Mapping Vehicle Emissions through Urban Streets and Intersections

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Abstract

Microscopic traffic simulations coupled with instantaneous emission models are able to assess the environmental impact of traffic networks, management strategies and fleet renewal at a high temporal and spatial resolution. The approach couples traffic microsimulations, which model the movement of individual vehicles through a well specified study area road network, with instantaneous vehicle emission models that provide second-by second fuel consumption and tail-pipe emission predictions. As the traffic microsimulations consider all the vehicle movements second-by-second (stationary, accelerating/ decelerating, cruising), unlike alternative more aggregate approaches, they can study congestion effects, stop-start driving and local traffic flow conditions. The highly spatially resolved predictions also mean the vehicle emission source strength can be mapped through urban streets and intersections.

The mapping results will be of interest to atmospheric modellers simulating the dispersion of vehicle emissions within City streets e.g. canyon environments (local-scale). Visualising the variations in emissions can support traffic Network Managers and Policy Makers working to minimise the environmental and health impacts of road transport emissions, helping them understand which locations have the highest source strengths, so facilities where people congregate and are exposed to emissions such as Bus stops and Pedestrian crossings can be located away from emission 'hotspots'.

Background

Despite the implementation of measures to reduce total PM and NO_X emissions from the transport sector, primarily motor vehicle emission standards, recent evidence suggests an unwanted side-effect of new diesel pollution abatement technologies to control particle emissions is an increase in emissions of Nitrogen Dioxide (NO_2) directly from vehicles (Grice et al, 2009). It is also now recognised there has been little change in the total NO_X (Oxides of Nitrogen) emission performance of light-duty diesel vehicles in "real-world" (or in-use) urban driving conditions in the past 15 years or so (Carslaw et al, 2011). Emissions of NO_X from diesel vehicles in urban environments are now considered to be higher than suggested by UK and EU emission inventories. UK and EU emission inventories have historically considered traffic flow volume and emission rates for different vehicle categories and sub-types (i.e. car, fuel type, engine size, Euro standard). The emission rates for a road section (or link) have also been based on the road type or the average speed. The data under-pinning such inventories (e.g. www.naei.org.uk) are mostly derived from laboratory dynamometer tests, where vehicles are driven over defined (artificial) speed-profiles (or drive-cycles) and their exhaust emissions analysed. Whether these drive-cycles are representative of on-road traffic flow conditions and behaviour is often debated. Indeed, there is mounting concern that such approaches do not adequately reflect emissions from congested networks. The detailed approach used in this study, coupling traffic microsimulations and an instantaneous emission model, allows the influence of vehicle accelerations, road gradient, vehicle and engine load to be considered. This is clearly highly desirable when attempting to understand and map vehicle emissions across congested networks, evaluate environmental traffic management and vehicle fleet renewal policies.

Method

A traffic microsimulation (www.paramics.com) model of all the major roads in the City of York (UK) Air Quality Management Area (AQMA, $20km^2$) was setup and calibrated (Preater, 2012) using the best available information for seven average week-day hours (peak, inter-peak and off-peak) periods of free-flow and stop-start (congested) driving conditions could be accounted for. The validation of the traffic simulations included comparisons of:

- Observed and Modelled turning movements at 34 sites. The UK DMRB (2014) requirement was that over 85% of modelled turning movements pass the GEH statistic. The percentage of turning movements passing the GEH criteria in the AM, IP and PM peaks were 95%, 94% and 92% respectively.

- Observed and Modelled vehicle fleet proportions (8 sites - percentage of cars, vans, rigid-HGVs, articulated-HGVs, Buses, Coaches). The vehicle mix percentages were within ±1% for all survey points and vehicle types.

- Observed and Modelled journey times to ensure the model is satisfactorily representing queues and delays across the network. Journey times along 22 of the main routes in the network were extracted from the UK Traffic Master dataset. The UK DMRB requirement is that journey times on 85% of routes are within ±15% of the observations. In all the validation periods (AM, IP and PM peaks) 86% of routes met the DMRB criteria.

Additional models for the peak shoulders, evening and night-time periods were derived by factoring traffic demands in-line with observations and adjusting Bus service frequencies. Ten replications of each hour were simulated (stochastic modelling). The total distance travelled by the simulated vehicles exceeded 1 million vehicle kilometres for the *BASE* situation.

