC) requires member states to eliminate standard exceedences for a range of pollutants by defined target dates. To achieve these objectives, the UK has developed a national air quality strategy (NAQS) that defines policy, tasks and responsibilities for air quality management (DETR, 2000a). Under the NAQS local government is responsible for assessing future air quality and for establishing air quality management areas and action plans where objectives are not expected to be achieved.

Road transport, now the main source of atmospheric emissions in Western Europe (EEA, 1998), is a key focus of the NAQS. In addition to reducing congestion, tackling pollution is also a major objective of European transport pricing policy (CEC, 1995) and the UK government's national transport strategy (DETR, 1998a). This strategy includes a five yearly local transport planning process, the 2000 ten year transport plan, and a range of new powers for local authorities, including, controversially, the power to levy charges for road use (DETR, 1998b). London was amongst the first authorities in the UK to exercise these powers, introducing a £5 cordon charge to enter central London from February 2003. Initial appraisal shows reductions in traffic, congestion and emissions but to date, reliable evidence on changes in air quality (pollutant concentrations) has not been forthcoming due to atypical meteorology (TfL, 2005).

Other cities have not followed London's lead, as authorities are sensitive to the possible adverse public reaction (indeed citizens of Edinburgh rejected road pricing in a 2005 referendum), hence the London experience is being watched closely to better assess possible benefits. Evidence for congestion reduction comes mostly from desk 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).

Whilst there is growing evidence for traffic and congestion reduction, the air quality impact of road pricing has not been adequately quantified. For example, the UK government's advisory body on transport recommended distance based charging for the UK road network, but did not assess the environmental benefits of forecast reductions in traffic and congestion. They assumed such benefits to be positive, and called for research to quantify them (CfIT, 2002). This knowledge gap is significant as local authorities seek to reduce congestion and achieve binding NAQS objectives. Indeed, in addition to price, revenue use and effectiveness, environmental enhancement is a key factor in the public acceptability of road pricing (Jaensirisak *et al.*, 2002).

Environmental impacts are considered in road pricing studies, but not air quality explicitly. Instead emissions act as a proxy when assessing environmental impact (e.g. Ubbels *et al*., 2002; Beamon and Griffin, 1999) or deriving optimal charges (e.g. Johannson 1996; Mayeres, 2000). Air quality observations were made in Singapore following the introduction of a road user charge in 1975 (Chin, 1996), but general conclusions cannot be drawn as: an air quality evaluation of the scheme was not attempted; monitoring did not occur over a long enough period to assess the effect of the scheme within the charge zone; and the influence of other factors including better vehicle emission technology, changes in point source emission, and pollutant import from Malaysia, have not been adequately controlled for in the limited long term data that is available. Furthermore, road pricing in Singapore relates to a single scheme design and hence excludes evaluation of alternative schemes, including distance based charging.

2 Objectives of the Leeds transport - air quality study

To investigate the role of road pricing on urban air quality, a modelling study of Leeds, a medium size (740 000 residents) English city was conducted. Leeds has experienced strong economic growth since 1981, second only to London, and forecasts indicate this growth will continue. Car ownership has risen by 11% in the last decade, and net in-commuting is predicted to grow 50% in the next decade (LDA, 2000), threatening attainment of air quality objectives, and making Leeds a particularly suitable city to study the air quality implications of alternative road transport management options.

The study assessed the impact on air quality of five urban transport planning options: (a) do nothing; (b) cordon based road user charging; (c) distance based road user charging; (d) road network development; and (e) greater use of clean fuelled vehicles (CFV). Combined tests were also conducted (Table 1). Each option was assessed with respect to: (i) air quality, as pollutant concentration and exceedence of air quality standards for NO_2, particulates (PM_{10}), CO, SO_2, benzene and 1-3,butadiene; (ii) greenhouse gas (CO_2, NO_X) emission; (iii) spatial redistribution of NO_2 and PM_{10}; and (iv) road network performance, as mean road speed and trip length.

3 Modelling

The study applied TEMMS, software that integrates models of traffic assignment, pollutant emission and dispersion within NAQS modelling standards (DETR, 2000b). TEMMS, and its validation for Leeds, is discussed by Namdeo *et al.*, (2002), whilst its application in the road pricing study is described below.

3.1 Traffic modelling

Within TEMMS, the SATURN traffic assignment suite (Van Vliet, 1982) was used to estimate traffic flows and travel conditions (e.g. travel times, delays, average speeds) for the Leeds road network. SATURN includes: an assignment model, in which drivers choose routes through a 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 cost-flow relationships for the assignment are modified, based on a sophisticated representation of the interaction of traffic flows at junctions. These models were applied iteratively until critical outputs satisfied a series of stability criteria. Principle inputs to SATURN are travel demand (a trip origin-destination matrix); and network supply, including network topology, link cost-flow relationships, junction layout and traffic signal settings.

SATURN can be used to test traffic management options by modifying the road network or trip matrix. Road pricing was addressed in the assignment model by additions to generalised travel costs, calculated using appropriate values of time, within the SATTAX module (Milne and Van Vliet, 1993). In its conventional form, the assignment model assumes that input travel demand is fixed, but variable demand can be represented using the SATEASY module that employs an elastic user equilibrium assignment algorithm that modifies the trip matrix in response to changes in travel costs through the network, based on a simple own-price elasticity relationship (Hall *et al.*, 1992). The Leeds application represented morning peak hour travel throughout the city, out to and beyond the main strategic orbital routes. The network comprises 10250 links and

1314 intersections, while the trip matrix covers c. 85000 journeys between 370 spatial zones.

3.2 Transport Emission modelling

Link based emissions of six pollutants were then calculated within TEMMS. This used link flow and speed data from SATURN, and fleet composition data and speed dependent emission factors from MEET (EC, 1999). Fleet composition addresses vehicle type, gross weight, engine capacity and type, and fuel and emission control technology used, giving 72 vehicle classes with characteristic emission rates. Fleet data is based on vehicle sales, with future year projections based on historical trends in fleet ageing, and scheduled emission control legislation. Speed dependent emission factors for each vehicle class were derived from chassis dynamometer tests simulating observed drive cycles of different mean link speeds. Thus emissions from acceleration and queuing at junctions are included, although these are allocated along the length of the link, and not specifically to junctions. CORINAIR methods are used to estimate cold start emissions (Eggleston *et al*., 1991).

