H13-24A
COMPLEX AIR FLOWS AROUND URBAN INTERSECTIONS: CHALLENGES FOR MODELLERS

Alison S. Tomlin[1], Joel Millward-Hopkins[1], Ahmed Balogun[1], James Tate[2], Janet Barlow[3], Curtis Wood[3], Alan Robins[4]

[1]Energy and Resources Research Institute, SPEME, University of Leeds, Leeds, UK
[2]Institute for Transport Studies, University of Leeds, Leeds, UK
[3]Department of Meteorology, University of Reading, Reading, UK
[4]Faculty of Engineering and Physical Sciences, University of Surrey, UK

Abstract: The street canyon is a canonical form which helps to explain flow and dispersion patterns in many built up urban areas. The helical type flows which form in such canyons have been shown to impact on the development and location of traffic related pollution hot spots. These features have been demonstrated not just in idealised canyons, but also in real urban streets. Street intersections are a second basic element of urban geometry that could be critical in driving dispersion processes. Local hot-spots of traffic-related pollutants also occur at traffic signal controlled junctions, where vehicles tend to be accelerating causing elevated emissions. It is therefore important to assess whether generic air flow features occur at intersections and can be accurately represented within a modelling framework. Understanding their impact on in-canyon flows is also important. This paper presents field measurements of air flows from the vicinity of two urban intersections (in Central London and Leeds) as well as adjoining street canyons. The data will be used to demonstrate how asymmetries in local building geometry around the intersection, and small changes in background wind direction can have substantial influences on the behaviour of intersection and adjoining canyon flow patterns. Features such as flow convergence within the intersection and the presence of corner vortices will be shown. Reversed in street channelling with respect to the above roof parallel flow component is also shown at a distance of ≈ 2-3H from the Leeds intersection. The influence of short time-scale variability in background wind direction and speed will also be explored, highlighting the multimodal features of the in-street flow around intersections. The challenges of representing such features within urban air flow and dispersion models will be discussed, including short time-scale features of relevance to emergency response models.

Key words: *street canyon, urban dispersion, intersection, corner vortex, emergency response*

INTRODUCTION

Many applications of dispersion e.g. air quality and emergency response, require knowledge of how emissions are transported through networks of urban streets. It is well understood that urban buildings interact with background winds to modify the turbulent flow structures within the street network. The street canyon is a commonly studied part of the urban form and simple models describing flows within street canyons have been proposed which aim to describe the helical recirculating flows that form within them (Ahmad *et al*, 2005). The conceptual model of Dobre for example (Dobre *et al*, 2005, Barlow *et al*, 2009) attempts to describe the in-street flow direction as a function of the parallel and perpendicular components of the above roof flow and has been shown to give a reasonable representation of the mean flows in real streets. However, street networks also contain intersections and several studies have demonstrated the influence of the flow characteristics at such junctions on how pollutants are distributed to the adjoining streets (Scaperdas and Colvile, 1999, Scaperdas *et al*, 2000, Robins *et al*, 2002, Boddy *et al*, 2005, Soulhac *et al*, 2009). It is therefore important to understand the flow structures within intersections and how they may depend on the local building geometry, and background wind speed and direction.

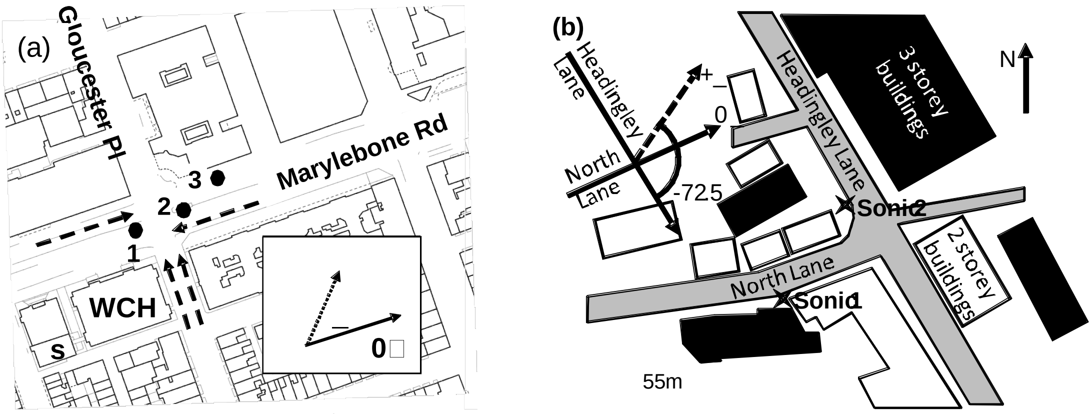

Figure 1 Site schematic for (a) the DAPPLE site (Copyright Edina map) (b) the Headingley intersection in Leeds.