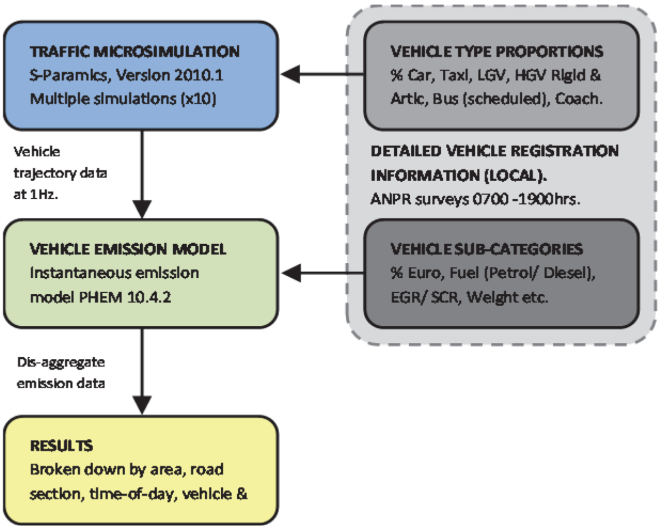

Figure 1: The coupled traffic-emission modelling framework

Vehicle trajectories (speed profiles) were harvested and supplied to the instantaneous Passenger car and Heavy-duty vehicle Emission Model (PHEM version 11; Hausberger et al, 2012) that is able that is able to predict fuel consumption and NO_X, NO_2, CO, HCs, Particulate Mass and Particle Number tail-pipe emissions of the whole European vehicle fleet of: light- and heavy-duty, Euro standards 0 to VI, petrol and diesel fuelled vehicles. The model is based on light- and heavy-duty vehicle engine speed – power emission maps established from engine and chassis dynamometer measurements (Zallinger et al. 2005). PHEM has a time alignment and correction sub-model to relate engine speed – power events to predicted engine-out emissions. These methods make PHEM capable of simulating the instantaneous fuel consumption and emissions for any speed profile or driving cycle. The gradient of road sections was also considered by the emission model, derived for each link in the traffic model from the Google Earth (2011) terrain model. All the PHEM simulation results assumed vehicles were in a 'hot-running' condition.

The modelled (traffic microsimulations) vehicle dynamics (acceleration rates) were verified against sample on-road vehicle tracking observations.

The step to a more detailed modelling scale inherently demands higher specification input information. Every effort was made to source and use the best available, local information. The local, operational vehicle fleet was accurately specified in both the traffic and emission models. Vehicle registration numbers observed in the AQMA were cross-referenced with the UK vehicle registration database so the share of cars, vans, buses (single-decker, double-decker, bendy-bus) and commercial vehicles; and their respective fuel type, engine size, weight and Euro standard proportions were known and accounted for. The scheduled Bus services and their fleets (age and Euro standard distribution, type - single-decker, double-decker, bendy-bus) operating each route were accurately specified in the models. This facilitates a realistic assessment of the spatial changes and re-distribution of vehicle emissions due to Bus fleet renewal policies or Low Emission Zone interventions for exaple. As the modelling approach is a step towards a second-by-second "virtual" representation of the "real" traffic network, it naturally encapsulates many events and processes that effect vehicle emissions such as urban Buses having to make additional stops-and-starts to pick up passengers on their scheduled routes.

Results

The traffic-emission NO_X, NO_2 and PM modelling results are analysed to:

- illustrate the emission performance of the modelled vehicles per kilometre travelled; and
- predict the contribution of each vehicle sub-category to the emission totals.

