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Short-term measurements of airflow and turbulence in two street canyons in Manchester

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Abstract

Ultrasonic anemometers have been used to make measurements of airflow and turbulence in two urban street canyons in Greater Manchester, UK This paper concentrates mostly on results from one—an asymmetrical city centre canyon with complex building geometry, building heights up to 28 m and busy traffic. Data was recorded for a total of five working weeks in four separate periods in 2001 at one roadside location at a range of heights from 2 to 18 m. This data was supplemented by a series of mobile measurements at 2–4 m height at 18 different roadside locations within the same canyon. Although some features of a vortex-flow, as assumed in some (but by no means all) numerical models, was observed, other important flow features were found which, although canyon-specific, nevertheless indicate the ways in which flow in all real canyons may differ from the assumptions implicit in some models. Of particular importance were lateral channelled flow and sheltering in perpendicular flow. Profiles of turbulence are presented along with a simple model relating turbulence to wind speed and traffic flow rate. A strong influence of traffic on vertical turbulence production was found in a layer no deeper than 3 m. This influence was absent in measurements in a traffic-free suburban canyon.

Keywords: Street canyon; Traffic-induced turbulence; Turbulent intensity

1. Introduction

Increased mortality and morbidity is increasingly being linked to the emission of airborne pollutants from traffic. These pollutants are dispersed on the wind; however, high concentrations of both traffic and people can be found within the network of urban street canyons that make up city and town centres. The canyon network modifies the wind flow and generates localised turbulence unrelated to the better-characterised flow and turbulence above and beyond the city. As the spatial and temporal variation in pollutant concentrations across the city depend upon advection and turbulent dispersion, these processes need to be understood and modelled in order to manage and regulate urban air quality.

Operational street canyon models, in which dispersion processes are described by simple parameterisations, are routinely used for air quality regulation, but even the most sophisticated are based upon unrealistically simplified situations, or on limited experimental datasets of questionable generality. Research into improving our understanding has mostly been based upon numerical models with a $\kappa-\varepsilon$ closure description of turbulence, which have been used to systematically investigate the influences of geometry and heating on vortex flow, turbulence and pollutant exchange in symmetrical, empty canyons (e.g. Sini et al., 1996; Kim and Baik, 1999), but two-dimensional (2-d) modelling studies have been much more common than three-dimensional (3-d). Limited 3-d modelling of canyons has been carried out by Hunter et al. (1992) in which canyon geometry, and

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in particular lateral vortices, were found to have an influence upon the main vortex regime in perpendicular approach flow. Chan et al. (2001, 2003) derived various general 'rules of thumb' to indicate the influence of building and canyon geometry, including canyon asymmetry, upon pollutant dispersion. The presence and location of breaks in one side of a canyon were shown to have significant local effects on flow and pollutant dispersion. Canyon intersections have been modelled using a coarse grid (5 m) by Scaperdas and Colville (1999).

Such modelling studies have given a basic framework that can be used to interpret and predict the major features of flow and turbulence in a canyon. However, they are necessarily highly idealised and it is unknown to what degree the results can be applied to highly complex real canyons. $\kappa-\varepsilon$ modelling also gives a false impression of a dynamic equilibrium, which is very unlikely to exist. Numerical models are often only validated against other numerical models, or against wind tunnel data.

Large eddy simulation (LES) modelling can deliver a greater accuracy and more information, particularly concerning the temporal evolution of flow and turbulence. Walton et al. (2002) compared the predictions of both an LES model and a standard $\kappa-\varepsilon$ model with anemometric measurements made in a cubic canyon (roof garden, $H/W = 0.63$). They found that the LES model made improved predictions of a stronger vortex and greater turbulent intensities compared to a $\kappa-\varepsilon$ model, supporting previous observations that $\kappa-\varepsilon$ models might predict stronger concentration gradients than actually occurs (Johnson and Hunter, 1998). The LES model was then applied to the case of an idealised canyon of aspect ratio 1 (Walton and Cheng, 2002) in which the main canyon vortex appeared to precess and meander along the length of the canyon, and venting of the canyon was intermittent. However, LES modelling is computationally much more demanding and a fully 3-d numerical study of the influence of the neighbourhood building geometry (canyons, open spaces, tall buildings, etc.) will involve an impractical number of variables.