METHODOLOGY

The study uses in-street and reference flow data from two separate field campaigns conducted in Central London (the DAPPLE site) and Leeds to explore the influence of intersection geometries on air flows through the intersection and into the adjoining streets. At the DAPPLE site, centred around the intersection between Marylebone Rd. and Gloucester Place (Lat/Long: 51° 31′ 19″ N, 00° 09′ 35″ W), a 6 week field measurement campaign was conducted in the spring of 2007 between 22 May and 4 July. An overview of the DAPPLE project and comprehensive description of the measurement site and set-up have been presented in Arnold *et al* (2004) for the 2003 campaign and Wood *et al* (2009) for the 2007 field measurements. Further information is also available at www.dapple.org.uk. Marylebone Road is a busy seven lane dual carriageway, approximately 38 m wide and orientated WSW–ENE. Gloucester Place is a three-lane road approximately 20 m wide and with the traffic flow one-way towards the NNW (as marked by dashed lines in Figure 1a). The roads intersect perpendicularly and have a similar vehicle traffic density of approximately 500 vehicles per hour per lane (Scaperdas and Colvile, 1999). Data from five in-street ultrasonic anemometers (‘sonics’) operating at a frequency of 10 Hz and a roof-top reference sonic operating at 20Hz were investigated. Four sonics were deployed at the intersection at heights of 7.90 m for the top sonics at sites 1 and 2 (see Fig. 1a) and 3.95 m and 4.15 m for the bottom sonics at sites 1 and 2 respectively on two opposite lampposts in the central reservation of the Marylebone Road and Gloucester Place intersection (see Fig. 1a). Another sonic (site 3) was deployed at 4.15m on a lamppost within the Marylebone Road street canyon for comparison. The reference roof-top sonic was located on the SW corner of the WCH library roof and is marked by S in Figure 1a.

The second data set is from a permanently instrumented site in North Leeds centred around the junction between North Lane and the Headingley Lane. North Lane forms a complex, irregular street canyon approximately 15m wide and lined by a mixture of two and three story buildings. The approximate heights of these are 10m and 12m (shown as 2 storey buildings in white) and 20m (3 storey buildings in black), giving a canyon geometry of H:W ≈ 0.67-1.3, depending on the direction of the approaching winds. Also lying directly behind the buildings lining the North of the canyon is the large building of Headingley church. Three sonics are located around the Headingley junction in Leeds, again measuring at 10 Hz, and the two used in the following discussion are marked in Figure 1b with star symbols. Data used was collected July 2008-Feb 2009. Sonic 1 is located within the North Lane street canyon, approximately 35m west of the intersection at a height of 4m and a distance of ≈ 3m from the nearest wall. Sonic 2 is directly within the intersection at a similar height. Reference data in this case is taken from the roof of the Houldsworth building at the north end of Leeds University approximately 2 km to the south of the site (represented by subscript hlds).

All reported wind directions use a Cartesian vector system with respect to either Marylebone Road or North Lane (Dobre *et al* 2005), so that the roof-top reference wind directions (θ_{ref}, θ_{hlds}) are positive anti-clockwise from 0° when the wind blows along North Lane/Marylebone Road (roughly towards the East) and +90° when the wind is blowing up Gloucester Place at the DAPPLE site (from SSE to NNW); and presented in the wind vector sense (pointing in the downstream flow direction).

