A congestion sensitive approach to modelling road networks for air quality management

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Abstract: This research establishes an approach to modelling a congested road network for air quality management, which enables the assessment of traffic management solutions that may create only subtle changes in the traffic flow regimes. Road network emissions have been calculated using standard factors taking into account details of vehicle fleet composition, average speeds and road type. Additionally, the use of microsimulation traffic modelling in conjunction with an instantaneous emissions model (IEM) has been adopted to allow comparison between methodologies and enable congestion sensitive analysis of the impact of air quality management measures on the network.

Findings from microscale modelling have revealed that the use of an IEM to calculate emissions as an input for air quality dispersion modelling significantly improved the performance of the dispersion modelling when measured against monitored data. Moreover, this methodology has been successfully applied to assess the performance of a traffic scheme in Durham, UK.

Keywords: (Air quality, emissions, Instantaneous emissions model (IEM), microsimulation, dispersion modelling)

Biographical notes: James O'Brien: Is currently completing a PhD in the Transport Operations Research Group at Newcastle University, England. His research is in developing and modelling transport scenarios for improving air quality across the North East of England. Anil Namdeo: Is a Chartered Environmentalist, a Chartered Scientist and a Senior Lecturer in Transport and Sustainability at Newcastle University. Margaret Bell CBE: Professor Bell's main contribution to knowledge rests with queuing model for TRANSYT, ageing of traffic signal plans and pioneering research in assessment of impacts and management of traffic related environment, exposure and health. Paul Goodman: Is a Research Associate at Newcastle University, UK. His research interests lie at the interface of transport models of various kinds with environmental models.

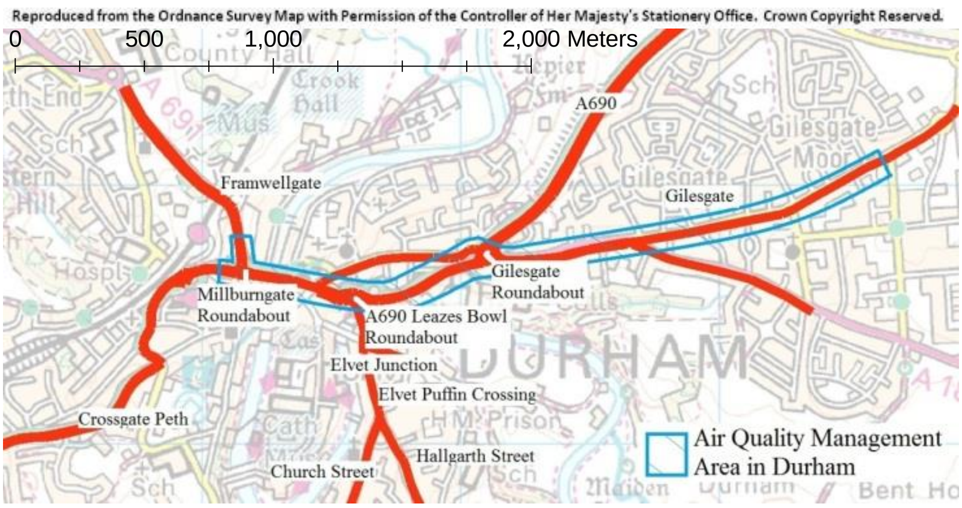
Introduction

Today the major threat to clean air in urban areas is posed by traffic emissions (DEFRA, 2011). There is clear evidence of the adverse effects of outdoor air pollution, especially for cardio-respiratory mortality and morbidity (Kapposa *et al*., 2004). It is estimated that each year in the UK, air pollution is associated with 50,000 premature deaths (EAC, 2010a). Despite existing air quality legislation, EU countries (including the UK) are failing to meet targets, particularly for nitrogen dioxide (NO_2) (EAC, 2010b).

The City of Durham is located in the North East of England in County Durham. Durham is the largest urban area within the county with a population of 38,000. It is a significant administrative, educational, employment and service centre within the region (Durham County Council, 2010).

