An approach to modelling road networks for air quality management

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Abstract

Air Quality monitoring by Durham County Council has indicated that significant areas of the City of Durham are failing the national annual mean objective / EU limit value for Nitrogen dioxide (NO_2). In response to this an Air Quality Management Area (AQMA) was declared in May 2011.

This research aims to establish an approach to modelling the Durham road network for air quality management, which enables the assessment of a traffic management solution which may create only subtle changes in the traffic flow regimes. Road network emissions have been calculated using emissions factors and details of vehicle fleet composition, traffic 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 network.

Preliminary findings from microscale modelling have found that the signalling of two key junctions and co-ordination with several adjacent junctions can reduce emissions in Durham, as well as improve journey times and total network delay.

1. Introduction

1.1 Air Quality

Up until the 1950s the main air pollution problem in both developed and rapidly industrialising countries was typically high levels of smoke and sulphur dioxide emitted following the combustion of sulphur-containing fossil fuels such as coal, which were used for domestic and industrial purposes (CATE, 2009). However, today the major threat to clean air is posed by traffic emissions (DEFRA, 2011a). Petrol and diesel-engined motor vehicles emit a wide variety of pollutants, principally carbon monoxide (CO), oxides of nitrogen (NOx, the collective name for all compounds formed by the combination of oxygen with nitrogen when fuel is burnt), volatile organic compounds (VOCs) and particulate matter (PM) (DEFRA, 2011b).

A wealth of literature and comprehensive reviews of the health impacts of both regulated and unregulated air pollutants can be found and the impacts of pollution episodes on human health in the UK and across Europe are well documented (e.g. Balmes, 2011; COMEAP, 2010; Anderson, 2009; DEFRA, 2007). 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, short-term air pollution is associated with 50,000 premature deaths (EAC, 2010a). In 2010 air pollution was estimated to reduce the life expectancy of every person in the UK by an average of 6 months (DEFRA, 2010).

In the UK the Government is required under the Environment Act 1995 to produce a National Air Quality Strategy (NAQS) that contains standards, objectives and measures to improve air quality (Bell and McGillivray, 2000). At the local level, the Environment Act 1995 required local authorities to carry out a review of air quality, resulting in the regulatory regime Local Air Quality Management (LAQM). Since December 1997 each local authority in the UK has been carrying out a review and assessment of air quality in their area. Air pollution is measured and predictions have to be made on how it will change in the next few years. If a local authority finds any places where the objectives are not likely to be achieved, it must declare an Air Quality Management Area (AQMA). The local authority is required to put together a plan to improve the air quality - a Local Air Quality Action Plan.

Despite existing air quality legislation, EU countries (including the UK) are failing to meet targets, particularly for NO_2 (EAC, 2010b). Political pressures for development and conflicts with short term economic objectives all have an impact on efforts to improve air quality. This reality comes despite guidance highlighting the economic benefit of improving air quality (DOH, 2010).

1.2 City of Durham

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 the County Council has indicated that significant areas of Durham are failing the national annual mean objective / EU limit value for NO_2. In response to this an AQMA in the City of Durham was declared in May 2011. The AQMA incorporates the Highgate, Milburngate and Gilesgate areas and dependent on further assessment work in the City this boundary may be subject to revision in the future.

Durham County Council (DCC) is currently working in accordance with the Environment Act 1995 to produce an AQMA Action Plan (DEFRA, 2010). Additionally, Further Assessment work is on-going within the proposed AQMA and other Detailed Assessment works are on-going in other areas within the City boundary.

1.3 Development of Action Plan Options

Air Quality Action Plans must consider a wide range of emissions reduction strategies and technologies when determining and prioritising Action Plan options. Guidance from Defra. (LAQM.PG(03) and LAQM.PGA(05)) issued under the Environment Act 1995, provide detailed direction on the preparation and appraisal of Action Plan measures.

Transport is the main contributor to poor air quality in AQMAs (Mitchell and Dorling, 2003). Understandably therefore, typical Action Plan Options include Public Transport provision; Cycling and Walking Initiatives; Travel Plans; Road User Charging; Demand Management strategies; as well as other non-transport based emission controls. Finally, Traffic Engineering Schemes may be a consideration. This paper studies the feasibility of a Traffic Engineering Scheme in Durham. Depending on the outcome, a successful scheme may come under consideration as an Air Quality Action Plan Option.

1.4 Durham Traffic Engineering Scheme

Preliminary designs for the scheme can be found in Appendix A.

The scheme comprises:

- Signalising Gilesgate Roundabout
- Signalising and amending the layout of Leazes Bowl Roundabout
- Co-ordination of signals
- Network co-ordination across five adjacent junctions and one Puffin crossing (with the potential to expand to up to 8 junctions)

The aims of the scheme are to:

- Reduce network emissions (Specifically NOx)
- Improve bus journey times
- Reduce overall delay

1.5 SCOOT Co-ordination of signals

Initial microsimulation runs of the proposed scheme layout confirmed the importance of co-ordination of traffic signals across the network to prevent queues from one junction interfering with the operation of another.

Co-ordination would be possible using the signal controller ‘cableless linking facility’ (CLF) which operates each junction to rigid timings but has little scope to deal with abnormal traffic conditions or incidents. Alternatively, Split Cycle Offset Optimisation Technique (SCOOT) could be used to deliver a more dynamic and responsive approach to control and automatically adjust timings when incidents and events occur in the city that change normal traffic flows and patterns. Outside of peak traffic periods, e.g. late evening and overnight, SCOOT/CLF would not be used, as activity in one part of town can lead to unnecessary delays at another part, and traffic flows would not warrant co-ordination of signals.