RESULTS AND DISCUSSION

Mean flow patterns

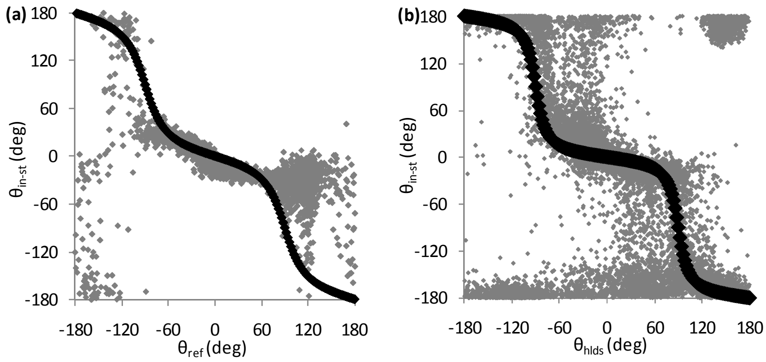

Figure 2 Plot showing the relationship between the reference wind direction θ_{ref} and the instreet wind direction for (a) DAPPLE site 3 (b) the North Lane canyon, Leeds. The gray symbols are 15-minute averages of the measured data and the black symbols the fitted model of (Dobre et al., 2005).

The first question addressed is whether the mean flows at the sites resemble the flow patterns predicted for the usual canonical street geometry, the street canyon. 15 minute average data was used for this purpose and comparisons were made with the model of Dobre *et al* (2005) which predicts the best-fit in-street wind direction compared to the reference wind direction (θ_{ref}) based on assumptions of helical flow patterns. Figures 2a and 2b show that for DAPPLE site 3 in the London Marylebone Rd. canyon and the North Lane canyon in Leeds, the helical flow assumption is reasonable for most θ_{ref} with a combination of flow channelling and flow reversal due to cross canyon re-circulation being present in the flow patterns. The recirculation part of the in-street flow leads to a gradual decrease in in-street flow direction as θ_{ref} increases due to flow reversal at the canyon floor. Switching (channelling of recirculated weak mean flow in either direction along the street canyon) of the channelled component of the flow for near perpendicular roof-top wind directions, θ_{ref} around +120° and –120°, leads to large scatter in the mean in-street flow direction at site 3. For North Lane, there is significant scatter in the flow between wind angles (±30°-120°) which suggests that for comparable θ_{hlds}, there can be a complete switching of the mean in-street channelled flow component. Figure 3 shows similar scatter plots for the intersection sites 1 and 2 in Marylebone Rd. Again, although there is evidence of in-street flow channelling and some flow reversal, there are areas where a narrow region of background flow directions can lead to a huge variety of in-street mean flow angles. The scatter is even greater for lower background wind speeds where additional sources of turbulence such as that produced by passing traffic may begin to dominate. The intersection sites do not show the non-linear negative relationship between in-street and roof-top direction consistent with helical flow. The neat picture offered by the conceptual helical flow model does not therefore seem to explain the relationship between background wind direction and in-street mean flows for sites within or close to the intersections. To further explore the influences on fluctuations in in-street flow angles, short time-scale analysis was therefore performed at the sites using 10 Hz data.

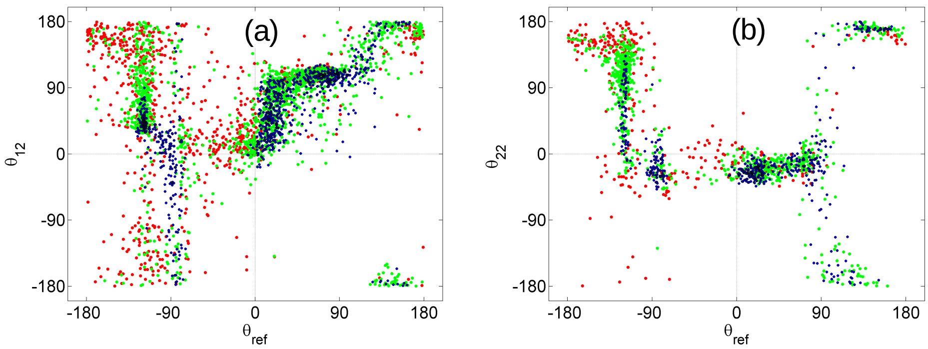

Figure 3. 15-minute mean wind direction (θ_{ij}) against roof-top wind direction (θ_{ref}) for in-street sonics, (a) Site 1 lower, (b) Site 2 lower. Thresholds of roof-top wind speed (U_{ref}): ♦ U_{ref} < 1.1 m s^{-1}, ♦ 1.1 ≤ U_{ref} ≤ 2.5 m s^{-1}, and ♦ U_{ref} > 2.5 m s^{-1}.

