

Air quality mapping: combining models, in situ measurements and remote sensing

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Abstract: This paper presents a system for modelling traffic flow, estimating vehicle emissions and validating them against remotely sensed and in situ data. The results showed that the queuing model was satisfactory and that the vehicle emissions model was internally consistent. The validation results were inconclusive and point to future important areas of research. Notably, it is necessary to develop a system to predict concentrations (rather than emissions) in time and space.

Keywords: *Queuing model, emissions, PM10, remote sensing, in situ data*

I. INTRODUCTION

Air quality has major implications for both societal and scientific activity. From a societal perspective ground-level air quality has potentially major implications for human health. It can also impact negatively on the built and natural environment (e.g., via acid deposition).

Air pollution can be mapped and monitored using in situ or remotely sensed measurements or some combination of the two. It can also be predicted using air quality models, which model the atmospheric dispersion as well as physical and chemical changes in pollutants. Models may incorporate in situ and remotely sensed data. Their spatial resolution of such models is 1 km x 1 km or coarser with a temporal resolution of hours to years (van de Kasstele, 2006).

In the urban environment there is a need for finer spatial resolution information about air pollution in order to assess human exposure. This is also required at various temporal resolutions in order to assess long-term average pollution levels as well as peak values. In many urban environments road traffic will be the major pollution source and this is the focus for this paper. It is recognized that there are various other potential pollution sources (industry, dust from building

and agriculture, rail, shipping etc), but these lie outside the scope of this research.

The research proposed here takes a different approach to predicting air pollution due to road traffic. This proceeds from two directions. The first direction is to *predict* pollution based on vehicle counts and vehicle emissions. The second direction is to *measure* pollution using *in situ* measurements and remote sensing.

Vehicle counts on major roads are recorded by many municipalities. Vehicle counts and vehicle speeds can also be predicted using queuing models. The vehicle measurements could potentially be used to model pollution levels in real time, whereas the predictions could be used to model pollution levels at some point in the future – for example when assessing the pollution implications of building a new road or implementing a new traffic routing system. The current research is restricted to a proof of concept to predict vehicle counts, speed and pollution emissions. This is demonstrated for the city of Rotterdam, The Netherlands. Particulate matter (PM10) is the pollutant under consideration.

At this stage the measurements are used to validate the predictions. In the long term it may be possible to incorporate the measurements to improve prediction

II. METHODOLOGY

A. Queuing Model

Queuing theory is established in operational research (Nelson, 1995). Its application to modelling traffic flow was reviewed by van Woensel and Vandaele (2007). In this study a simplified version of the highway system around the city of Rotterdam was modelled as a queuing network. This is shown schematically in Figure 1.

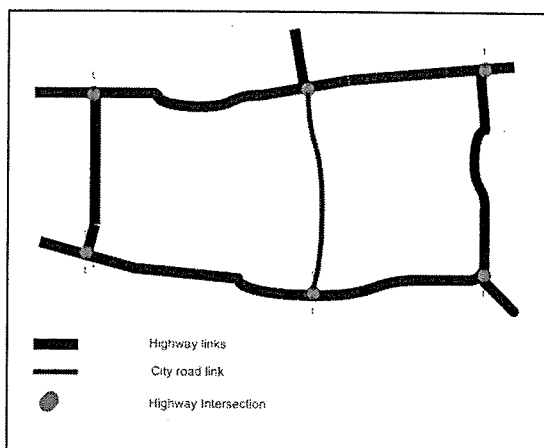


Figure 1. Schematic diagram of the highway network.

The highway intersections are shown in Figure 2. Each intersection was modelled as a system of 3 or 4 intersection queues. The roads between the intersection were modelled as link queues. There were a total of 34 queues.