A composite emission factor was then determined for each link (from fleet data, vehicle class emission factors, link speed) and total link emissions estimated as the product of this factor and link flow. SATURN speed and flow data were for the weekday AM peak hour only. Flow and speed for the remaining hours, and for hours on weekend days were estimated by applying time sensitive correction factors developed from observations of vehicle flow and speed collected hourly throughout the week for a range of road types. These corrected profiles were used to estimate emissions for every hour in the year.

3.3 Air quality modelling

Air quality was then estimated using the ADMS-Urban dispersion model (CERC, 1999). A stationary sources emission inventory details pollutant annual mass emission, stack location and height, gas exit velocity and temperature, for the 416 regulated point source emissions in Leeds. Area and point sources emissions (< 0.1 tonne yr^{-1}) are quantified with reference to observed concentrations from an upwind background rural monitoring site and via calibration of modelled and observed data. For all scenarios, non-transport emissions were assumed to be constant.

ADMS-Urban was applied using default surface roughness values to represent topography, and the Generic Reaction Set model to calculate NO_2 concentration from NO_x emission. We used sequential (hourly) meteorological data for 1999. This closely approximates to the long run (1990-99) averages, has the same hourly time step as used in the emission modelling, and gives better estimates of peak concentrations than statistical meteorological data (CERC, 2001). In hourly steps, a year of pollutant concentrations is modelled; from which compliance with UK air quality annual mean and percentile standards is assessed. Emissions were modelled for a 30 x 25 km box, and concentrations for an inner 12 x 12 km box covering the entire built area. Concentrations were modelled for 3600 receptor points within this box on a regular grid pattern, giving air quality values at 200 m intervals.

TEMMS permits rapid preparation of inputs to a dispersion model, but as dispersion modelling is computationally intensive, the study was limited to 14 dispersion model runs, plus a further five sensitivity runs to better investigate possible pollutant 'hot spots' not seen using the 200m grid cell receptor pattern. These tests used ADMS-Urbans street canyon model and 'intelligent gridding' function that allows 5000 extra receptor points to be added around roads (Table 1).

4 Transport scenarios

4.1 Do nothing 'Business as usual'

The effect of a do-nothing 'Business as usual' strategy was assessed by modelling air quality for 1993 (validated base year), 2005 and 2015. This addresses the impact of changing trip demand and fleet characteristics, but network developments between 1993 and the 2005 do-minimum networks are also represented (including the A1-M1 link to the south east of Leeds, that joins two existing regional motorways). Traffic volumes in passenger car units (PCU hr^{-1} link) are derived from SATURN, and show that from 1993-2005, trips grow by 21%, and total vehicle-kms travelled by 34%. SATURN modelling was not conducted for 2015 due to limited resources, so link flows were scaled from the 2005 flows, hence for 2015, potentially significant assignment effects are poorly represented. The scaling factor was derived from TEMPRO 3.1, the national trip-end forecast model (HMSO, 1997), which predicted a growth in Leeds road traffic of 17.3 % from 2005-15. Subsequent projections using TEMPRO 4 (which accommodates mode switching) are marginally above the growth rate used in this study. Fleet characteristics for future years are based on MEET (1999) forecasts (see section 3.2).

4.2 Road user charging

We assessed the impact on air quality of charging road users to cross cordons and on the basis of distance travelled within a charge zone. Cordon pricing technology is proven hence local authorities are most interested in cordon charging. However, in terms of network performance (generalised cost, travel time and distance, delay), modelling suggests that cordon pricing is the least beneficial of the charging approaches available, albeit sensitive to detailed design issues related to location and charge level. In contrast, distance pricing provides network performance benefits that are comparable to more sophisticated charging approaches based on travel time and congestion, but without many of the potential pitfalls of complexity and adverse driver responses (May and Milne 2000; Fridstrom *et al.*, 2000). Thus, we also considered distance based pricing.

Both charging approaches were represented in SATURN using the SATTAX and SATEASY modules in combination to apply the charges and to allow road travel demand to respond to changes in generalised cost. Cordon pricing was modelled by adding an appropriate time penalty (a proxy for a charge) to each affected link, and distance pricing by adding appropriate time penalties, as a function of lengths, to all links in a charge zone. Charges were calculated using a value of time of 7.63 pence per minute consistent with recommended values for PCU based assignment models (May and Milne, 2000). Demand response was applied using an exponential function, calibrated by data from a stated preference survey, which gave elasticity values (for the network, not individual links) in the range of 0 to -1.0 for most conceivable changes in generalised cost on the network (May *et al.*, 1998). A sensitivity analysis of elasticity values was not conducted as Milne (1998) showed that link flow and speed data, the critical inputs to the emissions model, are among the most stable of the SATURN model outputs when demand elasticities are varied. Thus SATURN addresses both driver re-routing and change in trip demand. However, it should be noted that the elastic assignment algorithm in SATEASY is unable to indicate whether changes in road travel demand arise from modifications to mode choice (e.g. public transport, car sharing), time of travel, or trip frequency.

Five charge scenarios were addressed (Table 1), with their cordon locations and charge zones illustrated in Figure 1. Firstly, an inner (city centre) cordon charge of £3, the maximum politically acceptable by the city council, was investigated. The second cordon test also charged £3 to enter the city centre, but split this fee over the inner cordon (£2) and an outer cordon just inside the outer orbital road. This double cordon gives a revenue of £97 000 for the 470 000 PCU kms travelled in the charge zone (AM peak), from which a 20 p/km distance toll was derived, consistent with charges considered elsewhere (May and Milne, 2000; CfIT 2002), and apparently reasonable given a mean trip distance of 10 km. However, 20 p/km gives a trip suppression that is probably above the economic optimum, even if externality effects are valued highly. Therefore, distance charges of 10 p/km and 2 p/km were also tested, the latter giving a trip suppression similar to the £3 inner cordon charge. All charges were levied per PCU for the morning peak, with no attempt to differentiate by vehicle type.

