The impact of road pricing and other strategic road transport initiatives on urban air quality

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Abstract

The UK National Air Quality Strategy (NAQS) 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. Whilst there are numerous policy options available for managing urban traffic their air quality implications at the city scale are largely unknown. This paper presents preliminary results from the 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 (TEMMS) to assess the impact of alternative transport scenarios on air quality for the city of Leeds, UK.

The scenarios addressed include "business as usual" traffic growth to 2015; network development; road pricing with cordon charging; road pricing with distance charging; and the wider adoption of clean fuel vehicle technology. The impact of these developments on air quality (nitrogen dioxide, particulates and sulphur dioxide), including exceedence of air quality standards is identified. Finally, differences in the spatial distribution of air quality (as \(\text{NO}_2\)) between scenarios are highlighted, in light of their significance to social equity concerns.

1 Air quality review and assessment

Over the last few decades significant improvements in urban air quality have been made in many countries, yet in 1998 the European Environment Agency (EEA) concluded that significant problems remain, particularly with nitrogen oxides, sulphur dioxide, carbon monoxide and particulates, all of which
sometimes exceed World Health Organisation guideline values. The EEA [1] estimate that in the EU's 115 largest cities, 40 million people experience at least one exceedence of a health based air quality standard every year.

These problems have fuelled the demand for a coherent regulatory framework for the management of atmospheric emissions and air quality at local, regional and national levels. In the UK, government passed the 1995 Environment Act stating national policy concerning air quality.

The Act required the development of a National Air Quality Strategy (NAQS) to enable the UK to achieve its air quality objectives, and meet it's international commitment's, including those of 1996 EU Air Quality Framework Directive (96/62/EC) and subsequent daughter directives. These directives set legally binding limit values for a range of pollutants, and the target dates by which these standards must be met, but it remains the responsibility of member states to decide how best to achieve the objectives set by the directives.

The NAQS, published as a consultation document in 1997, and formally adopted in 2000 (DETR [2]) defines UK policy, tasks and responsibilities for achieving ambient air quality objectives. A major task is the review and assessment of urban air quality, where local government must determine if ambient air quality is likely to meet EU standards by the target date of 31 December 2005.

The NAQS recommends a three phase assessment approach, with the final phase employing detailed modelling if the earlier screening phases indicate the possibility of standard exceedence(s). If this stage 3 assessment confirms this possibility, then local government has the power to designate air quality management areas (AQMA's), which must be supported by an air quality management action plan detailing measures that the authority intends to pursue to ensure that the air quality objectives for that location are met in time.

In Western Europe road transport has overtaken industrial processes and coal combustion as the main source of atmospheric emissions (EEA[1]), and for most UK cities, it is the main source of NO₂ and PM₁₀ pollution (Carruthers et al.,[3]; Stedman, [4]) 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.

To support air quality management action planning, we investigated the impact of several strategic road transport scenarios and policy options on urban air quality, through application of a series of linked dynamic models. The research addressed Leeds, UK, a large (562 km²) metropolitan district with 740,000 residents.

Leeds 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, [5]). Such rapid growth suggests that air quality in 2005 may be at risk of failing the directive standards. However, this growth also makes Leeds an ideal city to study the 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 The transport-air quality modelling system

2.1 Overview and traffic modelling

Central to the integrated transport-air quality model system is TEMMS (Traffic Emission Modelling and Mapping Suite), a GIS-model using 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., [6] give a detailed description of TEMMS development and application.

To date, TEMMS has been exclusively applied in conjunction with SATURN, a widely used interactive simulation and assignment model (Van Vliet [7]), although any source of link flow data can be used.

Using a fixed trip (origin-destination) matrix and description of the network, assignment and simulation procedures run iteratively, until an equilibrium point is reached at which costs (e.g. times) are optimised. These procedures consider parameters of minimum gap acceptance, junction type, number of lanes, turn data, traffic signal stages and cycle rate, which all impact upon time spent at junctions, the key parameter fed back to the cost optimising routine. The final result is a detailed spatial representation of traffic flow (PCU’s) and mean speed for each link of the network for a specified period such as the morning peak.

2.2 Emission modelling

Using its integral model ROADFAC, TEMMS calculates link based emissions of NOx, CO, CO2, SO2, PM10, PM2.5, 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 [8]). The fleet is described according to vehicle type, gross weight, engine capacity and type, fuel and emission control technology used, giving 72 sub-classes with characteristic emission rates. Data is based on vehicle sales, with projections for future years based on historical trends in vehicle ageing, and scheduled emission control legislation.