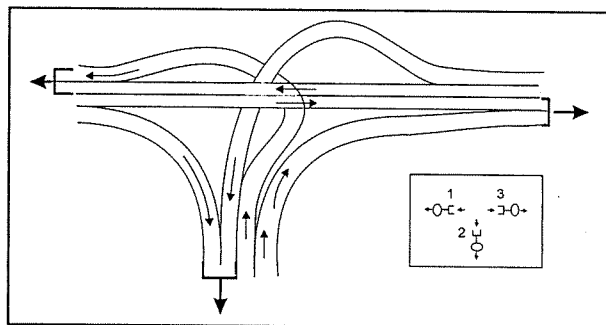


Figure 2. Intersection of queues

The queuing network was characterized as follows:

- Traffic was modelled as uninterrupted flow. The flow of traffic was regulated by vehicle-vehicle and vehicle-highway interactions.
- The flow into and out of the queue was in equilibrium (steady-state).
- At each intersection, the probability of a vehicle making a left or right turn was the same (0.5).
- The relationship between speed, flow and traffic density was governed by established equations (Greenshield 1935). Peak traffic flow was associated with moderate speeds and moderate traffic density (high speeds are associated with empty roads and low speeds with congested roads).
- At each intersection hourly traffic counts entering the system were available. This was split into cars, light trucks (including buses) and heavy trucks.
- The model then returns the expected number of vehicles and their average speed for each intersection or link queue. This was performed hourly for each day in May 2008.

B. Emissions Model

The UK National Atmospheric Emission Inventory (NAEI) publish empirical equations that allows prediction of PM10 emissions for particular types of vehicle travelling at a specific speed¹ (in general emissions are lowest at moderate speeds and highest at low or high speeds). This takes into account vehicle class (car, bus, HGV), engine size and fuel type. Clearly this does not match exactly with the vehicle classes available for Rotterdam. Heavy trucks were matched to HGVs and light trucks to buses. For cars the fuel types and engine sizes were estimated based on information from Statistics Netherlands (CBS).

The NAEI equations were combined with the vehicle speeds and numbers from the queuing model to predict PM10 emissions on each intersection or link for each hour. These can be aggregated to provide daily, monthly or annual values

C. Concentration Model

The emission model gives only vehicle emission on the roadway. In order to calculate emission at a point (or area) other factors need to be considered. These include distance from the roadway, wind direction and trees. For example the Dutch Ministry of Housing, Spatial Planning and the Environment provide the CAR II² model which allows calculation of annual concentration of PM10 on a roadway. This was not incorporated into this study.

D. Model Validation

Traffic data entering and exiting the system were available. The output of the queuing model was validated against the exit data.

Validation of the queuing model output was more difficult because there was no directly comparable data. In situ measurements of PM10 were available – but the measurement stations were not located directly next to the highway. Remotely sensed data were also available – although these were at a coarse resolution and were not direct measurements of PM10. Nevertheless, the utility of these two data-sources was examined.

III. STUDY SITE

It was possible to obtain all required data for May 2008, so this was the time period used in this research. Where hourly data are shown, these are for 13th May.

A. In-Situ Measurements

In situ hourly measurements of PM10, as well as other pollutants, were available for two sites in Rotterdam (Floreslaan and Bentinckplein) from the Netherlands Environmental Assessment Agency (PBL). Meteorological data (hourly and daily) were also available from the Netherlands Meteorological Institute (KNMI). The location of these is shown in Figure 3. The PM10 data were used for validation of the emissions predictions.