4.3 Network development

The impact of road building on air quality was investigated through two networks. The first represents the network for 2005 under a 'do-minimum' assumption (see 4.1). The second (2005 'do-all') additionally includes two main highways and ancillary roads: 3 km of inner-city dual carriageway completing the inner orbital road; and the East Leeds Link, a 4 km dual carriageway intended to relieve congestion and promote economic regeneration in east Leeds (Figure 1).

4.4 Clean fuel vehicle technology

The air quality impact of clean fuel vehicle (CFV) use was investigated, addressing liquefied petroleum gas (LPG), electric and hybrid vehicles. These vehicles are technologically viable, have proven emission benefits, and qualify for grant aided promotion under the government's 'Powershift' programme. Air quality was forecast for 2015 only, as little CFV growth was expected by 2005. For electric vehicles, fleet composition was adjusted using MEET CFV high growth forecasts for the European fleet of 2% electric vehicles, 3% hybrid and 1% fuel cell. These are based on evolutionary, not revolutionary market changes, and are very speculative. MEET has no forecast for the proportion of the UK vehicle fleet using LPG in 2015, so we used a value of 5%, consistent with MEET high growth forecasts for the Netherlands and Italy. Thus overall, 11% of conventionally fuelled cars were replaced with CFV's for 2015.

CFV emission factors were also drawn from MEET, although the data are limited and meant only as a guide. For electric vehicles (hybrid; methanol fuel cell), factors are not speed dependent, and only address three vehicle classes: passenger cars, light duty vans and buses. Emissions from battery operated vehicles are assumed to be zero at point of use. For LPG vehicles, emission factors relate only to vehicles <2.5 tonnes, and address uncontrolled and Euro I standards only. Euro I LPG factors were therefore applied to Euro II-IV LPG vehicles.

5 Results

Aggregate network performance statistics comparing the principal tests are shown in Figure 2. Table 2 summarises the air quality results. Results for benzene or 1-3, butadiene are not shown as concentrations were substantially below permitted levels at all sites under all tests. For the other pollutants, concentrations are shown as a city wide mean of the 3600 sites (receptor locations) and as the number of sites where the air quality standard is exceeded. Modelled NO_2 concentrations at the government's city centre monitoring station are also shown. Street canyon and intelligent gridding results are not shown as very few additional standard exceedences were detected, demonstrating adequate spatial resolution of the receptor points in the standard tests.

5.1 Business as usual

Under do nothing, travel demand increases 1.7 % per annum, resulting in slower, longer trips, an increase in total PCU-kms of 2.5 % per annum (Figure 2), and potentially elevated emissions. However, from 1993-2005, this effect is countered by the increasing efficacy and prevalence of emission control technology (catalytic converters, cleaner fuel). This clean technology varies in effect by pollutant. For example, fine particulates were identified as a problem later than NO_X and CO, hence particulate emission control technology, and its representation in the vehicle fleet, is less advanced. This is evident in Figure 3, which shows that the fleet weighted emission factor (emission per 'average' vehicle) falls significantly for NO_X, CO and VOC over the 'Business as usual' period, reducing total emissions. In contrast, the fall in fleet weighted emission factor for particulates and SO_2 is insufficient to counteract the rise in PCU-kms travelled, hence total emissions of these pollutants increase. In summary, emissions of SO_2 and fine particulates increase, whilst NO_X, CO and total VOC emissions decline. The net effect is a major improvement in air quality with reference to air quality standards. City average concentrations of NO_2 and CO decline by 2005 to the point where standard exceedences are eliminated (Table 2). Exceedences for PM_{10} and SO_2 are attributed to industrial point sources, not traffic. Small increases in the concentration of benzene and 1,3-butadiene occur to 2015, but levels remain well below permitted standards.

These air quality gains are attributed to clean technology which, in the case of NO_x, CO and VOC's, counteracts the 35% growth in total trip distance from 1993-2015. However, clean technology does not counteract the effect of growing vehicle use with respect to particulates. This is not a major issue for Leeds, as increases in particulate emission do not cause additional exceedences of the PM_{10} standard (point sources contribute 68% of particulate emissions in Leeds). However, were such an increase repeated in a city where traffic dominates particulate emissions, as is more usual (see e.g. Buckingham *et al.*, 1998), and where compliance with standards is already marginal, then many site exceedences of the PM_{10} standard may be expected. Furthermore, tightening of the PM_{10} objective (to 20 $\mu g\ m^{-3}$ as an annual mean from 2010; DEFRA, 2001), means that particulate emissions are a potential major problem in Leeds, with most of the city centre non-compliant. Rising travel demand also significantly increases greenhouse gas emission (Figure 4), particularly CO_2, forecast to rise by 76 % from 1993-2015.

5.2 Cordon based road user charging

Road pricing using a £3 inner cordon charge suppresses trip demand, improving travel speeds and reducing total vehicle kilometres travelled on the network (Figure 2). Note that mean trip length increases (by 5.5%) suggesting that drivers re-route to avoid the toll, and possibly that shorter trips are suppressed. This effect is less marked with the double cordon (same £3 charge to enter city centre) as the larger charge zone intercepts more trips, and gives fewer opportunities to avoid the toll cost effectively. The smaller increase in mean trip length under the double cordon is interpreted as a product of the balance between less re-routing around the inner cordon, which has a lower charge to cross the cordon line than under the single cordon, and additional re-routing generated by the external cordon. All the cordon schemes suppress total vehicle kilometres, reduce emissions of all pollutants and improve mean city-wide air quality significantly ($P<0.0001$) (Table 2). City-wide annual mean NO_2 for example, falls 0.13 $\mu g\ m^{-3}$ (0.7%) under the single cordon and by 0.8 $\mu g\ m^{-3}$ (4%) under the double cordon.