With reference to the Appendix A the junctions considered for co-ordination are:

- Church Street / Hallgarth Street Junction (‘T’ junction with pedestrian facilities)
- Elvet Puffin Crossing
- Elvet Junction (‘T’ junction with pedestrian facilities)
- A690 Leazes Bowl Roundabout (existing 4 leg roundabout with all four entries within 180°)
- A690 Gilesgate Roundabout (existing 5 leg roundabout)
- A690/A691 Millburngate Roundabout (4 leg signal controlled roundabout with pedestrian facilities and an entry which includes all buses leaving the bus station)

If the proposals to signalise A690 North Road roundabout were to be implemented as part of a redevelopment scheme, then it would also have to be included together with the nearby A690 Margery Lane / Crossgate Peth junction and optionally the A167/A690 Nevilles Cross junction. The expansion to include additional junctions could provide the option to stack traffic further out from the city centre for air quality management reasons.

Prior to modelling the scheme in microsimulation, Linsig v3 was used to design and optimise the signal operation of the proposed network (Optimised for 'Practical Reserve Capacity' (PRC)). A diagram of the network can be found in Appendix B.

As a preliminary feasibility study the signal operation in the Paramics model has been modelled in fixed time with timings derived from the Linsig v3 network. When timings obtained from Linsig were transferred to the Paramics model it was apparent that there were several alternative route choices for drivers across the city and that the signal changes were resulting in changing vehicle volumes. Therefore, a process of iteration followed; traffic flows from the model were input to Linsig then timings from Linsig were input to the model until flows stabilised. This allowed the “best all-round result” to be achieved.

It is anticipated that some additional benefits either side of the peak network operation could be derived as a result of further optimisation using additional tools such as PCMOVA or attempts to imitate SCOOT operation in the microsimulation. Such work could be incorporated in to a future detailed design process should the preliminary scheme gain support for further development.

2. Methodology

2.1 Emissions Modelling

Two independent emissions modelling techniques have been adopted for modelling the existing Durham network. Typically, emissions factors used in air quality models are based on average speed, average flow of traffic on each road/link in a network. These emissions factors are calculated from studies by averaging the total measured emissions over driving cycles including urban, rural and motorway. These provide a reasonable estimate of total emissions over an area. The Durham road network was modelled using PITHEM (Platform for Integrated Traffic, Health and Emissions modelling) developed by Newcastle University. PITHEM contains an integral emission model which calculates emissions and particulates using latest UK emission factors (i.e. National Atmospheric Emissions Inventory) (Figure 1). 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 5.1.2.

However, it is recognised that this method leads to significant underestimation of emissions on particular streets and junctions where congestion and queues build and prevail for a high proportion of the day. As a consequence emissions benefits of introducing Intelligent Transport Systems (ITS), vehicle technologies and traffic management measures may be underestimated. 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 (Figure 1). IEMs calculate the emissions of an individual vehicle, based on the type of vehicle, its speed, its acceleration and the gradient to which it is 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, 2007). Calculations are carried out for every time step (0.5 second) for every vehicle in the network. Emissions outputs for NOx, PM and CO_2 are given (Transport Scotland, 2011). 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 NOx outputs as this is the exceedance pollutant in Durham.

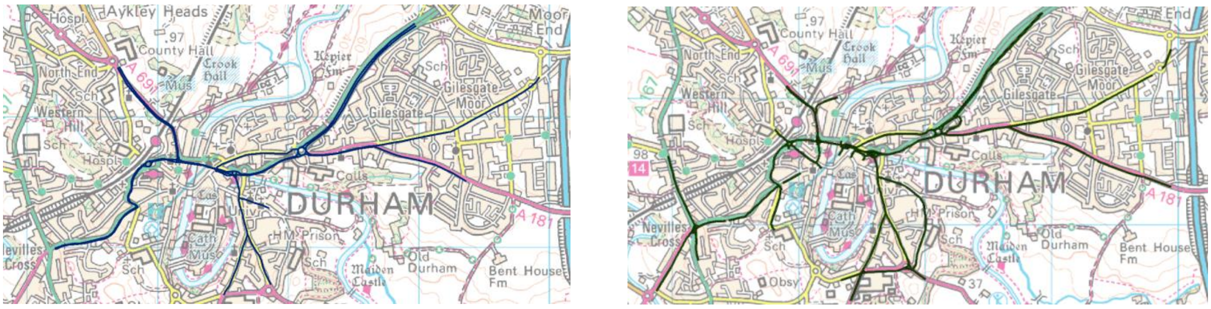


Figure 1. Emissions Modelling Networks (PITHEM network, left; IEM Network (AIRE), right).

2.2 Durham Microsimulation Model

The Durham County Council's Paramics model was developed by SIAS and Durham County Council covering the core area of Durham City in detail and significant sections of the surrounding highway network including major routes incorporating the A1, A167, and A691. The model extent broadly includes Chester-le-Street to the north; Stanley, Brandon and Crook to the west; Newton Aycliffe and Spennymoor to the south; and Peterlee, Seaham and Houghton-le-Spring to the east. AM Peak (06:30 - 09:30), and PM Peak (15:00 - 18:30) models were developed as well as the recede and build-up Interpeak model.

The model is a full 4-stage transportation model which models trip generation, distribution and mode split based on the distribution of trip generations and attractions. These generations and attractions are produced from national and local land-use data; trip patterns are generated using trip data from intercept surveys which provide details of movement patterns and journey purposes. Where such data is not available, traditional matrix estimation processes are employed to match modelled flows to traffic count data.