Field studies and 3-d model studies indicate that lateral flow in the canyon is significant, and concentrations may vary with wind direction in a complex way, especially away from the centre of the canyon, even in simple symmetrical model canyons (Kastner-Klein and Plate, 1999). The 3-d numerical model of Scaperdas and Colville (1999) also indicated a strong influence of wind direction and the interaction of intersecting canyons of varying aspect ratio. Wind tunnel modelling of the intersection (Scaperdas, 2000) indicated that when the incident wind was parallel to a source canyon upwind of the intersection, most of the air was removed laterally through the three exiting canyons with very little vertical flux, even when an offset between the upwind and downwind canyon was introduced. The flow patterns and flux budget were sensitive to deviations from a precisely symmetrical scenario. Similarly, data from a field study in a full-size model canyon (Johnson and Hunter, 1999) indicated a complex lateral flow and channelling, and the authors argued that knowledge of the basic canyon geometry was insufficient to describe the flow patterns within it.

Logistical difficulties have meant that few datasets exist from real canyons. Extensive turbulence measurements have been made at multiple levels above, and in the upper half, of a real urban canyon during the Zurich Urban Climate Program (Rotach, 1995), and long-term measurements of velocity and turbulence from 2 ultrasonic anemometers on each side of a relatively uniform street canyon were presented by Nielsen (2000). In both of these cases turbulence at emission and pedestrian level was not measured and the influence of traffic was not explicitly considered.

Field data is necessarily representative of local conditions and data from more locations is required to identify general properties. Field studies to date have generally opted for sites that offer the closest practical approximation to a simple geometry. There is little information on how the flow characteristics will differ in a more complex (but more common) layout. When field data has been used to validate models, data corresponding to less common conditions, such as very low wind speeds or high stability (or instability) may be discarded because of their inherent variability or because they do not suit the formulation of the model (Schatzmann and Leitl, 2002). Yet, it may be precisely these conditions that lead to increased concentrations or emission fluxes from street canyons, and there are of at least equal interest to the more common situations.

Key questions that need to be addressed include the variation in turbulence within the canyon volume; the common and different features between one canyon and any other, including the degree to which the geometry of the canyon has an effect; how the presence of moving traffic modifies flow and turbulence, and how results from modelling exercises can be applied to a real canyon.

In order to provide an insight into the issues raised, observations are presented in this paper from a series of short measurement campaigns in two different urban street canyons.

2. Activities

2.1. The two campaigns—overview

The City of Manchester, in the north west of England, is at the heart of the conurbation of Greater Manchester, which has a population of 2.5 million. Data is

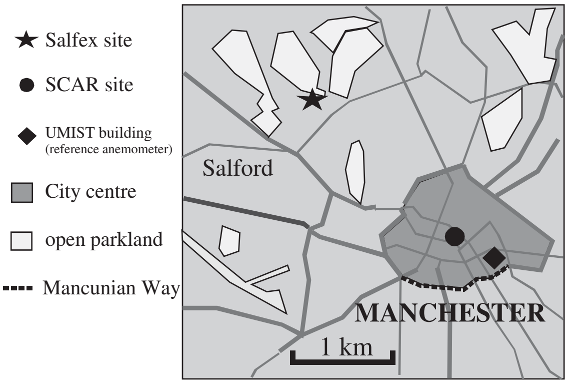

Fig. 1. Location of experimental sites in Manchester.

presented from a field study in a canyon with busy one-way traffic in central Manchester, and some aspects are compared with similar data from a traffic-free suburban canyon in the nearby inner city district of Salford (Fig. 1).

The Manchester data was obtained during four separate periods in 2001 as part of UMIST's Street Canyon Aerosol Research (SCAR) campaign. In this campaign the flow and turbulence measurements were made to help interpret the fine-scale variation in size-segregated aerosol concentrations (Longley et al., 2003). The Salford data was obtained during the Salfex campaign, part of the UWERN Urban Meteorology programme in April and May 2002 (Barlow et al., 2003).

2.2. SCAR, Manchester

The SCAR site was in Princess Street in the centre of Manchester. The chosen section of the street (Fig. 2) is 120 m long and asymmetric with the large Town Hall building along the southwest side, with a height of 22–28 m, and a variety of buildings on the northeast side of heights 10–18 m. Rooftops are complex and varied on both sides. It has open squares at both ends (Albert Square and St. Peter's Square) and the canyon is aligned at 130° to North. The street canyon itself is 17 m wide with two lanes of traffic both travelling towards the southeast (the direction referred to as *down-canyon* throughout SCAR), plus parking bays on the south side and a row of bus stops on the north side.