Short time-scale analysis

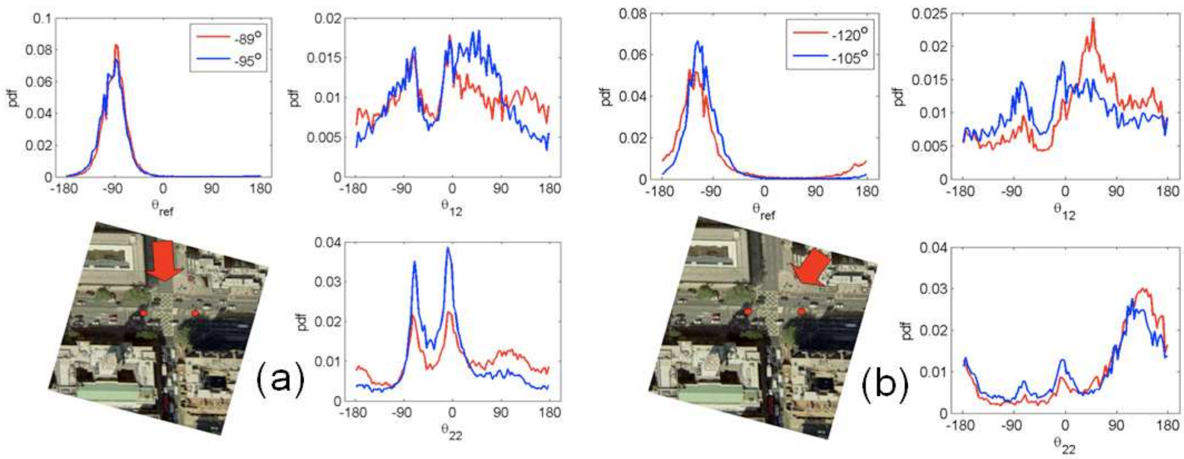

Figure 4. Wind direction pdfs for 1 hour segments of 10 Hz data at the DAPPLE intersection sites for θ_{ref} wind sectors a) –75° ≤ θ_{ref} ≤ –105° b) –105° ≤ θ_{ref} ≤ –135°. Top left: roof-top wind direction pdf where legend indicates mean flow direction, bottom left: site layout with arrow pointing in the direction of flow, top right: site 1 (lower sonic) and bottom right: site 2 (lower sonic).

Pdf plots of in-street wind direction are shown for 1-hour segments of 10 Hz data from DAPPLE sites 1 and 2 in Figure 4. In the plots the large arrow overlaying the aerial photograph indicates the mean background wind direction for each case study. In the top left of the plots the pdf of the background wind direction is shown. The width of this distribution suggests that there can be significant short time-scale variability in θ_{ref} throughout the hour of sometimes up to 180°. In Figure 4a the mean background wind is channelling down Gloucester Place (θ_{ref} ~ -90°). It might be expected that under these conditions, flow would channel through the intersection towards the southern section of Gloucester Place. However, the pdf's of the in-street wind angles for the lower sonics at site 1 (θ_{12}) and site 2 (θ_{22}) show multi-modal characteristics. θ_{22} shows two sharp peaks including one which suggests channelling along Marylebone Rd. (θ_{22} ~ 0°) due to the rectification of the fluctuations in background flow by the buildings along Marylebone Rd. The second peak at -60° is associated with deflected flow to the ESE. Dobre *et al* (2005) also reported a peak at -60° in the pdf at site 2 for reference roof-top winds in the sector -90° < θ_{ref} ≤ 0° observed during the DAPPLE 2003 field campaign. They attributed the flow deflection to the presence of a car park next to the NNE corner of the intersection that deflects the flow at negative angles into Marylebone Rd. The flow is also less constrained on the NNE corner of this intersection due to the arc in the building of Dorset House. A third broader peak is also present around θ_{ref} ~ +90° which represents flow reversal with respect to the background wind. This would either be due to the influence of the helical flow regime established in the canyon part of the Marylebone Rd., or perhaps to the effects of one-way traffic travelling up Gloucester Place. At site 1, in-street flow angles are observed in all sectors, despite the mean roof-top direction being constrained to a 30° sector. Strong peaks exist for θ_{12}≈ -90° illustrating channelled flow along Gloucester Place, and θ_{12}≈ 0° illustrating channelled flow along Marylebone Road. While flow channelling along Gloucester Place could be expected to dominate, there is also clear channelling along Marylebone Road at site 1 on short time-scales, showing that even slightly oblique components of roof-top flow in this sector can lead to bifurcation type flows. It is the averaging of these modal peaks that leads to the scatter in the longer time-averaged data shown in figure 3. This suggests that the mean flow direction data based on a 15-minute average does not give an accurate picture of the bifurcation behaviour which occurs at the intersection and is better demonstrated by the multi-modal peaks in the pdf's. When the background flow becomes oblique (Figure 4b), the multi-modal behaviour of the in-street flows persists, again demonstrating peaks in the channelled directions of the adjoining streets. Another interesting feature of Figure 4 is that very small changes in the mean θ_{ref} and its pdf can dramatically change the relative strength of the modal peaks in the in-street pdf's. The ability to represent such multi-modal behaviour and its sensitivity to background wind speed and direction would be a challenge for any model attempting to represent the air flow through an asymmetric intersection. It is therefore worthwhile to ask the question whether such multi-modal features are a common feature of intersections. Similar analysis was therefore carried out for the Headingley canyon.