It was necessary to adapt the existing Paramics microsimulation model to make it suitable for use with the AIRE 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). A Digital Terrain Model (DTM) was obtained from Ordinance Survey (OS) for the core area of Durham City and gradients calculated for all links of the modelled network using Geographical Information Systems (GIS) techniques.

As gradient has an effect on the acceleration and deceleration of vehicles within the modelled network it was necessary to recalibrate and validate the model. These procedures were completed in line with DMRB guidelines.

3. Results

3.1 Comparative Emissions Results

Analysis was performed to investigate the relationship between the NOx Emissions results derived from the traditional NAEI average speed emissions methodology and the AIRE derived IEM technique described in section 2.1. Each network was split into approximately thirty road sections to aid comparison.

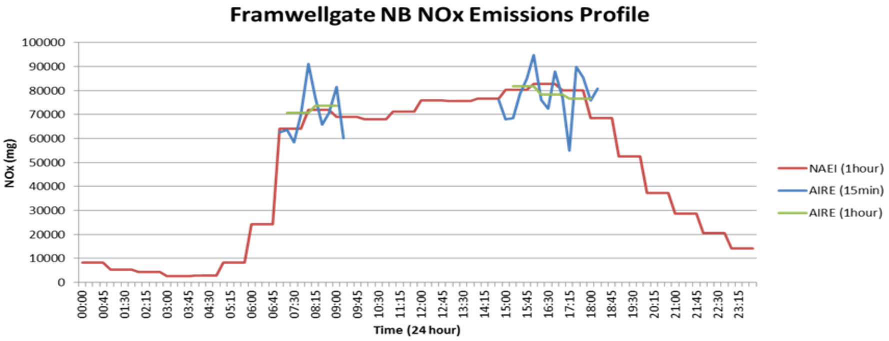


Figure 2. Framwellgate north bound link emissions (NOx).

Figure 2 shows average speed NAEI emissions for a full 24 hour period, at a one hour resolution. IEM emissions outputs have been summarised into fifteen minute averages, as well as hourly averages to compare directly with the average speed emissions results. A strong correlation between the two methodologies was identified on a number of links providing confidence in the techniques adopted.

However, a large number of links showed evidence of 'congestion' emissions in the AIRE results. Figure 3 shows the modelled shoulders either side of the peak periods appear to broadly correlate between the two methodologies. Conversely, the peak results, when congestion is highest, show significant increases in emissions outputs derived using the AIRE methodology. The fifteen minute time resolution better indicates when within the three hour peak period the congestion 'events' occur compared to the hourly modelling approach.

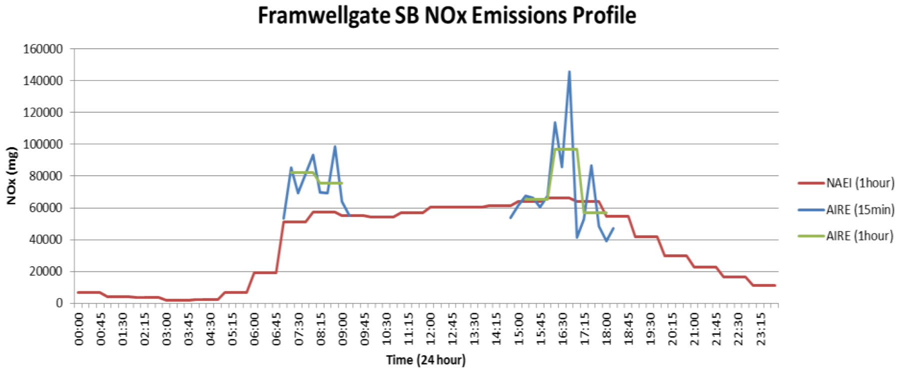


Figure 3. Framewellgate south bound link emissions (NOx).

Furthermore, analysis of a number of arterial routes provides evidence of tidal congestion emissions. Figures 4 and 5 show the Crossgate Peth area of Durham City. During the morning peak the east bound movement is congested with people travelling in to Durham, and we see significant increases in emissions in the AIRE outputs compared to the average speed NAEI results. However, in the afternoon peak flows going in to Durham are lower, conditions are less congested and the two methods correlate.

Conversely, for the west bound movement it is the afternoon peak when congestion is observed due to high volumes of traffic exiting Durham. Once again this trend is reflected in the AIRE emissions results, whereas the NAEI methodology does not appear to reflect observed conditions.

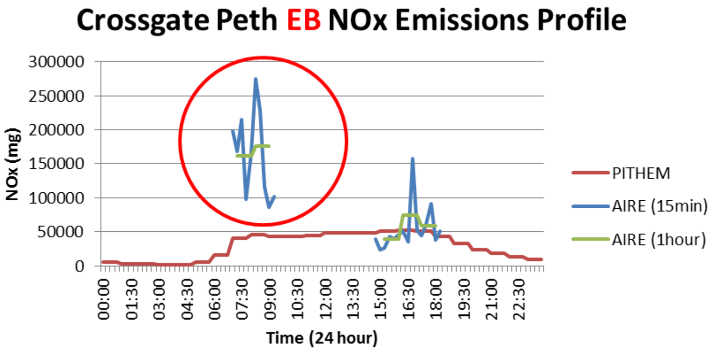


Figure 4. Crossgate Peth east bound link emissions (NOx).

