Effects of congested vs. freeway urban traffic flow on air pollutant concentrations in a street canyon

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Keywords: nitrogen oxides, traffic flow pattern, emission, congestion, statistical modeling.

1 Introduction

The pollutant concentrations in an urban roadway street canyon depend largely upon vehicular emission rates, meteorological parameters and the background levels of the pollutant concerned. Many of the deterministic and statistical models that have been developed for street canyons have concentrated upon the influence of meteorological parameters on air pollution levels (e.g. Berkowicz, 2001). The relationship between traffic flow and emissions has received less attention with emissions often being estimated crudely from traffic flow data.

In congested urban streets the complexity of the traffic flow pattern and the incidence of stochastically occurring traffic jams mean it is very difficult to accurately estimate pollutant emissions. Although it is generally accepted that traffic congestion leads to the increase in air pollution levels only a few studies have been carried out to estimate the effects of the traffic flow pattern using on-road observational data. The majority of these previous studies have investigated the influence of traffic flow patterns on CO levels (Marsden et. all, 2001), since CO is generally regarded as an indicative tracer pollutant for vehicle emissions. In the urban environments it is nitrogen oxides (NOx) that cause most major air pollution problems but the impact of acceleration, deceleration and idling on NOx emissions is less pronounced for than for CO. Not surprisingly, studies of the effects of traffic flow patterns on NOx levels have provided rather ambiguous results (Pischinger et. all., 1998).

Using a multivariate adaptive regression splines (MARS) model this study has removed the effects of wind speed and wind direction on measured NOx concentrations to allow a more detailed analysis of the effects of traffic flow on NOx. The traffic flow patterns responsible for the highest NOx concentration levels have been identified and the effects of traffic speed have been estimated. The study used measured hourly pollutant concentrations, meteorological data and traffic data for a street canyon in Cambridge, UK between 1995 and 1997.

2 Measurements

The measurement site is located in a busy two lane, bi-directional inner ring-road within the city of Cambridge, UK. Average daily flows reach 21,000 vehicles with 11.0% being large vehicles (e.g. heavy goods vehicles, buses etc). The street segment has an almost uniform building facade over a distance of 100 m and a height-to-width ratio of approximately 0.8. It is aligned 35° - 215° relative to North.

Busy computer controlled signal intersections define the end of the monitored street segment. Two signalled pedestrian crossings (one very close to the monitoring cross section) also exist within the segment. All monitoring data were collected at a single street cross-section. A chemiluminescence monitor was used to measure NOx concentrations, at a receptor point 4.0 m above the canyon floor and 2.5 m away from the wall of the building. Traffic data was collected using a standard magnetic induction loop system installed within the road surface. The data set contains hourly traffic volumes, types of vehicles (short and long vehicles) and vehicle speeds. Hourly averages of wind speed and wind direction were collected from a 7m meteorological mast situated on a building roof .

3 Speed-Flow relationships

Traffic streams are described by three variables: density (k), speed (v), and flow (q). At the macroscopic level these variables are defined under stationary conditions at each point in space and time, and are related by the identity $q = k \cdot v$. Driver behaviour creates a second functional relationship between the three variables that can be shown by plotting any one variable against another. Figure 1 shows the observed dependency between hourly averages of the traffic speed and flow in the investigated street canyon during working days (Monday to Friday). It demonstrates a classic speed-flow relationship (Gartner et.all., 1988). The upper part of the curve describe how, as flows increase, there is an increase in vehicle interactions and a decrease in speeds. These interactions are accompanied by an increase in the frequency of vehicle accelerations and decelerations, and consequently also an increase in pollutant emissions. In engineering terms flow in this part of the curve is described as *uncongested*, *unrestricted* or *free*. If traffic continues to enter the flow past q_{max} (maximum street traffic throughput capacity), the flow rate decreases further and a queue forms, resulting in further stop-and-go driving. In this portion of the curve traffic flow is referred to as *congested*, *restricted* or *queued*. The precise shape of the speed-flow curve for a given road segment depends on various factors such as the number and width of traffic lanes, grade, road curvature, speed limit, location entrance and exit ramps, weather, mix of vehicle types, etc. In the Cambridge data set the decrease in flow caused by interaction and queuing is only observable following periods of stable uninterrupted flow.