Network flows from SATURN show that despite reducing the total volume of trips, cordon charging increases flows on some roads outside the charge zone, as drivers re-route. A cordon charge thus risks generating new exceedences of air quality standards on the periphery of the charge zone. With the single cordon, for example, emissions in the CBD fall up to 50% in places (km grid squares), but increase by > 25% in areas outside the cordon. The redistribution is less marked with the double cordon, due to greater overall trip suppression and the sharing of re-routing impacts between the inner and outer cordons. A significant number of the 3600 receptor sites experience reduced air quality under the single cordon charge (Table 3), but the net effect is an overall improvement in air quality due to suppression of trips. Redistribution under cordon charging was not sufficient to induce additional standard exceedences.

5.3 Distance based road user charging

The 10 p/km and 20 p/km charges improve mean link speeds to above the level experienced in 1993, but the trip suppression rates (Figure 2) are high, and are unlikely to be economically optimal, even were externalities highly valued. However, the 2p/km charge is notable as the only road pricing test in which trips become shorter. Trip suppression for the 2 p/km charge is comparable to that of the single cordon tests where, in contrast, trips become longer. This reduction in mean trip length is most likely due to greater suppression of long trips (May and Milne, 2000). Drivers may also take more direct routes in a less congested network, or distance charging may simply encourages shorter routes, regardless of the level of congestion. Higher mean trip length under the higher distance charges is attributed to greater re-routing to avoid the charge zone or minimise the distance travelled through it (May and Milne 2000).

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 hr (in 2005). In urban networks, mean link speeds are generally low, c. 25 km hr for the Leeds network, hence even under a high trip suppression, speed increases will not lead to elevated emissions. 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.12% under 2 p/km, 47-52% under 10 p/km, and 56-63 % under 20 p/km, illustrating a diminishing marginal return in emission abatement with a rising charge. A charge of 2 p/km is sufficient to improve air quality significantly ($P<0.0001$) for all pollutants studied (Table 2). Pollutant redistribution does occur under the distance charging regimes (Table 3), but is only apparent in the air quality data under the 2 p/km charge, as trip suppression under the higher charges substantially reduces total emissions, masking the redistributive effect. The diminishing marginal return apparent in the emissions data is less pronounced for air quality as point source emissions are a significant determinant on pollutant concentrations.

5.4 Network development

Network development results in a small but significant decline in air quality, particularly in the vicinity of new roads, but delivers no improvement in network performance (mean speeds). Increasing road capacity lowers the generalised trip cost, and induces an additional 2.4% trips. Mean speed for the network is unchanged, but mean trip length falls 1.3 %, as the new roads provide more direct routes for some trips. On balance, the additional trips generated by the added capacity result in a 1% increase in total PCU kms travelled. Consequently, city-wide, road emissions increase 0.7 -1.4 % (depending upon the pollutant), and air quality declines slightly (Table 2). Increased emission occurs in the vicinity of new roads (e.g. NO_x increases by >25%), but these increases are too small to cause any additional exceedences of current standards. The change in pollutant distribution farther afield is less clear, with localised increases and decreases due to re-routing. Overall the net effect is an increase in emission, with more sites experiencing a decline in air quality than an improvement (Table 3). This pollutant redistribution, undesirable from a social equity perspective, is more significant than with any other transport scenario.

5.5 Clean fuel vehicles

The clean technology scenario assumes strong growth in CFV use to 2015. However, it is necessarily speculative with respect to CFV market penetration rates, whilst emission factors are poorly specified compared to those for conventional fuels. However, the test is sufficient to provide a simple comparison of the impact of clean technology on urban air quality, relative to the road user charge options. Excepting NO_2, emissions fall for all pollutants (4% for CO_2), and significant improvements in air quality occur ($P<0.0001$). NO_2 is an exception as Euro II-IV

LPG emission factors were unavailable, and the Euro I LPG factors used in their place give a higher fleet weighted NO_X emission at low speeds than conventional Euro II-IV vehicles.

6 Discussion

In the absence of new transport interventions, urban air quality is likely to improve further, despite the fact that rising trip demand results in longer, slower journeys and an increase in total PCU kms travelled on the network. These improvements arise as continual fleet turnover results in a vehicle fleet with more and better emission control technology. However, trip growth from 2005-15 will counteract much of the emission benefits of clean technology, and the rate of air quality improvement over the next decade will be much less than that experienced during the 1990's. An exception is fine particulates where increased travel demand will cause PM_{10} emission to increase substantially. This is likely to be a significant problem for cities where particulate emissions are dominated by road traffic, especially given that a much tighter PM_{10} standard will be enforced from 2010.

With respect to road user charging, we must note some caveats to our analysis. First, we have no assessment of what happens to suppressed trips. Those realised as car sharing, walk, cycle or 'no travel' will not alter our emission estimates. Increasing bus provision is also unlikely to significantly raise emissions as new buses are likely to be CFVs. Second, if charging is only applied for part of the day, then trip suppression may be less (no suppression of trips outside charge period; changes in time of travel), and hence emissions could be higher than our estimates. Conversely, if differential charges were levied according to vehicle size (larger vehicles paying more), then emissions could be below our estimates. These factors were beyond the scope of the current study, but merit further analysis.

This study shows that road pricing can deliver improved air quality by constraining trip demand and reducing emissions. Whilst emissions are speed dependent, the key factor behind air quality improvement is a reduction in the total PCU km travelled on the road network (Figure 5) (this reduction is primarily driven by suppression of trips by private vehicle, as most road pricing regimes do not lead to shorter trips). A 1% suppression in total PCU-km reduces aggregate concentrations of CO and VOC species by 1.3%, but other pollutants are less responsive (0.25 % for NO_2, 0.025 % for PM_{10} and SO_2). Note however, that the effects are spatially highly variable. For example, a 10 p/km charge reduces annual mean NO_2 concentration by 11.2% across the whole city, but by 22.2% in the city centre (figures based on Table 2 data). NO_2 concentrations here are within permitted standards, but such a reduction in other cities may be highly significant with respect to standards compliance.