Air quality monitoring by Durham County Council (DCC) has indicated that significant areas of Durham are failing the national annual long-term mean objective / EU limit value for NO_2. In response to this an Air-Quality Management Area (AQMA) in the City of Durham was declared in May 2011. The AQMA incorporates the Highgate, Milburngate and Gilesgate areas (Figure 1). DCC is currently working in accordance with the UK Environment Act 1995 to produce an AQMA Action Plan (DEFRA, 2010).

Figure 1. Extent of Air Quality Management Area in Durham.



This paper presents findings from a comprehensive study of the feasibility of a particular traffic engineering scheme proposed by DCC. The scheme is under consideration for inclusion in Durham's Air Quality Action Plan, as significant peak period congestion on Durham's road network has been identified by DCC; and road transport is the main contributor to 89% of the UKs AQMAs (Chatterton, 2008). The stated aims of the scheme are to reduce network emissions (specifically NO_2) and reduce congestion and delay. Key features of the scheme include the introduction of traffic signals at two roundabouts (Gilesgate and Leazes Bowl Roundabouts), amending the layout of the Leazes Bowl Roundabout; and co-ordination of the timing of the traffic signals between both the roundabouts and across adjacent junctions.

Methodology

In order to model the existing and proposed scenarios in Durham an S-Paramics (SIAS, 2001) micro-simulation model was developed. It was necessary to adapt an existing Paramics microsimulation model of Durham, developed by DCC, to make it suitable for use with an instantaneous emissions model (IEM). The most significant development was the addition of gradient as it is accepted that gradient has a significant impact on traffic emissions (Harris, 2004). Given the hilly terrain of Durham, road gradient was considered an important aspect affecting the acceleration and deceleration of vehicles within the network. This necessitated a full recalibration and validation of the model, in line with DMRB 12 (DfT, 2013) guidelines.

Two independent emissions modelling techniques were adopted for modelling vehicular emissions. Firstly, the Durham road network was modelled using PITHEM (Platform for Integrated Traffic, Health and Emissions modelling) developed by Newcastle University. (Namdeo and Goodman, 2012). PITHEM contains an integral emission model which calculates emissions and particulates using latest UK emission factors (i.e. National Atmospheric Emissions Inventory (NAEI)). National fleet emissions factors are determined as a function of vehicle type, age, emission control standard, engine size and fuel used. These factors are applied via PITHEM to twenty-four hour traffic count and traffic speed data obtained for each link in the network. PITHEM is currently under development to take in to account updated NOx emission Factors taken from the latest DEFRA Emission Factor Toolkit - Version 5.1.3.

However, it is recognised that methodologies which rely on average speed based emission factors can lead to significant underestimation of emissions on particular streets and junctions where congestion and queues build and prevail for a high proportion of the day (Boulter *et al.*, 2007). Therefore, a second methodology was adopted using a traffic microsimulation model (S-Paramics) in conjunction with an instantaneous emissions model (IEM) (AIRE) to estimate vehicular emissions in the Durham network. IEMs calculate the emissions of an individual vehicle, based on vehicle type, speed, acceleration and the gradient to which it is currently subject. In the case of AIRE, these conditions are matched against over 3000 vehicle emissions maps which were recorded in laboratory tests for a wide range of vehicles. This data was gathered from the Project Passenger car and Heavy Duty Emissions Model (PHEM), an output of the EU fifth framework ARTEMIS Project (Boulter *et al.*, 2007). The principle advantage of the adoption of an IEM methodology is to better capture congestion related emissions and more accurately reflect the potential scheme benefits. This research concentrates on NO_x outputs, given that the declaration of the AQMA in Durham was for NO_2. NO_x outputs may be subsequently converted to NO_2 levels by appropriate dispersion and chemical modelling.

Results

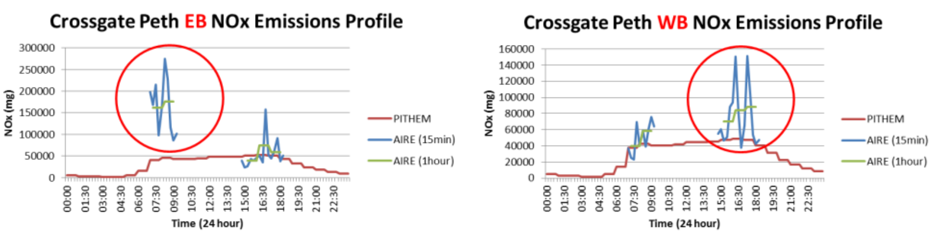
Comparative Emissions Results

Analysis was performed to investigate the relationship between the NO_x emissions results derived from the traditional NAEI-based average speed emissions methodology and the AIRE derived IEM technique. Each network was split into approximately thirty road sections to aid comparison. Average speed NAEI emissions were analysed for a full 24-hour period, at one hour resolution. IEM emissions outputs were aggregated into fifteen minute averages, as well as hourly averages to compare directly with the average speed emissions results.