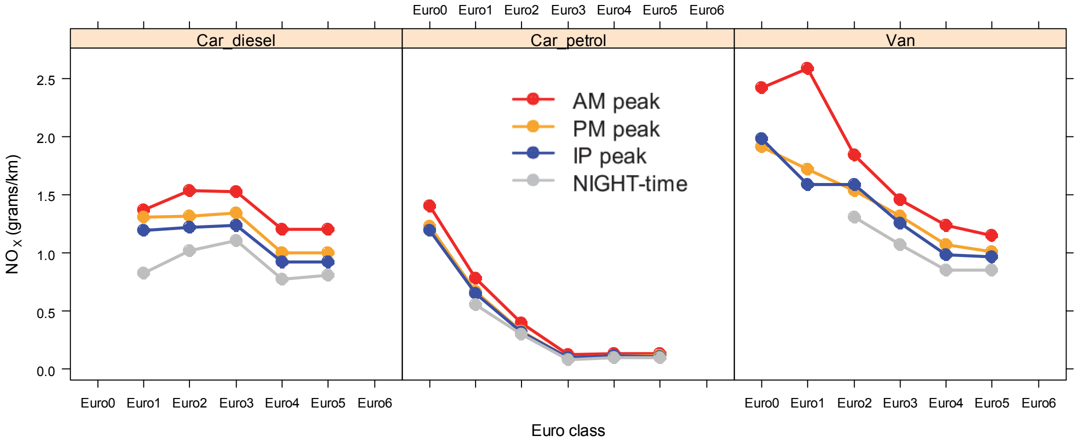

Figure 2: Light-duty NO_X emission factors for each time period (a) diesel passenger cars, (b) petrol passenger cars, (c) vans.

The average emissions per kilometre travelled for each vehicle sub-type have been calculated from the traffic-emission modelling outputs of the current or “baseline” conditions (May 2011). Figure 2 presents the modelled NO_X emission factors for the light-duty vehicle types in the AM, PM, IP and NIGHT-time periods. The results for each light-duty vehicle type are presented in a separate panel. The NO_X emission factors are presented for each Euro category where available. Results are not available if the combination of fleet proportion and demand level for a given time period do not lead to a vehicle of that sub-type being simulated.

The modelled emission factors for diesel passenger cars (left panel, Figure 2) are broadly similar through all Euro generations. During AM and PM peak periods, emission factors are elevated as the simulated vehicles perform more polluting stop-start motions as they negotiate a busier network with longer traffic queues. The modelled emission factors for petrol passenger cars (middle panel, Figure 2) decrease substantially through the Euro standards. Older pre-catalyst (Euro 0) petrol vehicles are modelled as having high NO_X emissions, similar to the levels from diesel passenger cars. The modelled emission factors for petrol vehicles suggest Euro standards have successful delivered improvements in the NO_X emission controls on petrol cars. The NO_X emission factors for Euro 3 and newer vans are similar to those of diesel passenger cars. This is expected as diesel cars and vans share engine and exhaust after-treatment technologies.

Diesel passenger cars are an increasingly important vehicle category with respect to NO_X emissions as:

- Their fleet share continues to increase. In the “baseline” simulations diesel passenger cars completed 33.8% of the vehicle kilometres in the average weekday simulations; and
- NO_X emission controls under-perform in urban driving conditions. Recent evidence and research is suggesting that diesel exhaust NO_X after-treatment technologies are in-effective in urban driving conditions, with their lower power demands, exhaust flow rates, exhaust gas temperatures and consequently catalyst temperatures.

Emission contributions

In this section the NO_X contributions from the different vehicle categories for the “baseline” conditions are presented. The results are presented as a weekday (24-hour) average (weighted mean of the AM, IP, PM and NIGHT-time periods). The Figure 3 bar chart therefore presents the predicted NO_X emission contributions from each vehicle type over an average weekday. The breadth of each bar is proportional to the share of total (simulated) vehicle kilometres completed by that vehicle type in the City of York AQMA. Approximately a third of the road transport NO_X emissions in the York AQMA are predicted to be emitted from light-duty diesel vehicles (cars and vans). Buses and Coaches contribute another third, the remaining third coming from HGVs. In relation to the vehicle kilometres travelled, the heavy diesel categories make a dis-proportional contribution. For example although Buses (scheduled) only complete 2.84% of the modelled vehicle kilometres, they are predicted to contribute nearly 30% of the NO_X emissions in the York AQMA. Light-duty diesel vehicles (cars and vans) are predicted to generate the majority (≈80%) of primary NO_2 emissions.