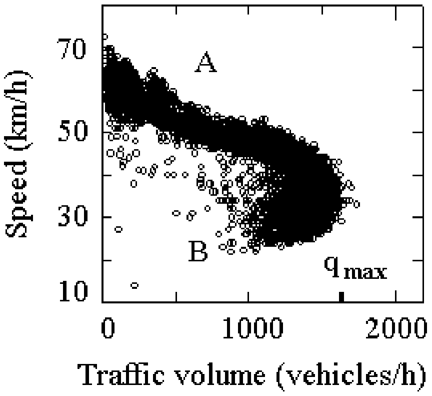

Figure 1 Observed speed-flow relationship. A - uncongested flow, B - congested zone. q_{max} - maximum traffic throughput capacity.

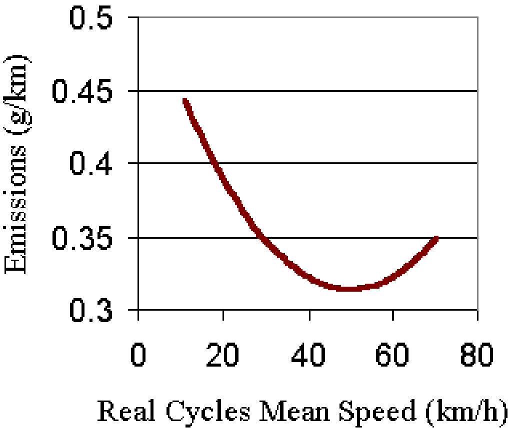

Figure 2 NOx speed dependent emission factors of EURO I gasoline passenger cars with engine capacity 1.4 - 2.0 l

4 Vehicle exhaust emission estimation

A vehicle's exhaust emission changes with its mode of operation, for example, whether it is cruising, accelerating, decelerating or idling. It is possible to calculate emissions based on recorded patterns of speed and acceleration cycles. However the most common approach is to use emission factors calculated as a function of average speed (Joumard, 1999). The average speed of the driving pattern is considered representative of an actual driving conditions which contains cycles of acceleration and deceleration. It assumes that vehicles travelling with the same average speed will also have a similar driving pattern. Figure 2 shows how NOx emissions vary with average speed for EURO1 gasoline passenger cars (1993 - 1996 European vehicles with a three-way catalyst) between 1.4 and 2.0 litre engine capacity. (Samaras et. all., 1998). For gasoline vehicles the NOx emissions are generally high at low average speeds, decrease up to 50 km/h and then increase again.

In the presented study the measured traffic speed represents the instantaneous speed as a vehicle passes a given point on the roadway. Although point measurements do not integrate the different driving phases (trip start and end, stops), they are likely to be representative of the average speed of a real cycle in the investigated street link (Gartner et.all., 1998).

5 Estimation of the influence of the traffic flow pattern on NOx levels

On order to remove the effects of meteorological variables on the observed variation of NOx concentrations an empirical model relating hourly NOx concentrations to wind speed and direction has been developed. Using a multivariate adaptive regression spline (MARS) modelling approach (Friedman, 1991) the following model was built:

$$\begin{aligned} \text{NOx} = {} & 299.524 - 58.657 * \text{BF1} + 334.636 * \text{BF2} - 9.961 * \text{BF3} - 0.605 * \text{BF4} + \\ & + 0.830 * \text{BF5} + 1.899 * \text{BF7} + 29.369 * \text{BF9} + 1.441 * \text{BF11} + 5.689 * \text{BF13}; \qquad (1) \end{aligned}$$

, where

BF1 = max(0, wind speed - 0.800);
BF2 = max(0, 0.800 - wind speed);
BF3 = max(0, wind direction - 112.700);
BF4 = max(0, 112.700 - wind direction);
BF5 = max(0, wind direction - 272.600);
BF7 = max(0, wind direction - 47.900);
BF9 = max(0, wind speed - 2.400);
BF11 = max(0, wind direction - 164.600);
BF13 = max(0, wind direction - 104.200);