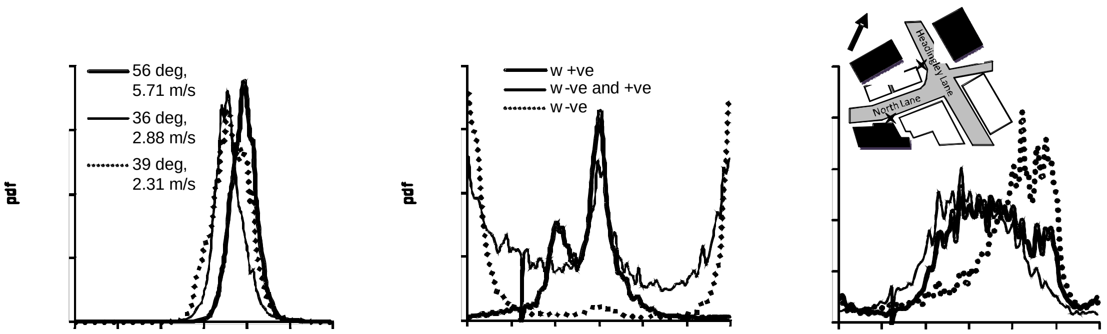

Figure 5 (a) Distribution of reference horizontal wind direction in three different 2 hr time periods, with legend indicating the mean wind speeds and directions. (b) Corresponding distributions of the wind direction within North Lane, with the legend indicating the predominant sign of the vertical velocity. (c) Corresponding distributions of the wind direction recorded at the intersection.