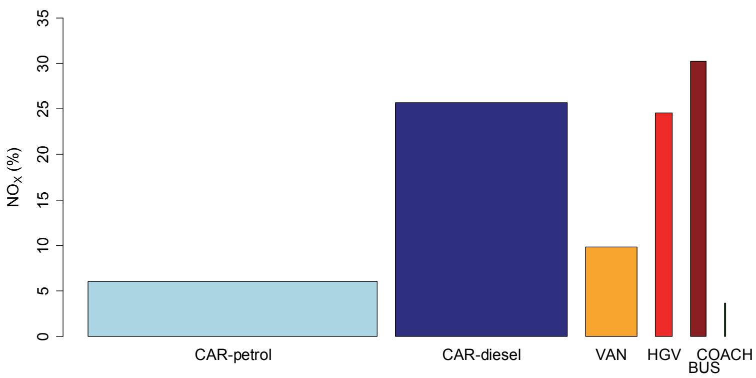

Figure 3: The NO_X emission contributions (%) from each vehicle type.

Mapping vehicle emissions

The highly temporally (1Hz) and spatially resolved vehicle emission predictions also mean the vehicle emission source strength can be mapped through urban streets and intersections. The spatial variation in NO_X emissions (not concentrations) during the AM peak (averaged across 10 replications) are visualised on colour-scale in Figure 4 for two streets on the York inner-ring road, a few hundred metres North of the City-centre. Buildings of different heights and roof shapes surround both streets forming a range of street canyon geometries (with height to width ratios varying between 0.65 and 0.8). The streets service a high traffic demand and are regularly congested during and outside peak periods (Boddy et al, 2005a, 2005b).

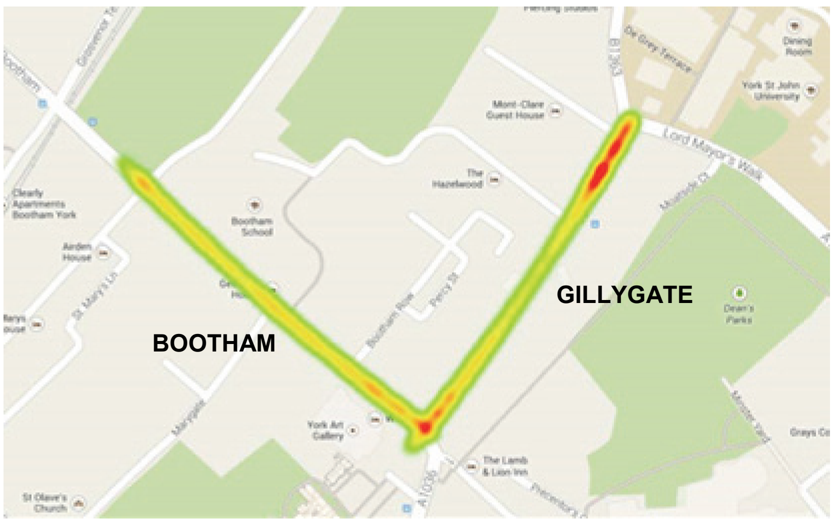

Figure 4: Visualisation of the spatial variation in NOX emissions for the Bootham and Gillygate streets (York, UK) in the AM peak. {©Copyright GoogleTM 2014}

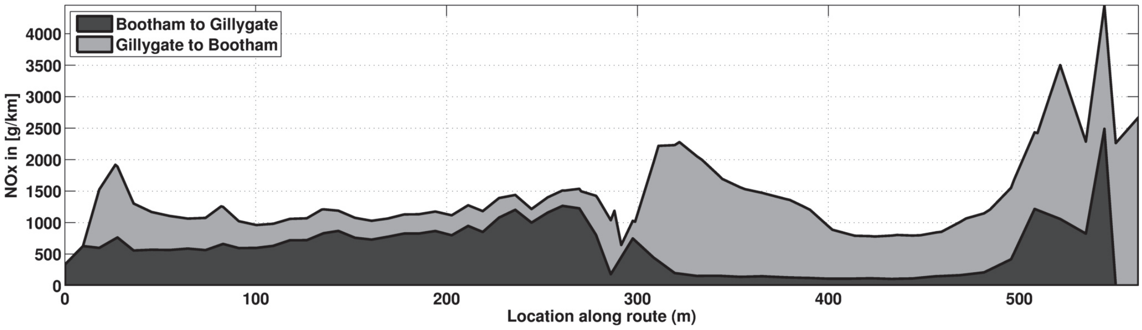

Figure 5: The spatial variation in NOX emissions for both directions of traffic flow along the Bootham and Gillygate streets (York, UK) in the AM peak