Road pricing could be an effective air quality management tool. However, its potential is context specific, dependent upon source apportionment and prevailing air quality (current spatial distribution, and level of standards compliance). Figure 5 shows that for Leeds, where particulate emission is dominated by point sources, road pricing will have little effect on concentrations of particulates. In contrast, NO_2 is strongly affected by traffic restraint (although by 2005, standard exceedences in Leeds have already been eliminated by better emission control technology). However, note that traffic restraint can very substantially reduce greenhouse gas emission (Figure 4) and can reverse projected CO_2 emission increases that would occur under a do-nothing strategy.

The effect of CFV use on urban air quality is broadly comparable to that of several of the road pricing tests. For example, total PCU-kms needs to fall by c. 10% to achieve an improvement in city mean annual PM_{10} concentration comparable to that achieved in the CFV scenario. Thus CFV's would be more effective at addressing particulate pollution than a £3 single cordon charge, but less effective than the double cordon or distance charging regimes. In practice, CFV benefits may be greater than this study suggests, as some CFV emission factors were poorly specified. However, CFV promotion and road user charging are not mutually exclusive policy options, and if implemented together, would clearly deliver more substantive air quality benefits. Lower charges for CFVs may thus be an effective mechanism to improve the uptake of CFVs.

Road pricing results in some re-routing to avoid the charge zone, an effect observed in Singapore (Chin, 1996). In the Leeds study, road user charging redistributes emissions spatially, with air quality declining in places, particularly along routes used to avoid the charge zone. In air quality terms, this effect is greatest under the single cordon regime, but is insignificant under the double cordon and distance charging regimes (Table 3). The reasons for this difference are that, firstly, the inner cordon encompasses the smallest charge zone, and induces a highly focused re-routing, leading to elevated emissions around the cordon exterior. Secondly, trip suppression under the inner cordon is much less than that of the double cordon and distance charge tests, where total reductions in emissions are much greater, and lead to a blanket improvement in air quality city wide. Note however, that even under the cordon charge, fewer sites experience a decline in air quality than would occur under the network development option. Furthermore, whilst there are clear social inequalities in the distribution of pollution (Mitchell, *in press*), with poor communities with low rates of car ownership located in the areas of greatest atmospheric pollution, measures that improves air quality city wide lead to a reduction in this inequity. Thus, whilst there may be social equity concerns over the application of road pricing, we find that environmental inequities can, perhaps contrary to expectations, be reduced by road pricing using realistic charges.

7 Conclusion

This study shows that road pricing can significantly reduce emissions and improve air quality, and that pollution redistribution, undesirable from a social justice perspective, is not a major concern. However, the success of road pricing as an air quality management tool depends upon prevailing air quality and the emission characteristics of the application city. If stationary sources dominate total emissions, and/or compliance with air quality standards is high, then the air quality benefits of road pricing will be modest. In the absence of a charge, air quality will continue to improve due to the increases in the efficacy and prevalence of emission control technology in the vehicle fleet, but CO_2 emissions will continue to rise.

Of the road pricing regimes investigated, a modest distance charge is considered appropriate based on the Leeds study. The 2 p/km charge delivers environmental gains (modest aggregate air quality improvements with no standard exceedences, greenhouse gas emissions decline c. 12 %), with minimal socially undesirable spatial redistribution of pollution, and was the only test investigated (road pricing or otherwise) with faster, shorter trips. This conclusion supports the government transport advisory body, who following a series of studies (with little attention given to environmental impact), recommended charging for road use via distance travelled (CfIT, 2002). Further evaluation is, however, required to identify an optimum distance charge, in which a wider range of costs such as noise, community severance, journey reliability and infrastructure costs are included. Whilst research has investigated optimal distance charges that include environmental considerations (Fridstrom *et al*., 2000), none has been conducted in which pollution effects are explicitly evaluated. Thus there remains a need to assess whether distance charges which are optimal when considering air quality impacts explicitly, vary from those in which environmental considerations are treated more generally. If explicit consideration of air quality proves important, then it is evident that the relative contribution of transport emissions to total emissions, together with the prevailing air quality, will be important in determining an optimum distance charge.

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CAPTIONS

Figure 1. Road user charging cordons and areas, and network developments, Leeds

Figure 2. Network performance statistics

Figure 3. Impact of emission control technology on emissions under Business as usual

Figure 4. Change in greenhouse gas emission from road transport in Leeds

Figure 3. Total vehicle kilometres and urban air quality in Leeds

Table 1. Summary of the Leeds transport-air quality simulations

Table 2. Air quality in Leeds under alternative road transport strategies

Table 3. Pollutant redistribution in Leeds in response to road transport strategies