The estimated relationships between measured NOx concentrations and wind speed and wind direction are presented in figure 3. In order to estimate the effects of traffic flow pattern on the measured NOx concentration the further analysis of the model (1) residuals has been carried out. Figure 4 shows the 3D (a) and 2D (b) plots of model (1) residuals versus traffic speed and flow. The fitted MARS model relationships between the model (1) residuals and the traffic variables are shown in figure 5. The model (1) residuals can be interpreted as NOx concentration with removed meteorology effects.

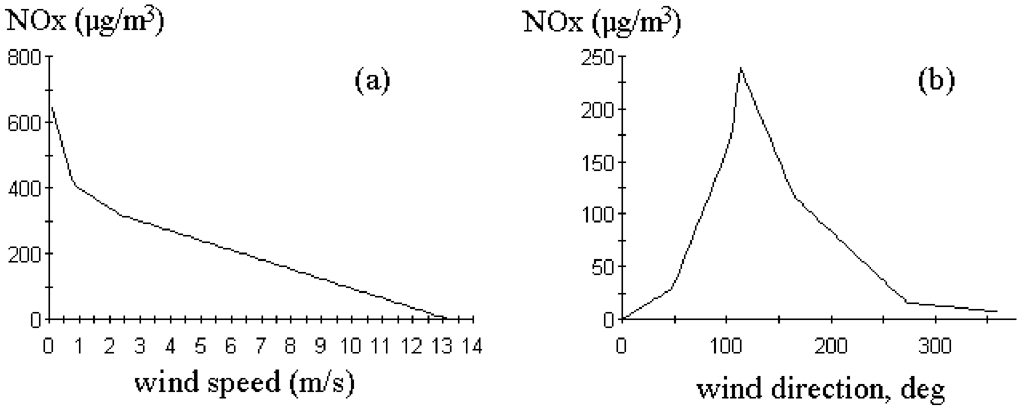

Figure 3 The relationships between NOx concentration and wind speed (a) and wind direction (b).