A close correspondence between the two methodologies was identified on a number of links, providing confidence in the techniques adopted. However, further analysis of the traffic and related outputs revealed that a large number of links showed evidence of ‘congestion’ emissions in the AIRE results. Generally, for periods immediately preceding or directly after the peak traffic period, a good agreement was found between the two methodologies. Conversely, during the peak, when congestion is highest, the emissions outputs derived using the AIRE methodology were found to be far higher than those from based on NAEI emissions factors.

Furthermore, an analysis of a number of arterial routes provided evidence of tidal congestion emissions. Figure 2 shows the Crossgate Peth area of Durham City. During the morning peak the eastbound (EB) movement is congested with people travelling into Durham, with significant increase in emissions in the AIRE outputs compared to the average speed NAEI results. However, in the afternoon peak, when flows going in to Durham are lower, conditions were found to be less congested and the two methods were in better agreement. Conversely, for the westbound (WB) movement it is the afternoon peak when congestion is observed due to high volumes of traffic leaving Durham. Once again the AIRE emissions agreed well with the NAEI-based methodology except in the congested period.

Figure 2. Crossgate Peth link emissions (NOx).



Across the network significant differences in modelled emissions between the two methodologies were observed. The most heavily congested links revealed +200% higher emissions predicted using AIRE compared to the NAEI outputs. The overall network results can be seen in Table 1.

Table 1. Overall network results, NAEI vs. AIRE (NO_x).

Peak	**NO_x (mg) NAEI**	**NO_x (mg) AIRE**	**Difference (mg)**	**Difference (%)**
AM	10,782,900	17,454,206	6,671,306	62
PM	19,261,700	26,830,555	7,568,855	39

Durham Traffic Engineering Scheme Results

Following the exploratory work and analysis of the emissions methods it was concluded that the impacts of Durham Traffic Engineering Scheme would be more accurately assessed using an IEM approach to emissions modelling. As a number of key areas of Durham’s AQMA are congested for significant periods of the day congestion sensitive modelling was deemed vital for estimating the potential benefits of the scheme.

Microsimulation models reflecting the existing traffic network in Durham; and the revised network following the introduction of the proposed Durham Traffic Engineering Scheme were created. These models were run for both morning and afternoon peak periods. Each microsimulation model was run ten times (total forty runs. The number of runs was chosen following variance analysis which showed the outputs stabilised within ten model runs. The resulting output files were processed through AIRE, and subsequently analysed using a bespoke software program. The overall average network results from both of the modelled peaks can be seen in Table 2.

Table 2. Results from scheme appraisal, NO_x emissions from AM and PM peak periods.

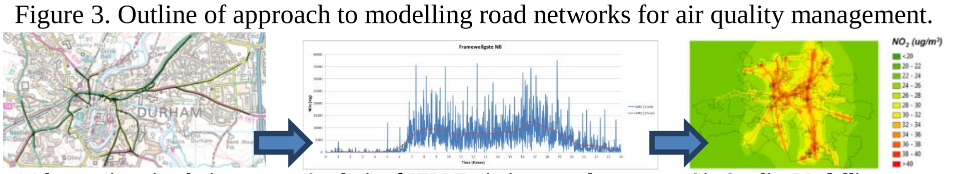
Peak	**NO_x (mg) Existing**	**NO_x (mg) Proposed**	**Difference (mg)**	**Difference (%)**
AM	47,387,363	43,913,854	-3,473,510	-7
PM	51,235,115	50,594,357	-640,759	-1

The results suggest that whilst the scheme shows a reduction of 7% in NO_x emissions during the morning peak, the benefits are much less at 1% for the evening peak. This may be due to the fact that the morning trips into the city are more constrained to the start times of employment and schools. The peak period during the evening peak is less stressed during the afternoon peak due to greater flexibility at the end of the day for businesses, industry and the school run.