Figure 1. Road user charging cordons and areas, and network developments, Leeds

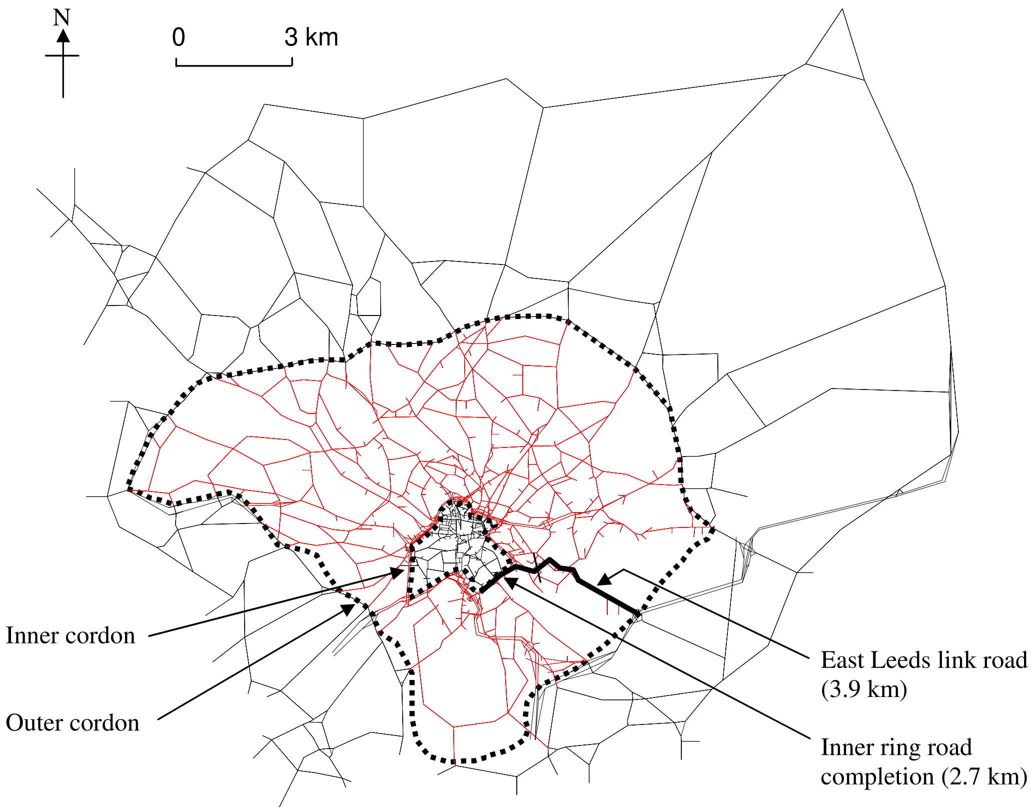

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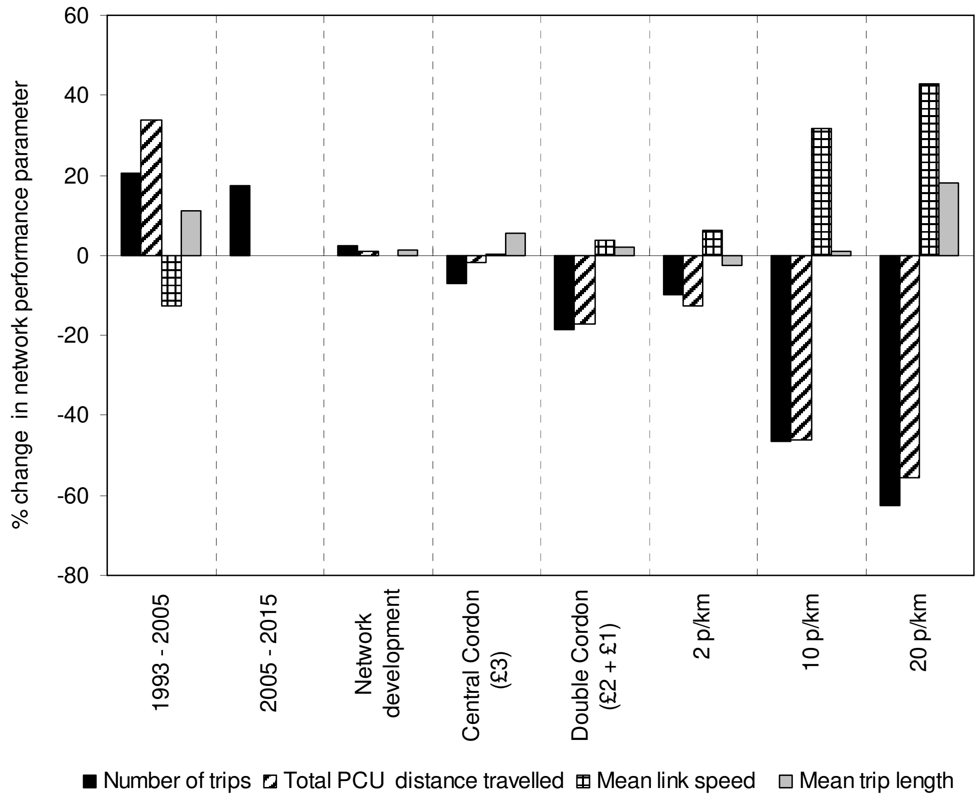
Figure 2. Network performance statistics



Notes:

1. All scenarios relate to the 2005 Do-minimum network
2. No assignment modelling conducted for 2015, hence no trip distance, speed or length data.

Figure 3. Impact of emission control technology on emissions under 'Business as usual'