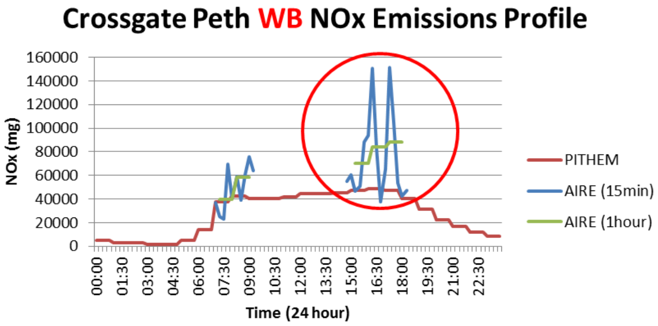


Figure 5. Crossgate Peth west bound link emissions (NOx).

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 Figure 6.

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

Figure 6. Overall network results, NAEI vs. AIRE (NOx).

3.2 Durham Traffic Engineering Scheme Results

Following the exploratory work analysing the emissions methods described in Section 3.1 it was concluded that the impacts of Durham Traffic Engineering Scheme would be more accurately assessed and developed using an IEM approach to emissions modelling. The comparative analysis provided reassurance of results in the context of Durham network, and 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.

Existing and proposed scheme microsimulation models were run for both morning and afternoon peak periods. Each microsimulation model was run three times (total twelve runs), the resulting output files were processed through AIRE and then analysed using a bespoke software programme developed during this research.

The overall network results from both of the modelled peaks can be seen in Figure 7 and 8.

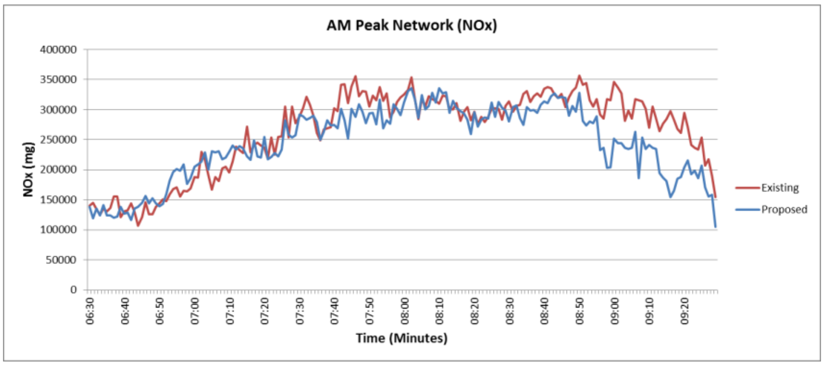


Figure 7. AM Peak Emissions Results (NOx).

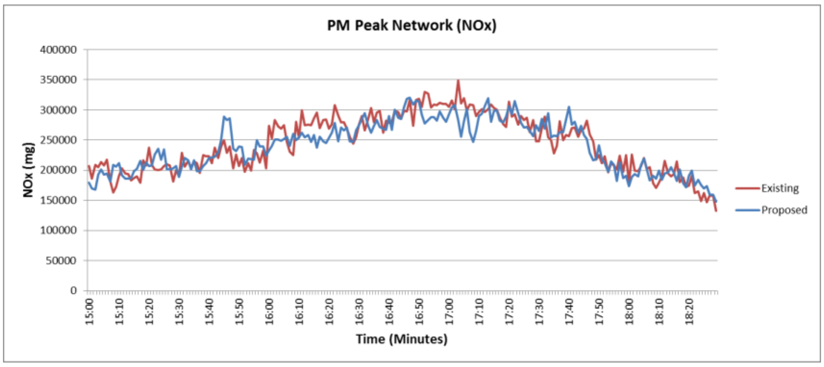


Figure 8. PM Peak Emissions Results (NOx).

Figure 9 summarises the overall network results.

	NOx (mg)			
Peak	Existing	Proposed	Diff.	Diff. (%)
AM	47,387,363.00	43,913,854.00	- 3,473,510.00	-7%
PM	51,235,115.40	50,594,356.89	- 640,758.51	-1%

Figure 9. Scheme Appraisal Emissions Results (NOx).

Whilst network emissions results give an indication of scheme performance there are significant limitations in interpreting results on a network wide basis.

3.3 Air Quality Concentrations

Whilst an emissions based approached to modelling air quality can provide insight into the sources of air quality, it is important to gain an understanding of how those emissions interact with local topography, built environment and meteorology to create air quality concentrations. The spatial location of traffic emissions are therefore of importance. Plans of Durham showing the percentage change of NOx emissions as a result of the proposals can be seen in Figure 10 and 11. It should be noted that particular caution is required in interpreting 'percentage change' results for air quality modelling due to the existence of air quality limit values.

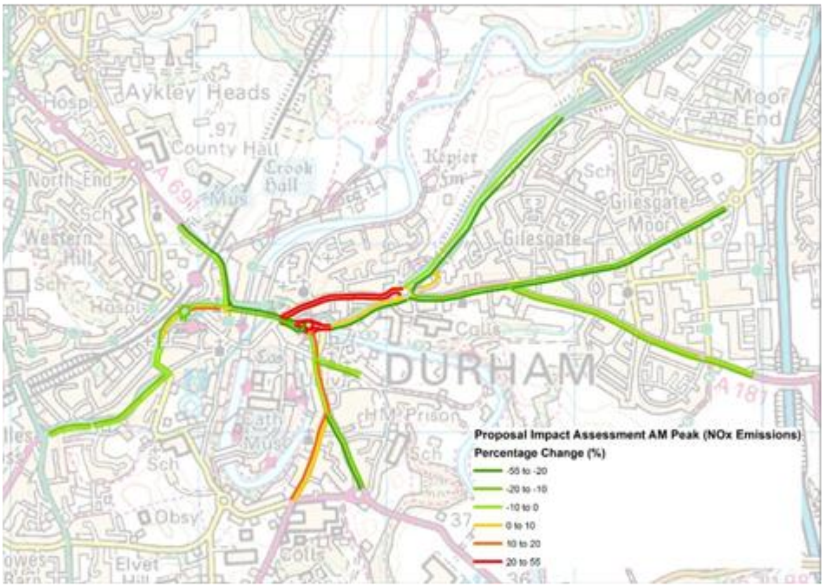


Figure 10. Effect of proposal on vehicle emissions (NOx) (Morning Peak).