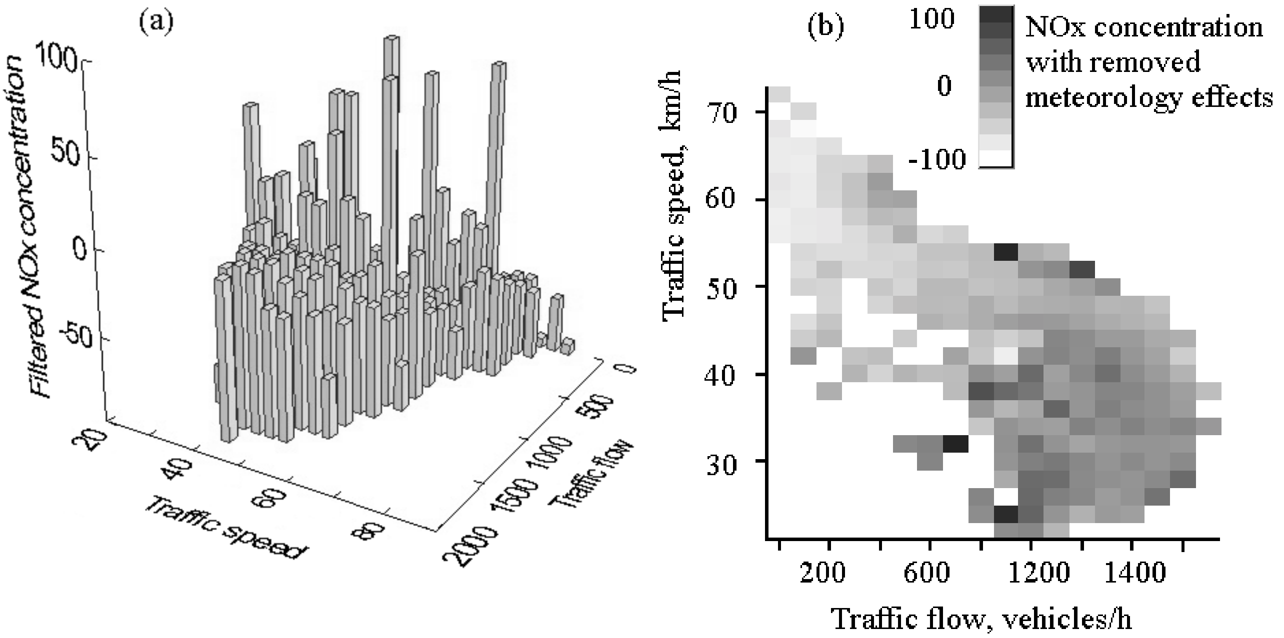

Figure 4 The 3D (a) and 2D (b) plots NOx concentration with removed meteorology effects against traffic speed and traffic flow.

6 Analysis of results and conclusions

Based on the estimated relationships between NOx concentration with removed meteorology effects and traffic variables (see figures 4 and 5) several distinctive effects of congested vs. freeway urban traffic flow on air pollutant concentrations in a street canyon can be identified. Under uncongested traffic flow conditions (traffic speed >50 km/h) higher traffic volume cause higher pollutant concentrations. Higher speeds also result in higher NOx levels, as per the average speed-based emission factor curve (see figure 2). Under congested traffic conditions (traffic speed <50 km/h) lower traffic volume travelling at the same speed result in higher NOx concentrations. Such flow conditions are present under a high emission stop-and-go driving pattern. The decrease of driving speed to 35 - 40 km/h combined with large traffic flows (>1000 veh/h) causes an increase in NOx concentrations. At speeds below this NOx concentrations are not affected. The increase of NOx concentrations with decreasing average speed under congested conditions (low speeds) is in accordance with the average speed based emission factor curve (see figure 2), however, it can not explain the flat part of curve in figure 5 b.

In summary, this study has shown that traffic flow patterns significantly influence air pollution concentrations in a street canyon and their effect differs under congested and uncongested traffic flow. These affects should be taken into account for uncertainty analysis and the development of the confidence limits of pollution dispersion models and for designing an effective air-quality improvement program. For explicit emission rate simulations microscopic traffic simulation models have to be used.

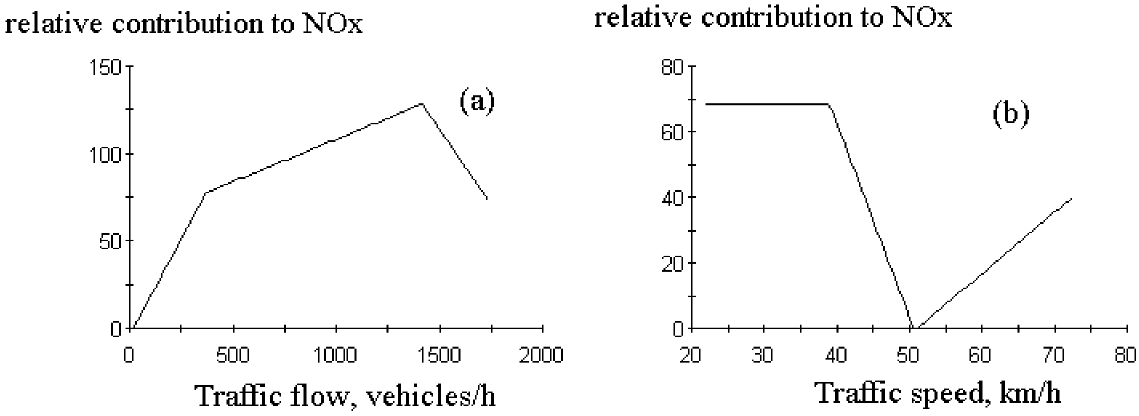

Figure 5 Relative contribution to NOx concentration by traffic flow (a) and traffic speed (b).

7 Acknowledgements

This study has been part of the EU funded project APPETISE "Air pollution episodes; modelling tools for improved smog management".

8 References

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