¹ http://www.naei.org.uk/other/vehicle_emissions_v2.xls (last accessed 6th April 2010)

² <http://www.infomil.nl/onderwerpen/klimaat-lucht/luchtkwaliteit/meten-rekenen/car-ii/> (last accessed 6th April 2010)

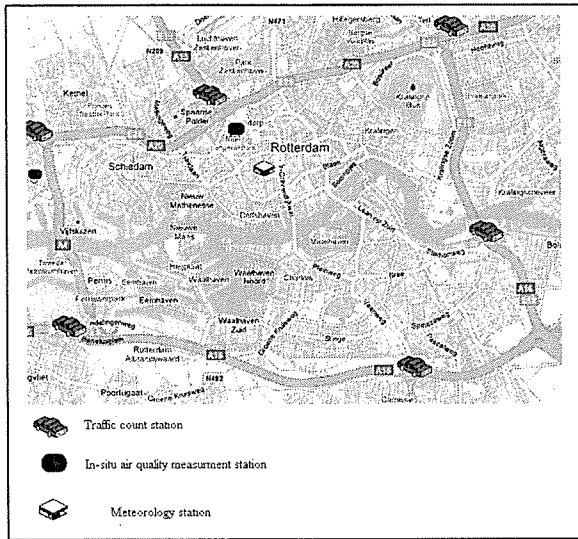


Figure 3. Map of Rotterdam showing the highway system and data gathering points.

B. Remotely Sensed Data

Aerosol optical thickness (AOT) is a measure of the attenuation and absorption of electromagnetic radiation by aerosols. This has been shown to be related to particulates (Koelemijer et al., 2006). AOT can be estimated from remotely sensed data and is a standard product from the Moderate Resolution Imaging Spectroradiometer (MODIS). The MODIS 10 km product is calculated on a daily basis for cloud free conditions. The study area coincides with 4 MODIS 10 km pixels. A question for this research was the extent to which the AOT was correlated with measured and predicted PM10 and whether this could be used to validate the model predictions.

IV. RESULTS

A. Queuing Model

The results for the queuing model for the first intersection station for 13 May 2008 are shown in Figure 4. The expected number of vehicles is the number of vehicles in the queue at any one point in time. The observed number is the total number in the queue at any point in time. The pattern of both is as expected – lowest at night with a peak in the morning and evening rush hours. The R^2 between hourly observed and expected number of vehicles was between 0.76 and 0.86, depending on which queue was examined. If daily (or other) traffic values are required these values can simply be aggregated

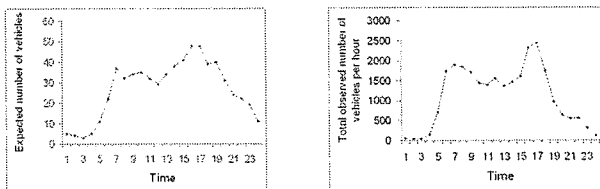


Figure 4. Expected and observed number of vehicles for 13 May 2008 for queue 1.

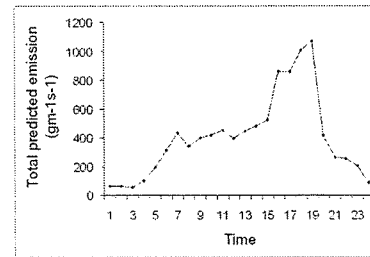


Figure 5. Estimated emissions per hours for 13 May 2008 for queue 1.

B. Emission Model

In addition to predicting the number of vehicles, the queuing model also gives their speed. The speed and class of vehicles were used to calculate the emission for each vehicle. This was then aggregated over the total number of vehicles passing through each queue. This is shown for queue 1 in Figure 4.

C. Validation

Estimated PM10, in-situ-measured PM10 and remotely sensed AOT data were available. AOT was only available for 10 days in May. This is because AOT is not calculated when there is cloud cover. For the remotely sensed data, the 4 pixels coincident with the city of Rotterdam were averaged (mean).

No correlation was found between the mean in-situ-measured PM10 (i.e., the mean from the two monitoring stations) and the mean AOT for the 10 cloud-free days.

No correlation was found between the total estimated emission from the network and mean AOT for the 10 cloud-free days.

The mean in-situ-measured PM10 was plotted against the total estimated emission for the entire network. For hourly data $R = -0.21$ and for aggregated daily data $R = -0.55$.