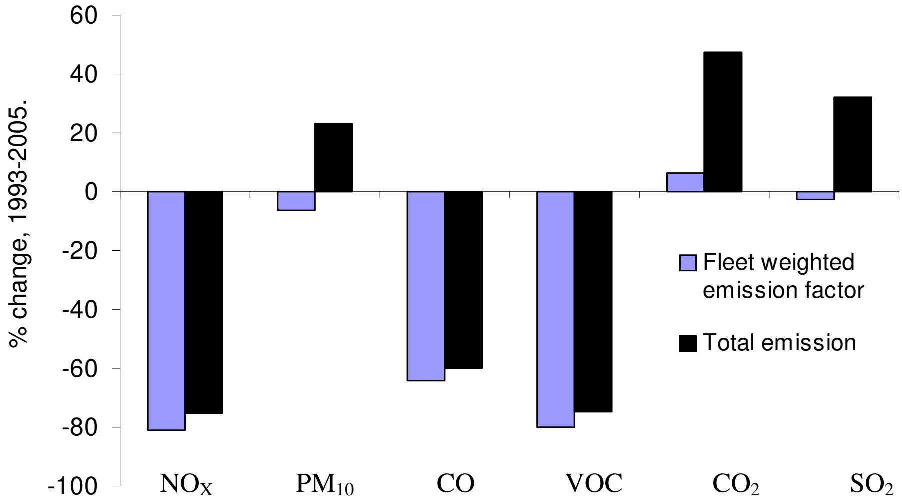
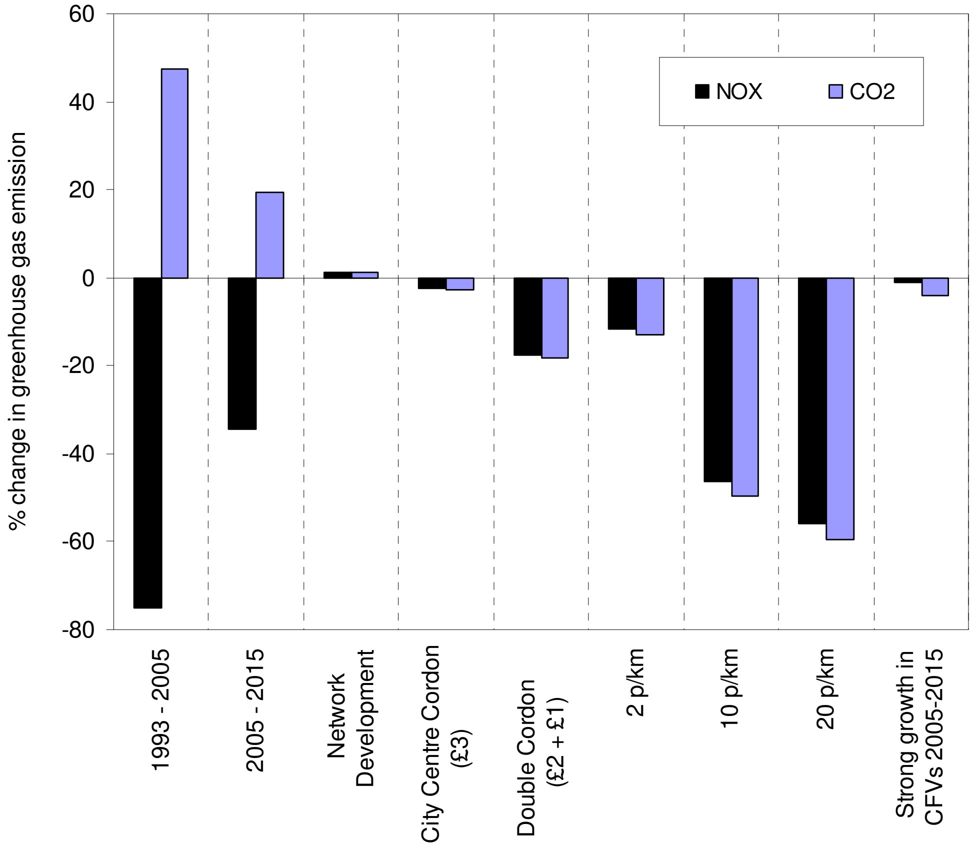


Figure 4. Change in greenhouse gas emission from road transport in Leeds



Notes:

1. All scenarios relate to the 2005 Do-minimum network
2. Emissions in 2005 are 4.04 t km^{-2} yr^{-1} of NO_X, and 1.272 kt km^{-2} yr^{-1} of CO_2

Figure 5. Total vehicle kilometres and urban air quality in Leeds

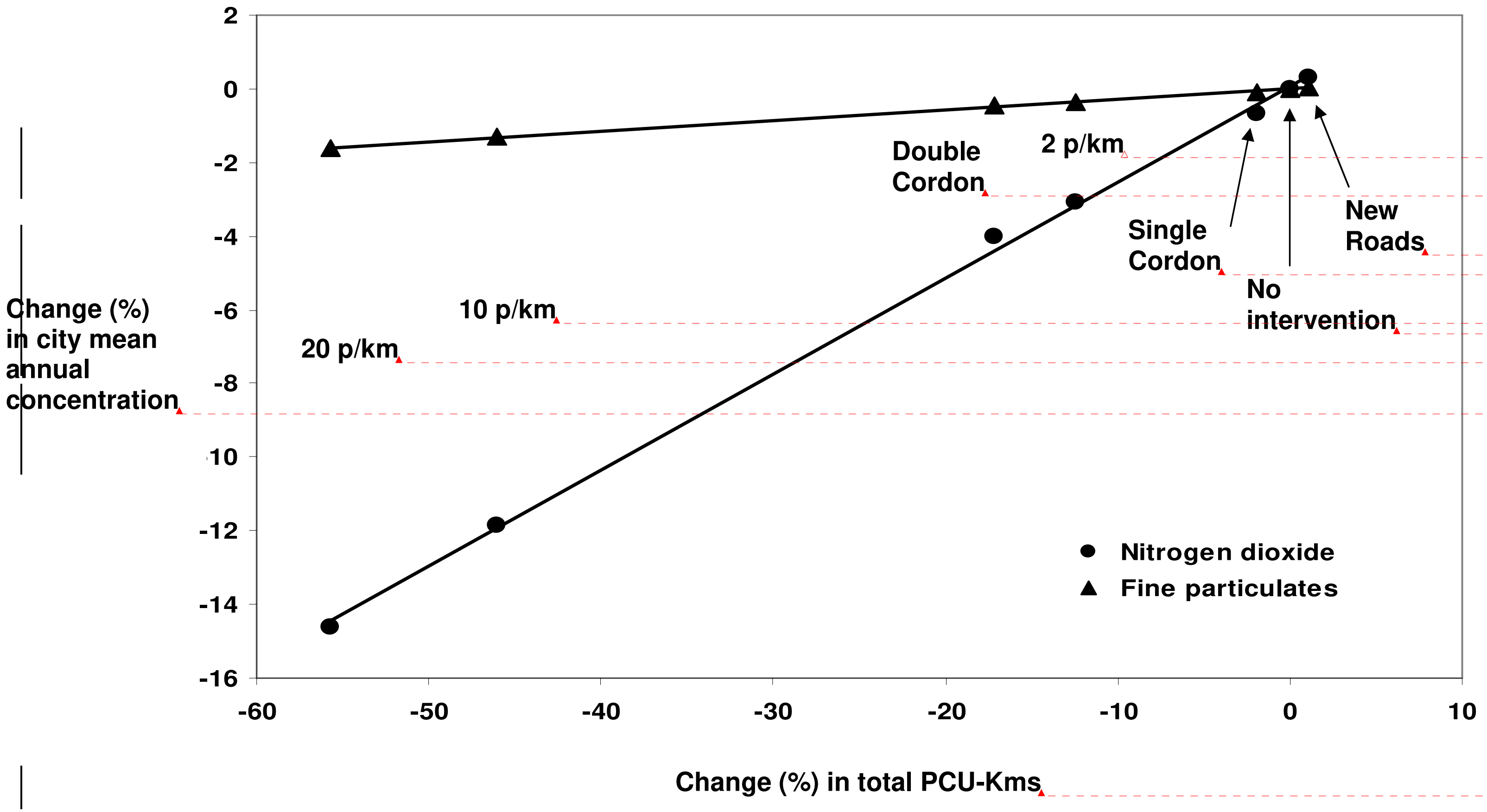


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Table 1. Summary of the Leeds transport-air quality simulations