Air Quality Concentrations

The emissions based approached to modelling air quality provided insight into the sources of air pollution. This is necessary to inform remedial measures. However, it is important to gain an understanding of how those emissions interact with local topography, built environment and meteorology. Atmospheric dispersion models use link based emissions estimates to predict the spatial distribution of pollutants over a given area by simulating the complex relationship between emissions estimates and outdoor air pollutant concentration (Hirtl, 2007). Meteorological and topography data (or surface roughness) are required to complete this process. Twenty-four hour estimates were produced for modelling, in order to allow the build-up and dispersal of emissions throughout the day to influence concentrations. The existing micro-simulation model was extended to include a diurnal profile when making estimates of emissions using AIRE. The 'minute-by-minute' emissions results were aggregated into hourly values for all links in the network. These were then fed onto a dispersion model enabling comparison of concentrations from the existing network compared to the proposed scheme (Figure 3).

Figure 3. Outline of approach to modelling road networks for air quality management.

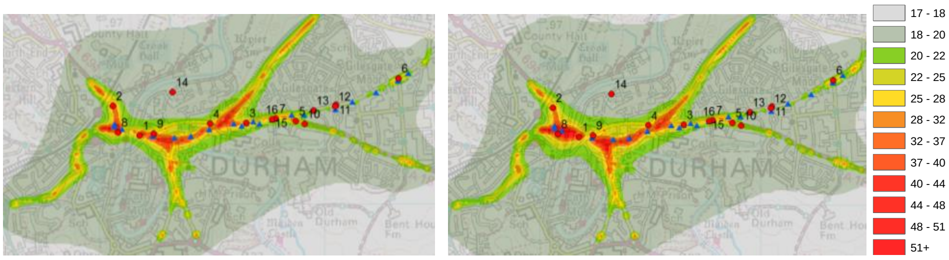


24-hour microsimulation ***Analysis of IEM Emissions results*** ***Air Quality Modelling***

ADMS-Urban (CERC, 2006) was used for this research as it is user friendly, stable and has been extensively validated by over 70 UK local authorities (Riddle *et al*., 2004). In this assessment modelled NOx values were converted to NO_2 using the DEFRA 'NOx to NO_2' calculator (DEFRA, 2012).

Analysis of annual mean NO_2 concentrations across key Durham receptors show that despite reporting an overall network reduction in emissions the proposed scheme does not improve air quality across large areas of the study area (Figure 4).

Figure 4. ADMS output (NO_2 μgm^{-3}) for 'existing' left, and 'proposed' right, scenarios.



However, improvements were observed at fifteen of Durham's twenty five key receptors identified from the DCC Local Air Quality Management Durham City Further Assessment report 2012.

Discussion

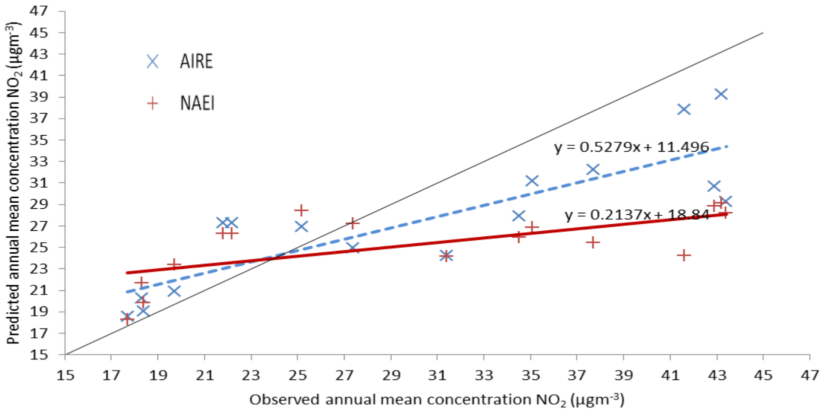
A key outcome of this research has been the successful application of IEM (AIRE) derived emissions outputs in to a dispersion model. This process was performed in an attempt to address identified weaknesses in average speed based emissions factors for estimating emissions in congested networks (Boulter *et al.*, 2007). In order to access the relative success of the IEM derived dispersion model outputs, and those from the NAEI derived modelling, both outputs have been compared to observed data at sixteen monitor sites maintained by DCC (Figure 4 and Table 3).