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.

For each link, a composite emission factor is determined from the fleet data, vehicle class emission factors, and mean link speed. 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.
2.3 Air quality modelling

For the work reported here, TEMMS was applied in conjunction with ADMS-Urban (CERC [9]), a commercial dispersion model formally recognised by the NAQS as being suitable for assessing compliance of urban air quality to standards. ADMS-Urban uses boundary layer similarity profiles to parameterise variation in turbulence with height within the boundary layer, and uses a skewed-Gaussian distribution to determine the vertical height of pollutant concentrations in a plume under convective conditions. Boundary layer stability parameters are calculated from wind speed, surface heat flux and boundary layer height.

Emission from sources other than vehicles were derived from the local government stationary source emission inventory, which quantifies pollutant annual mass emission and ADMS-Urban required parameters (stack location and height, gas exit velocity and temperature) for the 416 regulated point source emissions in the city. Minor point (< 0.1 tonne/yr) and other area source emissions are addressed through consideration of background concentrations (using observed concentrations from an upwind rural monitoring station) and via calibration of modelled and observed data.

ADMS-Urban was applied to Leeds using surface roughness default values to represent topography, and the Generic Reaction Set model to calculate NO₂ concentration from NOₓ emission. We used sequential (hourly) meteorological data for 1999 which is a close approximation to the long run (1990-99) average, has a time step corresponding to that used in modelling mobile emissions, and which gives better estimates of peak values than statistical meteorological data.

In hourly steps, the model simulates a full year of atmospheric pollutant concentrations from which compliance to the prevailing air quality standards is assessed as annual mean and percentile standards (Table 2). For example, the NO₂ 1 hour mean must not exceed 200μg/m³ more than 18 times a year, which is the 99.8th percentile of one year of hourly values. Emissions were modelled for a 30 x 25km box centred on Leeds, and concentrations simulated for a 12 x 12km box covering the entire built urban area, at a spatial resolution of 200m.

2.4 Model Calibration and Validation

Namdeo et al., [6] note that the likely error of the constituent models are c. ±12% for SATURN vehicle flows, ±4-35% for the emission factors, ±5-10% for fleet composition, and ±20% for the dispersion model, suggesting that the system should be capable of predicting pollutant concentrations within about 40-75% of observed concentrations, which NAQS guidance indicates is acceptable for conducting strategic level statutory air quality assessments.

To calibrate the system we modelled 1993 air quality, the only year for which we had corresponding SATURN matrices, meteorological and observed pollutant concentration data (NO₂, PM₁₀, SO₂ from the Leeds central AUN station). A calibration factor was derived by comparing observed mean concentrations (Jan-June) with modelled values for the same location. Application of the calibration factor to the modelled data (July-Dec) gave calibrated means within 4% of the
observed. Ideally, this procedure would be conducted over a wider spatial area using data from multiple monitoring stations, but this data is not available.

3 Development of road transport and emission scenarios

We investigated the air quality implications of five strategic transport and emission scenarios with potential city wide effects, including 'business as usual'; network development (new roads); road user charging using distance and cordon charges; and the introduction of clean fuel vehicle technology. These scenarios address strategies that are underway (new roads), under consideration in the local transport plan (road pricing), or promoted nationally (clean fuels).

3.1 Network development

The impact of major road schemes on air quality was investigated through three Leeds SATURN networks. The first represents the network as it was in 1993, with 10,250 links, 1314 intersections, 327 priority junctions and 17 roundabouts. For the morning peak simulation, over 85,000 trips between 370 zones are simulated. The second represents the network in 2005, with the minimum of major road schemes implemented (and >102,000 trips). This 'Do-Min' network includes the A1-M1 link road (opened in 2000), a motorway skirting the city to the south east, linking two existing regional motorways. The third network (2005 'Do-All') additionally includes 3 km of inner-city dual carriageway that completes the inner ring road, and is expected to remove much city centre through traffic, and the east Leeds link road, 4 km of dual carriageway intended to relieve congestion and promote economic regeneration in east Leeds.

3.2 'Business as usual'

The effect of a 'do nothing' strategy was assessed for 1993 (standard network), 2005 and 2015 ('Do-Min' network). For each simulation year, traffic volume, and fleet characteristic data are required. Traffic volume (PCU's / link) for 1993 and 2005 are output by SATURN, and the 2015 link flows obtained by applying a growth factor to the 2005 flows. The Leeds factor was derived from TEMPRO 3.1, the UK national trip-end forecast model (HMSO [10]). This predicted a growth of 17.3% (2005-15), which we understand forthcoming TEMPRO 4 projections will show are conservative. From 1993-2005 trips grew by 21%, and total vehicle/kms travelled by 34%. For all years, observed or predicted UK fleet composition and emission factors were obtained from MEET (EC, [8]).