A clearer visualisation of the spatial variation in emissions is presented graphically in Figure 5, with the NO_X contribution for 10 metre segments plotted for both directions of traffic flow:

- Bootham to Gillygate – Traffic heading South-East along Bootham towards the signalised intersection with Gillygate, is regularly held-up by a moving queue. At the signalised intersection traffic has move slowly to negotiate the tight turning radii before entering Gillygate. Traffic typically is in cruising mode along Gillygate, only joining a short queue at the signalised intersection with Lord Mayor's Walk.
- Gillygate to Bootham – Similarly a continuous moving queue is typically present along the length of Gillygate during the AM peak, for traffic heading South-West towards the intersections with Bootham. Traffic again has to turn through the intersection before progressing smoothly (cruising mode) along Bootham (heading North-West) heading away from the York centre.

The average traffic speed of vehicles travelling down Bootham, then along Gillygate during congested periods (AM peak and busy Interpeak) and when traffic is flowing freely (Evening and Night periods) are illustrated in Figure 6. This clearly illustrates that the simulations are correctly replicating the slow-moving queue along the length of Bootham (South-East bound) in the AM and Inter-Peak periods. Whereas at quieter times vehicles are only delayed by the presence and cycle of the traffic signals (280 metres along the route).

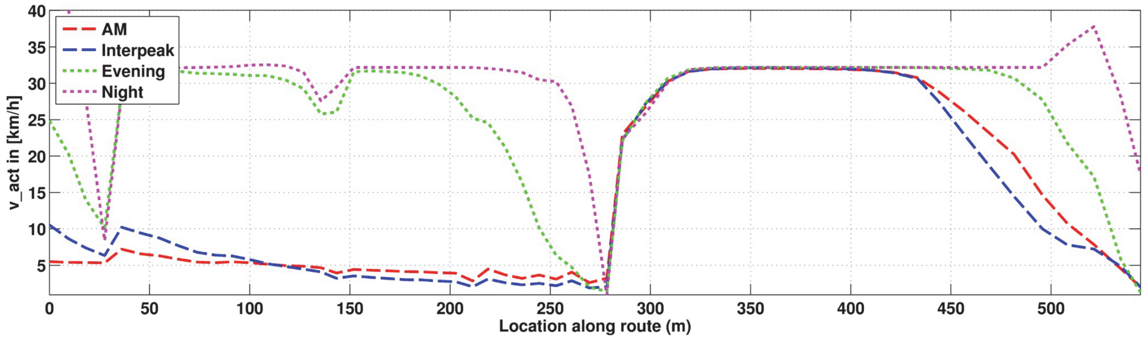

Figure 6. The spatial variation in average speed for vehicles travelling along Bootham and onto Gillygate during the AM, Interpeak, Evening and Night-time periods.

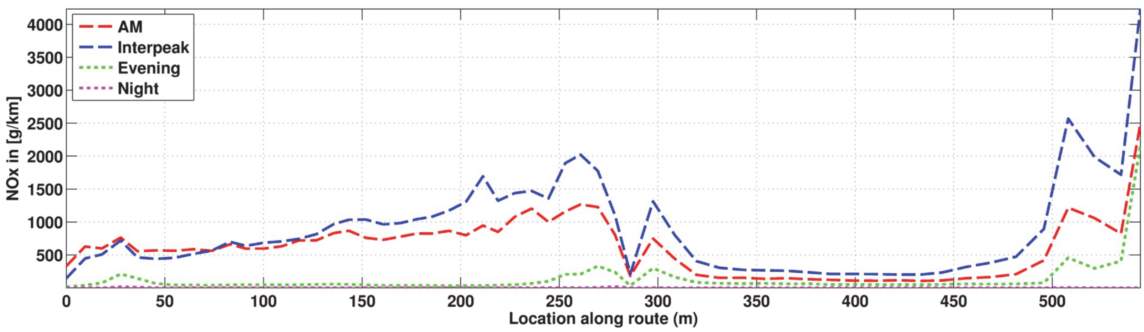

Figure 7. The spatial variation in NOX emissions generated by vehicles travelling along Bootham and onto Gillygate during the AM, Interpeak, Evening and Night-time periods.