Table 3. Annual mean concentration NO_2 concentrations

		Annual mean concentration NO_2 (μgm^{-3})				
ID	**Location**	**Observed**	**AIRE**	**NAEI**	**FB $_{(AIRE)}$**	**FB $_{(NAEI)}$**
1	Milburngate	34.5	27.88	25.9	0.21	0.28
2	Highgate North	42.9	30.69	28.83	0.33	0.39
3	Gilesgate	43.4	29.23	28.2	0.39	0.42
4	Claypath	31.4	24.21	24.15	0.26	0.26
5	Sherburn Road	25.2	26.9	28.42	-0.07	-0.12
6	Dragon Lane	41.6	37.81	24.25	0.10	0.53
7	121 Gilesgate	35.1	31.14	26.88	0.12	0.27
8	The Gates	43.2	39.26	29.12	0.10	0.39
9	Claypath	37.7	32.21	25.46	0.16	0.39
10	Young Street	27.4	24.96	27.21	0.09	0.01
11	56 McKintosh court	18.4	19.06	19.84	-0.04	-0.08
12	56 McKintosh court	19.7	20.92	23.38	-0.06	-0.17
13	49 Sunderland Road	18.3	20.25	21.6	-0.10	-0.17
14	The Sands	17.7	18.56	18.28	-0.05	-0.03
15	Monitor Gilesgate 1	22.2	27.26	26.25	-0.20	-0.17
16	Monitor Gilesgate 2	21.8	27.26	26.25	-0.22	-0.19

Figure 5 shows a scatter plot of observed versus predicted annual mean concentration NO_2 μgm^{-3} for both modelling approaches.

Figure 5. Observed versus predicted annual mean concentration NO_2 µgm^{-3}



Linear regression shows that the AIRE linked with ADMS model produces an R-squared value of 0.72, compared with 0.43 for the NAEI-ADMS model. This suggests a good association between the variables for both models, particularly in the AIRE-ADMS model. Though linear regression revealed the gradient of both lines to be different from 1, an analysis of fractional bias (FB) using the methodology of Chang and Hanna (2005) did not produce evidence of a systematic under- or over- prediction in either model. FB is a measure of mean bias. It is documented in the literature as being a robust evaluation performance measure (Chang and Hanna, 2005). It indicates the mean under or over-prediction (Hanna *et al.,* 2004). FB ranges from -2 (over-prediction) to +2 (under-prediction) and a perfect model has an FB of zero (Hanna *et al.,* 2004). For both models FB values were within a factor of two (-2/3> FB <2/3) of the observed, indicating no systematic under or over-prediction for either model. Furthermore, FB values were closer to zero for the AIRE-ADMS model at twelve of the sixteen monitor sites. Moreover, a review of site specific results for both models shows that the AIRE-ADMS model more accurately predicted NO_2 concentrations at twelve of the sixteen sites when compared to the NAEI-ADMS model. Furthermore, at eight of the sites this enhanced accuracy was a result of a higher concentration prediction for the AIRE-ADMS model when compared to the NAEI-ADMS model. Many of these sites were located in central areas of Durham including Milburngate, Highgate North, The Gates, and Gilesgate, where congestion and delay is highest. This can be considered evidence that the AIRE-ADMS approach allowed for better capture of ‘congestion’ emissions, highlighting the benefit of this approach to air quality modelling.

Conclusions

The methodology outlined in this paper presents a framework for assessing the impact of traffic schemes designed to improve air quality. Results show that whilst traffic scheme tested in this paper reduced overall vehicle emissions, the impact on air quality was less positive due to the critical location of some increases in emissions. Furthermore, the use of an IEM (AIRE) to derive emissions for use in the dispersion model (ADMS) has been shown to produce results that more accurately reflect observed data, compared to the more traditional approach using average speed-based factors. It is suggested that this enhanced accuracy comes from the ability of this approach to more accurately capture ‘congestion’ emissions in critical locations.

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