Next, the in situ data from the Floreslaan monitoring station were plotted against the emissions from the closest points on the highway network taking into account prevailing wind direction. For example, if the wind was blowing from the south-west parts of the highway to the north-east were not included. This showed no correlation for hourly data and a correlation of +0.70 for aggregated daily data.

V. DISCUSSION

A. Queuing Model

The number and pattern of vehicles predicted by the queuing model broadly reflects the observed vehicle counts. It is true that the highway system and the model are highly simplified and have considerable scope for development; however, this was actually the least uncertain element of the research.

Note that Figure 4 only shows the number of vehicles on the network. The model also estimates the vehicle speed and, hence, the flow of vehicles through the network. The highest flows are observed at moderate speeds since congestion slows

vehicles down and the highest speeds are associated with empty roads.

B. Emissions Model

The estimated emissions follow an reasonable pattern. Emissions are lowest at night, when there are few cars and peak during the afternoon "rush hour" – when more congestion and lower speeds would be expected. This argument, however, only shows that the model is internally consistent. Validation against independent data was also sought.

C. Validation

The lack of correlation between 10 AOT values and PM10 as measured at 2 city monitoring stations is, perhaps, unsurprising. Other studies have tended to examine data for longer averaging periods (e.g., monthly or annual) over wider geographical areas (national or continental) (Koelemijer et al. 2006; Paciorek and Liu, 2009). It may simply be unrealistic to compare the data sources uses in this study.

The monitoring stations are geographically separated from the highway so a direct impact of highway emissions on the measurements would not be expected. The first validation attempt considered the mean in situ measured PM10 for the two stations vs. estimated emissions for the whole highway. This took no account of wind direction or of objects (e.g., trees and buildings) between the highway and monitoring stations. Nevertheless, the negative correlation was unexpected.

The second validation attempt, where measurements at Floreslaan were compared to the nearest upwind points on the highway, yielded mixed results. There was no correlation for hourly data, but there was a positive correlation for daily data. It may be that the incorporation of wind direction is important here and that a change in emissions at the highway does not impact instantly at the monitoring station.

Overall, the validation results were disappointing and inconclusive; however, they do raise several important issues that should be considered in future research.

- The impact of temporal averaging requires further consideration. In order to meet statutory requirements predications at hourly, daily, monthly and yearly aggregations are required. The relationship between in situ data, remote sensing and model predictions may vary depending on the temporal aggregation.
- The research lacks a model to go from traffic *emissions* to pollutant *concentration* in time and space. The CAR II model (Section II.C) allows roadside pollution to be estimated, but could not be applied to predict at the monitoring stations used in this study. Ideally a concentration model would allow prediction at the location of the monitoring station, or would allow city-wide predictions for comparison with remote sensing.
- An alternative to the above proposal for a concentration model would be a system that uses in situ data, remote sensing and independent model

outputs to estimate pollution concentration at the highway. The assimilation of remotely sensed and in situ data with model outputs is an active area of research.

There are two further elements that were not considered in this research.

- The queuing model worked only with expectations. The variance was not modelled.
- Uncertainty in the emissions predictions was not modelled. The models from NAIE are empirical regression models; however, uncertainty in predictions was not considered. There are also uncertainties in the classes of vehicles, particularly for cars where the specific details (age, engine size, fuel type, etc.) were not known exactly. Uncertainty in the output from the queuing model would also propagate into uncertainty in the emissions model.

VI. CONCLUSIONS

This paper presented work in progress for predicting traffic counts and emissions and for validating them using remotely sensed and in situ data. The output from the queuing model was satisfactory and the predicted emissions were internally consistent. The validation was inconclusive and may be due to inappropriate comparisons between the estimated and measured data, rather than inaccuracies with the predictions.

The research points to areas that require development. Clearly uncertainties from the queuing and emissions model could be better quantified. More importantly a system for multi spatial and temporal scale pollutant predictions is required.

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