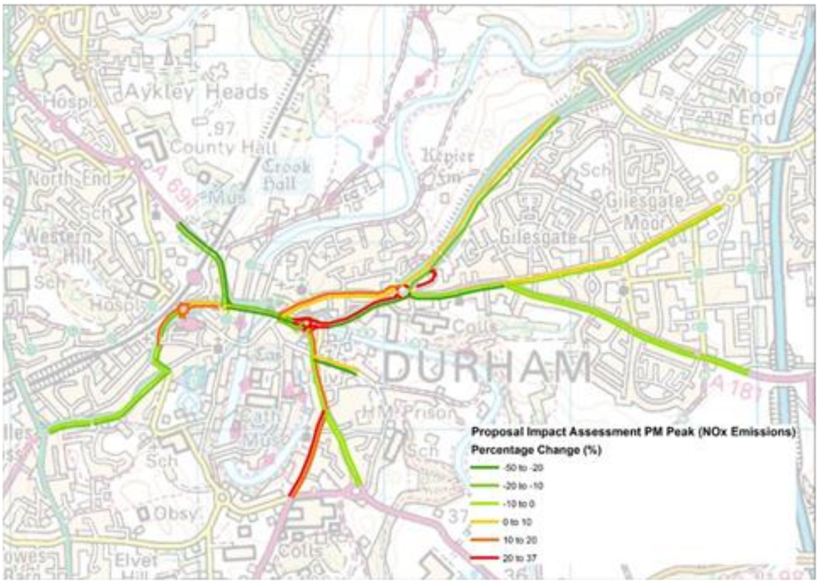


Figure 11. Effect of proposal on vehicle emissions (NOx) (Evening Peak).

These figures provide a spatial indication of how the proposed scheme impacts on Durham's traffic emissions. However, whilst this information provides a greater understanding of the effectiveness of the scheme, because emissions interact with topography and meteorology, their source location may not be of primary importance but instead to where the emissions are dispersed. The impact of a scheme aimed at improving air quality cannot be accurately assessed without performing dispersion modelling.

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 area coarseness) are required to complete this process.

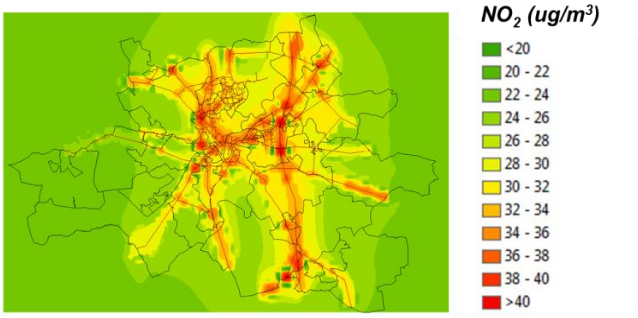


Figure 12. Dispersion modelling from PITHEM Emissions outputs.

ADMS-Urban (CERC, 2011) was used for this project as it is user friendly, stable and has been extensively validated by over 70 UK local authorities (Riddle *et al.*, 2004). ADMS-Urban uses boundary layer similarity profiles and also uses a skewed-Gaussian distribution to determine the vertical height of pollutant concentrations within the plume. The model has an integral street canyon model for simulating air quality for a particular street segment surrounded by buildings (Namdeo *et al*., 2002). Figure 12 shows an output from ADMS for City of Durham. This was produced using emissions outputs from PITHEM created using the methodology outlined in Section 2.1.

3.4 Twenty-Four Hour Emissions Modelling

Atmospheric dispersion models require twenty-four hour emissions estimates because emissions build and disperse throughout the day influencing daily pollution concentrations. It was therefore necessary to expand the existing microsimulation model to cover a twenty-four hour period in order to make improved estimates of the twenty-four hour emissions using AIRE.