3.3 Road user charging

Under the Transport Act 2000, UK local government has the power to implement road user charging to tackle congestion and traffic pollution. To date, only London has made a firm commitment to road pricing, but 24 other UK local
authorities, including Leeds, consider its implementation in their local transport plans for 2000-2005.

We assessed possible impact on air quality of road pricing using cordon and distance charging. Cordon charging was selected as it is proven technologically (Singapore, Norway), and hence of most interest to local authorities. However, from an assessment of network performance (generalised cost, trip time and distance, total trips) under road pricing, May and Milne [11] found that cordon pricing was the least effective regime, although it is very sensitive to cordon location. They concluded that, given concerns over added driver risk taking and the uncertain charge per trip associated with time and congestion charging, future road pricing work could usefully focus on distance based charging.

All our road pricing tests were conducted on the 2005 'Do-Min' network, using SATAX (Milne and Van Vliet [12]), a module of SATURN that uses the SATEASY elastic assignment algorithm to model trip demand in response to generalised cost. 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 details the tests and associated trip suppression.

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

<table>
<thead>
<tr>
<th>Road user charging (2005 'Do-Min')</th>
<th>% Reduction in trips [and v/kms]</th>
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</thead>
<tbody>
<tr>
<td>City centre (inner orbital) cordon : £3</td>
<td>7.0 [2.0]</td>
</tr>
<tr>
<td>Distance charge : 2p/km</td>
<td>8.8 [11.1]</td>
</tr>
<tr>
<td>Double cordon : £2 inner and £1 outer</td>
<td>18.5 [17.2]</td>
</tr>
<tr>
<td>Distance charge : 10p/km</td>
<td>47.0 [46.1]</td>
</tr>
<tr>
<td>Distance charge : 20p/km</td>
<td>62.5 [55.7]</td>
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</table>

The inner cordon charge was set to £3, deemed politically acceptable by the local government, but below the £5 toll fated for London in 2003. 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 [11]) 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.

3.4 Clean fuel vehicle technology

Finally, we investigated the air quality implications of growth in clean fuel vehicle (CFV) use, addressing technologically viable fuels with proven emission
benefits promoted through the government's 'Powershift' programme: liquefied petroleum gas (LPG) and electricity. For 2015, fleet composition was adjusted to include 2% electric vehicles, 3% hybrid, 1% fuel cell and 5% LPG. For electric vehicles we used the MEET (EC [8]) high growth forecasts. These are based on evolutionary not revolutionary market changes, and hence are very speculative. MEET has no UK LPG use forecasts, so we chose a value consistent with MEET forecasts for the Netherlands and Italy, which exhibit strong LPG growth.

Emission factors were also drawn from MEET (EC [8]), although the data is sparse and are meant only as a guide. For electric vehicles (hybrid and methanol fuel cell), emission factors are not speed dependent, and are given for three classes only: passenger cars, light duty vans and buses. Emissions from battery operated vehicles are assumed to be zero at point of use. For LPG, factors relate only to vehicles <2.5 tonnes, and only address uncontrolled and Euro I standards. Euro I LPG factors were therefore applied for Euro II-IV vehicles.

4 The impact of strategic road initiatives on urban air quality

Results from the study are summarised in Table 2 for nitrogen dioxide (NO₂), particulates (PM₁₀) and sulphur dioxide (SO₂). Results are given city wide for all three pollutants (annual mean, 1 or 24 hour mean, and number of sites exceeding the standard) and also for a single city centre location for NO₂.

Under the 'business as usual' scenario, 1993-2015, there is a great reduction in city wide annual mean NO₂ (by 42%, P<0.001), a small (1%, P<0.001) reduction in PM₁₀, and no significant change in SO₂. The NO₂ reduction is driven by a rapidly declining fleet weighted emission factor, c. 90% over the forecast period. For PM₁₀ and SO₂ the comparable emission factor reductions are c.10% and 2% respectively, insufficient to offset additional emissions arising from an increased trip volume. The modelling forecasts no NO₂ standard exceedence by the NAQS 2005 target year, and a few exceedences for SO₂ and PM₁₀. These exceedences are largely attributable to point sources, that typically account for 40% of all NOₓ emitted, 76% of PM₁₀ and 93% of SO₂ (i.e. NOₓ is most sensitive to road traffic).

