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The spatial variability in concentrations of a traffic-related pollutant in two street canyons in York, UK—Part I: The influence of background winds

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Abstract

The influence of background wind flow on the dispersion of carbon monoxide (CO) was investigated over a one-month period in two street canyons of differing geometry in the city of York, UK. Electrochemical sensors were used to measure CO concentrations at various heights and locations along each canyon. Six ultrasonic anemometers were used to measure the airflow and turbulence within one of the canyons. A seventh anemometer measured the above-roof (or background) winds at approximately twice the street building height. Bi-directional traffic flow was measured in each street using the Split, Cycle and Offset Optimisation Technique (SCOOT) system. The investigation indicates that differences in the street geometry and the background winds result in contrasting in-canyon wind flows and dispersion characteristics. Whilst there is evidence of a single cross canyon vortex in one street canyon for certain background wind directions, there are also a number of three-dimensional (3D) flow structures formed in the canyon due to the influence of flow channelling, both within the canyon and from adjoining side streets. For background winds with a strong perpendicular component relative to the canyon axes, the mean CO concentrations on the leeward side of the street canyons were on average, a factor of two greater than on the windward side. This feature can be attributed to the formation of vertical and horizontal vortices. However, when the concentrations were normalised by the background wind speed and total traffic flow, a three-fold difference exists between the windward and leeward sides of the street canyon. Evidence of flow channelling and helical flow regimes was also detected for background flows with a component parallel to the canyon axes. The difference in mean CO concentrations between the two street canyons was approximately two-fold, with the highest mean concentrations in the narrower canyon, which has a smaller cross-sectional area.

Keywords: Pollutant dispersion; Vortex; Wind flow; Urban

1. Introduction

Pollutants emitted by vehicle traffic in urban areas have now generally been accepted to be a cause of chronic health effects. In urban areas, where the population and traffic flows are often relatively high,

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human exposure to traffic-related pollutants is significant (Fenger, 1999). Increased incidence of congestive heart disease among the elderly and those with pre-existing conditions has been linked to increases in background concentrations of carbon monoxide (CO) (Morris et al., 1995). However, the concentrations of traffic-related pollutants in street canyons are controlled by a balance between factors that contribute to both pollutant accumulation and dispersion. What is currently required is not only a reduction in the emissions of harmful pollutants but also a method whereby it is possible to accurately predict wind flow and pollutant dispersion using numerical models. These models could then be used within strategic planning activities aimed at assessing the influence of a range of traffic management procedures on air quality within urban areas. In order to assess the validity of available models, a range of experimental data is required in networks of urban streets with varying geometries. A street with relatively tall buildings flanked on either side has been defined as a street canyon (Nicholson, 1975) and it is well known that complex street geometries composed of narrow street canyons modify the flow structures within urban areas and, therefore, influence the dispersion of vehicle emissions. The first step in achieving a greater understanding of complex urban wind flows, and their implication on pollutant dispersion, should, therefore, be to conduct a study of the wind flow and pollutant concentrations within urban street canyons of varying building and street geometry.

In an idealised situation, a street canyon is considered to be two–dimensional (2D) with a street of infinite length (L) and buildings of equal height surrounding the street, i.e. the street canyon is symmetrical. For this case, the only parameter required to describe the geometry is the aspect ratio (H/W), or the building height (H) to street width (W) ratio. Meteorological conditions such as background wind speed and direction, atmospheric stability and solar radiation may also influence wind flow inside street canyons. Within a symmetrical street canyon ($H/W \approx 1$) during perpendicular background winds, the majority of the background flow skims over the canyon, producing the *skimming* flow regime, which is characterised by the isolation of a single recirculating vortex within the canyon (Oke, 1987; Johnson and Hunter, 1999). This is similar to that formed by flow over transverse square cavities or *d-type* roughness (e.g. Djenidi et al. 1999), which has been measured in engineering boundary layer and channel flows. Many previous street canyon models have concentrated on skimming flow, since pollutants released by vehicles at street level during these background wind conditions are transported by a single across-canyon vortex. The classic recirculating vortex has been observed in the field by DePaul and Sheih (1986) and in the wind tunnel by Hoydysh and Dabberdt (1988). Louka et al. (2000) implied that a recirculating flow occurred during perpendicular winds, although measurements of the wind flow in their study were made above the urban canopy i.e. at or above roof-level. The classic recirculating vortex may, therefore, cause an increase in the concentrations of traffic-related pollutants on the leeward (or up-wind) side of the canyon relative to the windward side. Using direct numerical simulations of a 2D geometry with different aspect ratios, Leonardi et al. (2003) have shown that skimming flow within a canyon may occur for $0.33 < H/W < 1$. However for smaller H/W, the main recirculation breaks down and wake-interference flow develops (see also Oke, 1987). For more complicated street geometries, it has been demonstrated numerically (e.g. Sini et al., 1996; Leitl and Meroney, 1997), and by using wind tunnel modelling (Hoydysh and Dabberdt, 1988; Kastner-Klein et al., 1997, 2001; Rafailidis, 1997; Park et al., 2004), that wind flow and pollutant dispersion within continuous street canyons essentially depend on the aspect ratio, the street length and building roof geometry (Theurer, 1999). These effects are particularly prevalent during perpendicular and near-perpendicular background winds although in any study into the spatial variability of pollutant concentrations within street canyons, consideration should also be given to the effects of non-perpendicular winds. Kim and Baik (2004) conducted a numerical study into the effects of the background wind direction on flow and dispersion in short street canyons with cubic building geometries. They identified three in-canyon flow patterns with considerably different dispersion characteristics depending on the incidence wind angle. They found that as the incidence angle becomes oblique to the street axis more pollutants escaped from the street canyon. In addition, side streets interrupt street canyons within real urban networks and additional three-dimensional (3D) effects may influence the dispersion of emissions. Pollution may also accumulate in small cavities where additional recirculation regions occur (Oke, 1987), and whirling eddies, or corner vortices, developing around buildings are likely to accumulate traffic-related pollutants.

Despite the range of idealised numerical studies, few full-scale experiments have been conducted which provide data from simultaneous measurements of in-canyon wind flow and pollutant concentrations, relative to a suitable background wind measurement. Full-scale street canyon experiments, however, are only representative of local conditions and data from more locations are required to identify general properties (Longley et al., 2004). Inter-comparisons must also be made between street canyons of different geometry, as not all street canyons are symmetrical. Most streets have a non-uniform width or have buildings that differ in height on either side. Dispersion models are widely used in air quality and traffic management, urban planning,