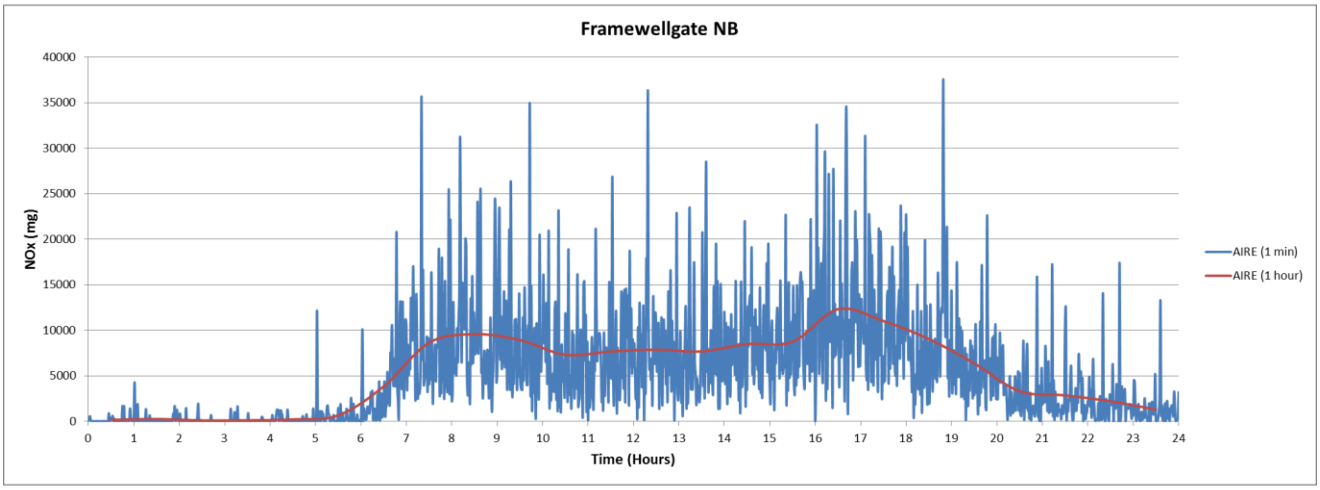
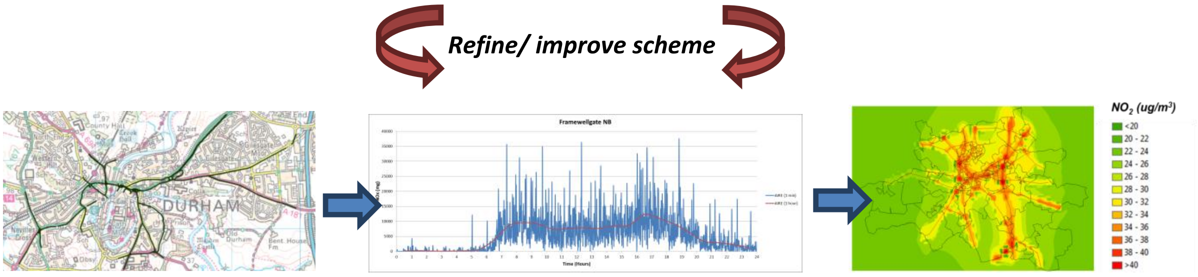


Figure 13. Twenty-four hour Emissions Results.

Figure 13 shows twenty-four hour minute by minute analysis of emissions outputs from AIRE for a typical link. These outputs will be used to feed a dispersion model enabling comparison of concentration levels for the existing network compared to the proposed scheme. Work is underway to complete this initial assessment.

Once these results are realised it will be possible to investigate how to further adjust signal timings to aid air quality, rerunning the proposed models, producing and dispersing new emissions outputs using the methodology established in this paper (Figure 14).



24-hour microsimulation ***Analysis of IEM Emissions results*** ***Disperse Emissions = Air Quality Concentrations***

Figure 14. Outline of approach to modelling road networks for air quality management.

4. Discussion

4.1 Limitations of Approach

Previous studies, existing literature and findings from this research indicate significant benefits in using IEMs to create emissions outputs, as opposed to using traditional average speed/ average flow derived emissions factors. However, analysis of twenty-four hour minute by minute emissions outputs has revealed some limitations.

Minute average speed, flow and NOx emissions were plotted for individual links of the modelled network. Typical results can be seen in figure 15. The graphs show two significant clusters of results broadly defined as ‘free flow’ and ‘congested’ traffic conditions.

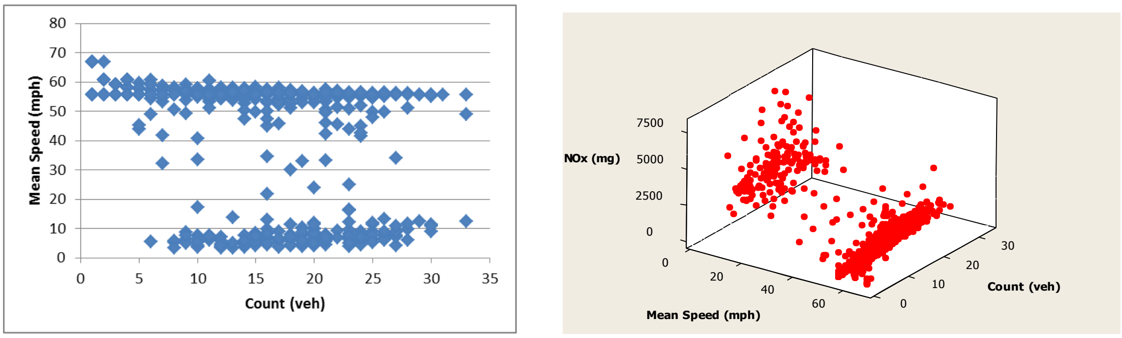


Figure 15. Analysis of minute-by-minute speed, flow and emissions.

Comparing these results to a similar graph from real world Motorway Incident Detection and Automatic Signalling (MIDAS) system data (Figure 16) (Bell *et al*, 2006), it is evident from analysis of a number of links that the microsimulation may not be correctly simulating the variations in the traffic speeds during the transition phase between traffic states. Whilst it is appreciated not all traffic links will follow the distinct pattern identified in figure 16, examples of real world emissions analysis following the distinct ‘two state’ pattern identified in the microsimulation have not been found in the literature. It appears that whilst ‘free flow’ and ‘congested’ conditions are accurately represented, the microsimulation model struggles to represent driver behaviour as traffic accelerates/ decelerates in transition to and from congested conditions. As these modes have a first order effect on emissions this is likely to lead to underestimation.