The planned Leeds network developments reduce air quality city wide for all three pollutants, as under the 'Do-All' scenario, trips increase by 2.4%, and vehicle kilometres by 4.2%, raising total emissions. The additional capacity reduces the generalised cost for some O-D pairs, bringing additional trips onto the network via the elastic assignment procedure, and causing re-routing of some trips to longer, but faster routes. City wide, the air quality differences are not statistically significant, but there is a significant spatial redistribution, with air quality reduced around the new links and their feeders, but improving elsewhere.

City wide, road pricing lowers NO₂ concentrations (P<0.001), reduces PM₁₀ under the 10p/km and 20p/km charges only (P<0.001), and has no effect on SO₂. Effects are greatest for NO₂, which is most sensitive to road emissions, and least in SO₂, where total emissions are dominated by point sources. Each pricing regimes has a different effect. City wide, NO₂ is reduced by just 0.7% under a single cordon, 4% under a double cordon, and 3%, 12% and 15% under the 2p, 10p and 20p per km charges respectively.
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<tr>
<th>Scenario</th>
<th>NO(_2) at city centre AUN site</th>
<th>PM(_{10}) Annual Mean</th>
<th>SO(_2) Annual Mean</th>
<th>PM(_{10}) 99.8th centile</th>
<th>SO(_2) 99.8th centile</th>
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1. Networks 2005 Do-Min unless otherwise stated; 2. 3600 sites at 200m intervals; 3. Modelled SATURN demand flow, not SATURN 'actual flow'.
These changes in NO$_2$ correlate highly with change in total vehicle kms travelled (Table 1). All pricing regimes reduce this distance. Under the single cordon, distance is reduced more strongly via trip suppression, with mean distance per trip increasing 6%, indicating re-routing to avoid the cordon. This is clearly seen in an NO$_2$ map, where a redistribution from the city centre to the cordon exterior occurs. The 2p/km regime is arguably most efficient from an air quality perspective: NO$_2$ reduction is comparable to that of the double cordon but at a fraction of the toll (mean trip fee is c. 20p), and with only 2.5% of locations experiencing increased NO$_2$ (cf. 0.4% double cordon, 24% single cordon).

Strongly growing the use of clean fuels produces a minor and statistically insignificant improvement in city-wide air quality. The proportion of the fleet as CFV's in 2015 is still small compared to conventional vehicles, and so might be expected to have a minor impact, but it is the crude CFV emission factors that underpin these results. In particular, emissions from LPG Euro I vehicles are greater than from petrol Euro II-IV vehicles, giving an elevated fleet weighted NO$_x$ emission at lower speeds typical of city centre traffic. Thus to assess the effect of CFV's on city air quality much improved emission factors are required.

5 Conclusions

The study has shown that air quality in Leeds is generally good, with forecast exceedences of PM$_{10}$ and SO$_2$ standards attributed largely to point sources, not road traffic. Management of road traffic does, of course, modify air quality. The network development for Leeds is likely to degrade NO$_2$ as the added capacity increases trips and hence emissions. The drop in air quality is most noticeable close to the new roads, particularly the radial East Leeds link route, but also occurs widely across much of the eastern suburbs. However, the associated re-routing effect also leads to an improvement in air quality in the south of the city, where air quality is currently poorest due to the urban motorways.

Implementation of road user charging also has strong implications for the redistribution of air pollution. The single cordon in particular reduces pollutant concentrations significantly in the city centre, but does so at the expense of all areas immediately surrounding the cordon. Road pricing only brings major improvements in air quality ($>1\mu\text{g/m}^3$ NO$_2$ reduction) under high distance charges. However, considering the overall impact and distributional effects, a modest distance charge appears to be most efficient in reducing concentrations.

The clean fuel analysis demonstrates a need for much improved CFV emission factors. However, Euro II-IV vehicles have very low emissions so it is difficult to make an air quality case for CFV's at the strategic level. They may of course have a role to play in tackling local pollution hot spots (which we confirmed are more numerous under street canyon than flat terrain modelling), in low emission zones (LEZ) for example. But even ambitious LEZ's only achieve the gains which will arise by 2005 through natural fleet renewal (Carslaw and Beevers [13]). From an air quality perspective, the lesson is to ensure effective control of point sources, and adopt 'do nothing' strategic traffic management. Reducing congestion (where emissions are poorly modelled) is also likely to be important.
Acknowledgements

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References