Figure 5 shows similar pdf's for the North Lane canyon for three background wind direction (θ_{hlds}) distributions which are oblique to the street as shown on the schematic map. Different background wind speeds are also explored as indicated in the legend for Figure 5a. Bimodal in-street channelling is particularly common for this particular sector of oblique background winds, potentially due to the combination of the off-perpendicular orientation of the intersection between the streets, and the high windward building on the South side of North Lane. Period 1 (thick, solid line) was a period of high background wind speeds. Within this period it can be seen from Figure 5b that the flow within North Lane was channelling up the street towards the intersection (0°) for the entire period, and the predominately +ve distribution of in-street vertical velocities was consistent with an in-street recirculation as shown in the schematic in Figure 6a. The widely distributed intersection wind directions in Figure 5c implied that the dominant flow at the intersection fluctuated within the period between flows channelled from Headingly Lane and North Lane. Background wind speeds in period 2 (thin, solid line) were much lower than period 1, and the in-street and intersection flow characteristics are more complex. This is particularly true within North Lane, where the relatively symmetric bi-modal distribution of wind directions implies channelling is fluctuating both up and down the street. As a consequence of this varying direction of in-street channelling, both updrafts and downdrafts are frequently observed, with the former corresponding to the formation of an in-street recirculation, and the latter to a convergence of flow within the street and hence a breakdown of the recirculation (see Figure 6a,b). In Figure 5c, although widely spread, the distribution of intersection wind directions is shown to be predominantly dominated by flow from the direction of North Lane. Potentially, this is due to flow over the roofs of the buildings lining the north of North Lane, dominating the flow at the intersection anemometer. In the period 3 (dotted line), despite the direction of the background winds within this period lying significantly more oblique to North Lane than those in period 1, the channelling within North Lane was observed to be reversed for almost the entire period (Figure 5b). The suggested reason for this is the low background wind speeds within the period, and consequently the weak in-street recirculation. Also, the predominantly –ve vertical velocities recorded were consistent with a convergence of flow within North Lane. At the intersection, due to the reversed channelling in North Lane, Figure 5c shows the wind direction is frequently dominated instead by flow channelled up Headingley Lane (+90°). It is suggested that the competition between flows from the two streets leads to a downdraft at the sonic site but a forced updraft of flow coming from North lane (see schematic in Figure 6b). This 3-dimensional feature indicates that flow in the vicinity of intersections is not always planar as suggested by Soulhac *et al* (2009).

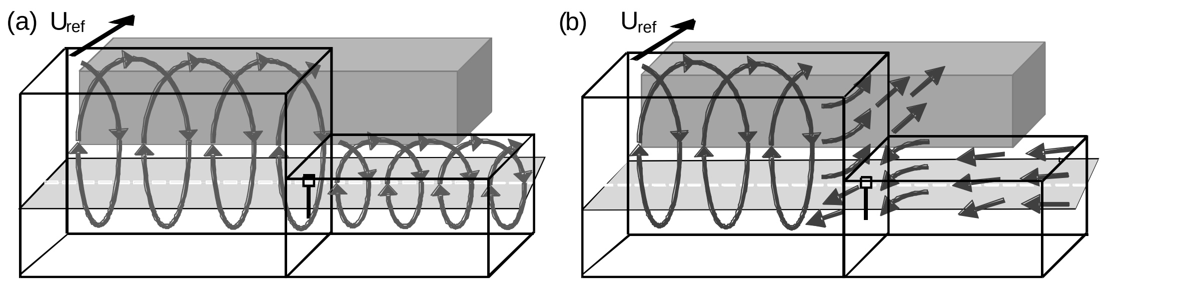

Figure 6 - Schematic diagram illustrating (a) the helicoidal flow within North Lane for oblique background winds approximately within the sector ≈ 175° < θ_{hlds} < 240° when in-street flow is being channelled towards the intersection (210° < $\theta_{in\text{-}st}$ < 300°), and (b) the convergence of flow within North lane when the in-street channelling recorded is away from the intersection (30° < $\theta_{in\text{-}st}$ < 120°).

CONCLUSIONS

High temporal resolution air flow data from two urban intersections has been presented and has demonstrated the complexities of flow patterns formed due to the competition of flows from the adjoining streets. 15-minute mean in-street wind direction data shows a wide degree of scatter for quite narrow ranges of background wind angles. Higher time resolution analysis suggests that this is due to the averaging of multi-modal distributions of in-street wind angle that occur due to the competition within the intersection of flows channelling from each of the perpendicular adjoining streets. Time-average data does not therefore seem to give a good picture of the flow directions which occur within the intersections. The multi-modal behaviour of the flows represents changes in the relative strength of flows from the adjoining streets, which is highly sensitive to fluctuations in the background wind speed and direction. When the adjoining flows converge, downdrafts and updrafts can occur within the street depending on the height of the measurement. Evidence of corner vortices was also observed within the intersection leading to deviations of angle from the directly channelled directions. The complexities of the features observed and their strong sensitivity to short term fluctuations in background wind direction pose challenges for even time-resolved dispersion models such as those based on Large Eddy Simulation, let alone time or statistically averaged network models (Soulhac, 2009). The flow features however, could determine the relative strength of dispersion of pollutants down streets adjoined to the intersection and models therefore need to be able to represent such features. Appropriate specification of the inlet boundary conditions which is representative of fluctuations in the background flow would seem to be crucial.

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