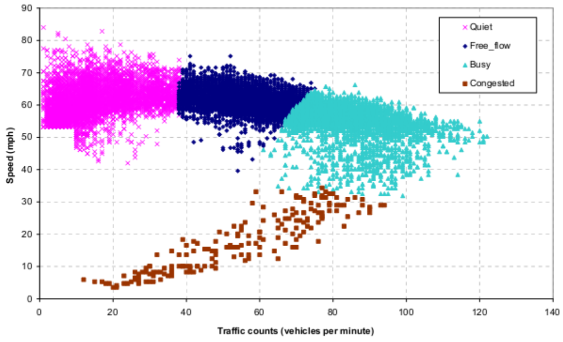


Figure 16. Classification of traffic states on speed flow plot.

Other limitations include accurate representation of gear changing behaviour which can contribute significantly to overall emissions outputs, and contributes to substantial variation in emissions outputs according to individual driving style (Bell *et al*, 2006). However, whilst these limitations are acknowledged it is recognised that obtaining direct real world emissions calculations is unlikely to be an achievable goal, particularly in the context of scheme appraisal, and IEMs remain the most accurate way forward for estimating traffic emissions.

5. Conclusions

An approach to modelling road networks for air quality management has been established. The methodology outlined in this paper presents a framework for assessing the impact of traffic schemes designed to improve air quality.

References

Anderson, H. R. (2009) 'Air pollution and mortality: A history', *Atmospheric Environment,* 43, pp. 142–152.

Balmes, J. R. (2011) 'How does diesel exhaust impact asthma?', *Thorax,* 66, (1), pp. 4-6.

Bell, M., Chen, H., Hackman, M., McCabe, K. and Price, S. (2006) Using ITS to reduce evironmental impacts. (Published by 13th world congress on Intelligent Transport systems, London, 9-12 October 2006).

Bell, S. and McGillivray, D. (2000) *Environmental Law: 5th Edition.* London: Blackstone.

Boulter, P. G., McCrae, I. S. and Barlow, T. J. (2007) A review of instantaneous emissions models for road vehicles. *Transport Research Laboratory*, PPR 267.

CATE (2009) *Atmosphere, Climate and Environment*. Available at: http://www.ace.mmu.ac.uk/eae/air_quality/older/History.html (Accessed: 6th March 2011).

COMEAP. (2010) *The Mortality Effects of Long-Term Exposure to Particulate Air Pollution in the United Kingdom.* Didcot, Oxfordshire: Committee on the Medical Effects of Air Pollutants

DEFRA (2007) *The Air Quality Strategy for England, Scotland, Wales and Northern Ireland.* Norwich: Department for Environment, Food and Rural Affairs

DEFRA (2010) 'Air Pollution: Action in a Changing Climate', Department for Environment, Food & Rural Affairs.

DEFRA (2011a) *Air Quality: Reducing Air Pollutant Emissions*. Available at: http://ww2.defra.gov.uk/environment/quality/air/air-quality/eu/ (Accessed: 17/03/2010).

DEFRA (2011b) *Causes of Air Pollution* Available at: http://uk-air.defra.gov.uk/air-pollution/causes (Accessed: 16/03/2011).

DOH (2010) *Fair society, healthy lives (the Marmot review).* London: Department of Health

Durham County Counil (2010) County Durham Economic Assessment (CDEA) Executive Report: Emerging Insights Available at: http://www.durham.gov.uk/MINAGENDASPDF/Overview%20and%20Scrutiny/Economy%20and%20Enterprise/090610-EE-Item-No7-CDEA-ER-Emerging-Insights.pdf (Acessed: 24/08/2012)

EAC (2010a) *Air Quality.* London: The Stationery Office Limited: Environmental Audit Committee

EAC (2010b) *Air Quality, Fifth Report of Session 2009-10.* London: Environmental Audit Committee

Harris, B. (2004) ‘The effects of street gradients on urban traffic emissions’, *Materials Research Centre*, University of Bath, Bath BA2 7AY.

Hirtl, M., Baumann-Stanzer, K. (2007) ‘Evaluation of two dispersion models applied to street canyons in Stockholm, London and Berlin’, *Atmospheric Environment*, 41, pp 5959-5971.