Test	Year	Road Network	Road user charge or clean fuel vehicle (CFV) test	Additional test (b) with ADMS sensitivity test
1	1993	Observed		
2a, 2b	2005	Do-min		Intelligent gridding
3a, 3b	2005	Do-min		Street canyons
4a, 4b	2005	Do-all		Intelligent gridding
5a, 5b	2005	Do-min	£3 inner cordon	Intelligent gridding
6	2005	Do-min		
7	2005	Do-min	£1+£2 double cordon	
8	2005	Do-all	£1+£2 double cordon	
9	2005	Do-min	2 p/km inside outer cordon	
10	2005	Do-min	10 p/km inside outer cordon	
11	2005	Do-min	20 p/km inside outer cordon	
12a, 12b	2015	Do-all		Intelligent gridding
13	2015	Do-all	11% of fleet as CFV's	
14	2015	Do-min		

Note: Air quality simulations for the road user charge tests are based on the preferred link 'demand' flow parameter, whilst all other tests were based on 'actual' link flows due to data availability. Tests confirmed that the different flow variables had a negligible impact on air quality, thus permitting a confident comparison of charge and non-charge tests.

Table 2. Air quality in Leeds under alternative road transport strategies [a]

Scenario / policy [b]	NO_2 at city centre AUN [c] site		City-wide (12x12km) [Number of site exceedences in brackets]				
	Annual Mean ($\mu g\,m^{-3}$)	1 hr mean 99. 8 centile ($\mu g\,m^{-3}$) [d]	NO_2 Annual Mean ($\mu g\,m^{-3}$)	PM_{10} Annual Mean ($\mu g\,m^{-3}$)	24 hr mean PM_{10} 90.41 centile ($\mu g\,m^{-3}$)	1 hr mean CO 100 centile ($mg\,m^{-3}$)	1 hr mean SO_2 99.72 centile ($\mu g\,m^{-3}$)
Air quality standard	40	200	40	40	50	11.6	350
Business as usual							
1993 network	39.36	146.72	29.24 [260]	28.65 [24]	42.88 [92]	3.37 [19]	288.20 [13]
2005	24.04	110.43	19.68 [0]	28.71 [24]	42.94 [91]	1.17 [0]	288.24 [13]
2015	21.99	107.99	17.09 [0]	28.38 [24]	42.59 [80]	0.48 [0]	287.95 [12]
Cordon based road user charging							
Zero toll	25.75	112.83	20.05 [0]	28.78 [25]	43.02 [95]	1.34 [0]	288.27 [13]
Single cordon £3	24.38	111.67	19.92 [0]	28.76 [25]	42.99 [93]	1.28 [0]	288.26 [13]
Double cordon £2+£1	24.02	111.45	19.25 [0]	28.66 [24]	42.89 [91]	1.08 [0]	288.22 [13]
Distance based road user charging							
Zero toll	25.75	112.83	20.05 [0]	28.78 [25]	43.02 [95]	1.34 [0]	288.27 [13]
2 p/km distance toll	24.63	110.99	19.44 [0]	28.68 [25]	42.92 [94]	1.08 [0]	288.23 [13]
10 p/km distance toll	20.05	107.39	17.69 [0]	28.41 [24]	42.66 [81]	0.48 [0]	288.12 [13]
20 p/km distance toll	17.58	107.25	17.12 [0]	28.33 [24]	42.58 [81]	0.34 [0]	288.09 [12]
Road network development							
2005	24.04	110.43	19.68 [0]	28.71 [24]	42.94 [91]	1.17 [0]	288.24 [13]
2005 Do-All	23.82	110.43	19.74 [0]	28.72 [24]	42.99 [92]	1.18 [0]	288.25 [13]
Clean fuel vehicle (CFV) promotion							
2015 Do-All	19.59	106.87	18.49 [0]	28.77 [24]	42.99 [92]	0.76 [0]	288.28 [13]
2015 Do-All CFV	21.83	107.91	18.48 [0]	28.70 [24]	42.93 [91]	0.71 [0]	288.25 [13]

a. Non-transport emissions are held constant hence differences in air quality between scenarios are attributed solely to the transport scenarios

b. All scenarios are based on the 2005 Do-min network unless otherwise indicated. c. The national air quality monitoring network.

d. i.e. the NO_2 1-hour mean must not exceed 200 $\mu g/m^3$ more than 18 times a year - the 99.8th percentile of one year of hourly values

Table 3. Pollutant redistribution in Leeds in response to road transport strategies

Scenario / Policy	NO_2 annual mean		PM_{10} annual mean	
	No. sites degraded [a]	No. sites improved [a]	No. sites degraded [a]	No. sites improved [a]
'Business as usual'				
1993-05	10	3584	122	10
2005-15	0	3600	1	1678
Network Development				
Do-Min v. Do-All	399	104	12	2
Cordon based road user charging				
Single cordon	231	824	9	64
Double cordon	7	3535	0	235
Distance based road user charging				
2 p/km	10	3222	0	130
10 p/km	0	3599	0	1734
20 p/km	0	3600	0	1953

[a] Number of sites (receptor locations) where concentrations have changed (degraded or improved) by at least 1%. 3600 sites were modelled on a regular grid with 200m intervals.