The corresponding impact on the spatial variation in NO_X emissions for vehicles travelling along Bootham and onto Gillygate during the AM, Interpeak, Evening and Night-time periods is illustrated in Figure 7. The volume of traffic flow is clearly higher in the peak periods, but also the presence of a moving queue spreads the emission load along the street, rather than simply being focussed around the intersection itself.

The contribution of the different vehicle types (Car, Bus, Heavy Goods Vehicle and Light-Commercial/ Van) can also be examined. Figure 8 visualises the contribution from the different vehicle types for the traffic, again heading down Bootham then along Gillygate. Cars, Vans and HGVs all broadly follow the same traffic flow patterns, hence their emission profiles track each other. Buses however have to perform additional stops-and-starts to service Bus stops. A Bus stop is located towards the end of the Bootham-Gillygate route, at approximately 500 metres. Bus emissions are significantly elevated in this region, a consequence of the heavy (≈11 tons plus the weight of passengers) diesel engine vehicles having to undertake additional power intensive accelerations when pulling away from the stop.

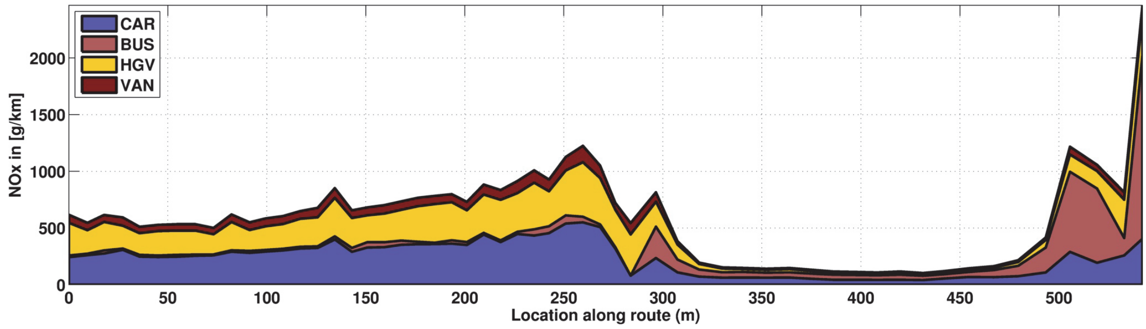

Figure 8: The spatial variation in NOX emissions generated by the different vehicle types along the Bootham - Gillygate route during the AM peak

Summary and Conclusions

This is believed to be the largest-scale application of coupled micro-scopic traffic and instantaneous vehicle emission modelling in Europe, and possibly anywhere.

The mapping results for a focussed part of the network are considered to be of interest to atmospheric modellers simulating the dispersion of vehicle emissions within City streets e.g. canyon environments (local-scale). The results suggest:

- During periods of light traffic demand, NO_X emissions are concentrated around the intersection itself, with emissions at mid-link location where vehicles are typically 'cruising' at a low-level. This finding suggests emissions would be better spatially represented in atmospheric dispersion models as a series of point sources at intersections and Bus stops, rather than the uniform line source representation commonly applied.
- In peak periods with slow moving queues on links, emissions are elevated in the vicinity of the intersection, but also spread along the length of the links. A combined point and line source representation would better describe the spatial variation in emissions.

Further work under-way is integrating these emission predictions within urban air pollution dispersion models.

Visualising the variations in emissions can also support traffic Network Managers and Policy Makers working to minimise the environmental and health impacts of road transport emissions, helping them understand which locations have the highest source strengths, so facilities where people congregate and are exposed to emissions such as Bus stops and Pedestrian crossings can be located away from emission 'hotspots'.

Acknowledgements

This research is supported by the www.EPSRC.ac.uk, DEFRA (www.DEFRA.gov.uk), City of York Council and TU Graz. The visualisations and analysis are an extension to the York Low Emission Zone Feasibility Study funded by the DEFRA (UK) Air Quality grant scheme, which evaluated the environmental benefits of a range of Low Emission Zones policies and strategies to deploy cleaner Buses in the York AQMA.

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