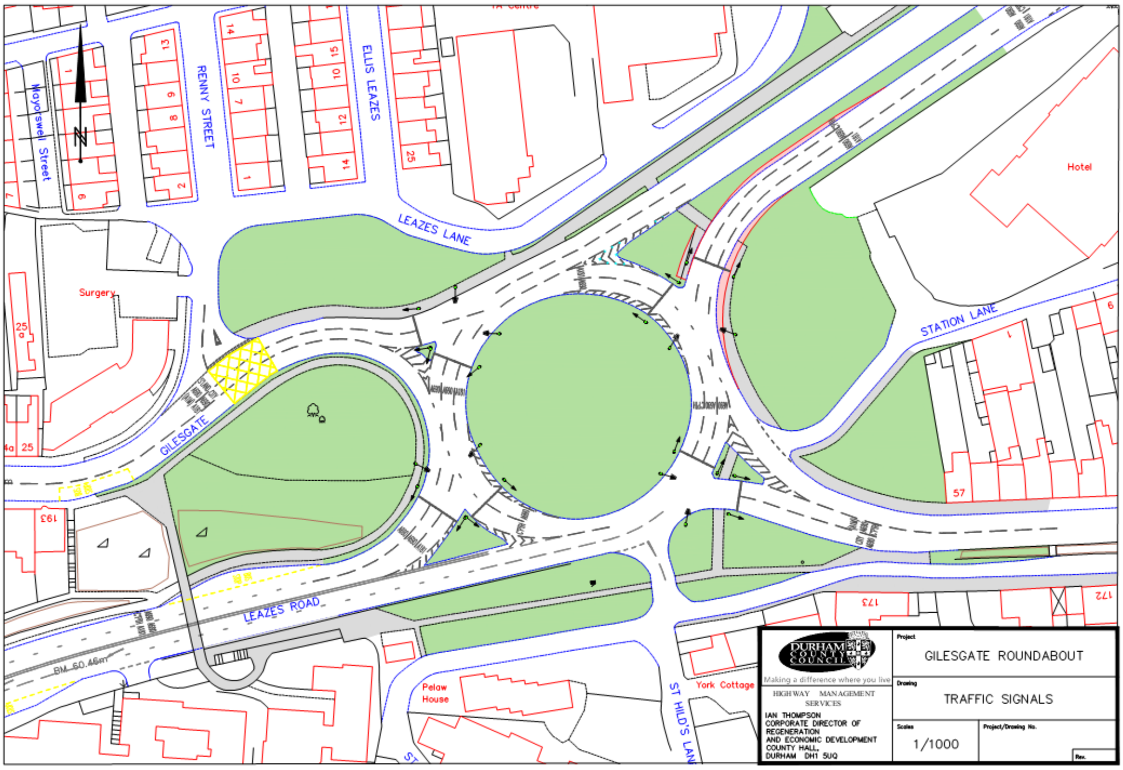
Kapposa, A. D., Bruckmann, P., Eikmannc, T., Englertd, N., Heinriche, U., Hˆppef, P., Kochg, E., Krauseb, G. H. M., Kreylingh, W. G., Rauchfussb, K., Rombout, P., Schulz-Klempj, V., Thielk, W. R. and Wichmann, H. E. (2004) 'Health Affects of Particles in Ambient Air', *International Journal of Hygiene and Environmental Health,* 207, pp. 399-407.

Mitchell, G. and Dorling, D. (2003) 'An environmental justice analysis of British air quality', *Environment and Planning A,* 35, pp. 909-929.

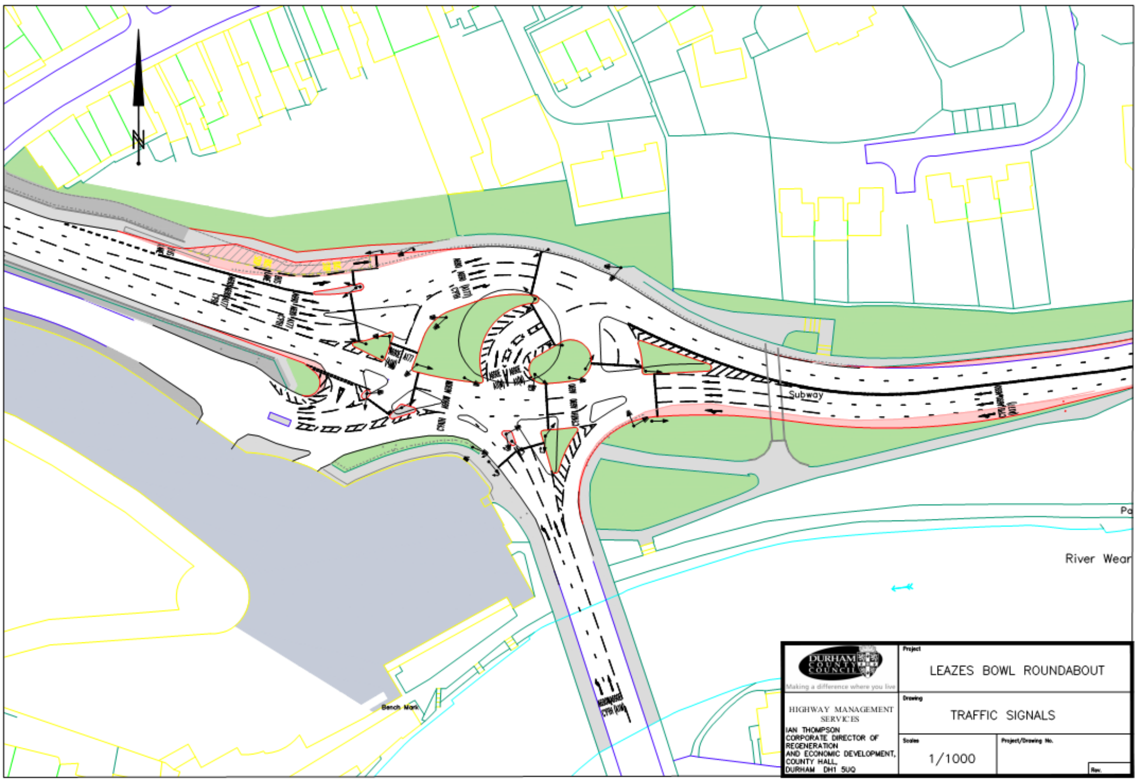
Rhys-Tyler G., Bell M.C., (2010), Derivation of Predictivemodels of vehicle exhaust emissions from instrumented vehicles measurements: Analytical and statistical challenges, Proceedings of the 35 th UTSG Conference Plymouth, January 2010

Riddle, A., Carruthers, D., Sharpe, A., McHugh, C. and Stocker, J. (2004) 'Comparisons between FLUENT and ADMS for atmospheric dispersion modelling', *Atmospheric Environment,* 38, (7), pp. 1029-1038.

Appendix A



A181 Gilesgate Roundabout – Proposed Traffic Signal Layout



A690 Leazes Bowl Roundabout – Proposed Traffic Signal Layout

Appendix B

Network Layout Diagram