Four experiments were performed. SCAR-1, 2 and 3 in February, April and May 2001 lasted a week each and concentrated on turbulence measurements. SCAR-4 lasted for 2 weeks in October 2001 (15–26 inclusive) and ran continuously for each Monday to Friday period. In SCAR-4 turbulence measurements were made to support measurements of aerosol concentrations and fluxes.

During SCAR-1, 2 and 3 a Gill Solent ultrasonic anemometer (model A1012R) with a response time of

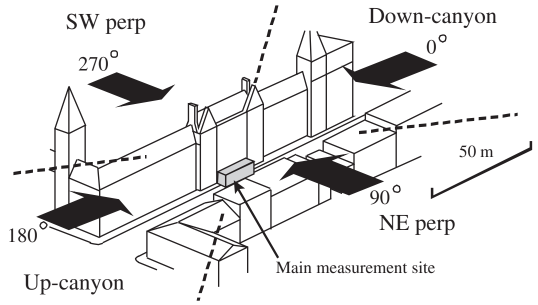

Fig. 2. SCAR site, including reference wind directions, γ, and wind direction sectors referred to in the text.

50 Hz and a resolution of $\pm 1\,\mathrm{cm\,s^{-1}}$ was deployed on the top of a slender telescopic mast. Throughout these campaigns the mast measurement heights were varied between 2, 4, 6, 12 and 15 m.

During SCAR-4 instruments were placed upon a hydraulic scissor lift platform, which was raised in 15-min stages to give data at four different heights up to 18 m. A RM Young Model 81000 ultrasonic anemometer with a response time of 50 Hz (25 Hz for sonic temperature) and a resolution of $\pm 1\,\mathrm{cm\,s^{-1}}$ ($\pm 0.05\,^{\circ}$C) was mounted in the centre of the lift platform with its sensor head 3 m above the platform floor. A degree of flow distortion caused by the platform cannot be discounted, although efforts were taken to reduce this impact by mounting the anemometer towards the outer (traffic-side) edge of the platform. The turbulence data obtained from the platform-mounted anemometer in SCAR-4 does not differ substantially from the mast-mounted anemometer at the same location and similar heights in SCAR-1, 2 and 3. During SCAR-4, a Gill Solent ultrasonic anemometer (model A1012R) was also fixed on a mast so that the sensor head was 3.5 m above the road, and was left in a fixed position 6.5 m behind the platform lift for the duration of the experiment. Both the platform- and mast-mounted systems were logged at 20 Hz.

In each of the four campaigns, the instruments were located in a set of parking bays on the southwest side of the canyon, on the opposite side to the bus stops, and at the mid-point of its length (Fig. 2).

A mobile anemometer system was also deployed during SCAR-2, 3 and 4 to investigate horizontal variation of turbulence within the canyon. This employed either a Gill Solent R2 (SCAR-2 and 3) or a RM Young 81000 (SCAR-4) mounted on a small mast so that the sonic head was 2–4 m above the pavement. After 10 min of recording it was moved 10 m along the pavement, completing a circuit of up to 9 locations on each side of the canyon in 3–4 h. This was repeated on successive days.

Wind speed and direction at rooftop level was acquired from a permanent ultrasonic anemometer (Gill

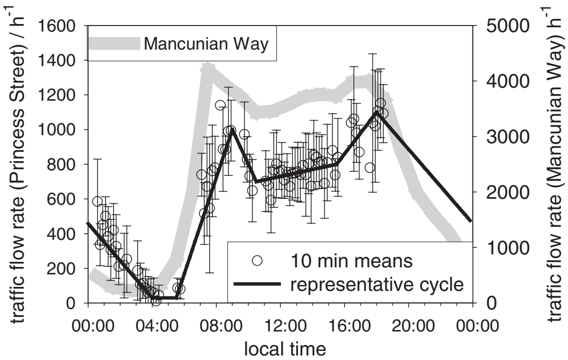

Fig. 3. SCAR traffic measurements and representative cycle. Error bars represent standard deviation of 1-min data within 10-min averaging period. Also shown is annual mean diurnal traffic flow on the Mancunian Way, Manchester's inner-city motorway (location on Fig. 1) for 1998 (data from Greater Manchester Transportation Unit).

Solent, Model Windmaster) at a height of approximately 30 m on the roof of the UMIST Main Building. This building is 750 m from the subject canyon (Fig. 1). It is taller than average for Manchester city centre and is not overlooked. Although the effect of the buildings on flow distortion cannot be discounted, this data is felt to be generally indicative of wind strength and direction in the upper levels of the urban canopy. The wind speeds recorded here are referred to as U_{ref} or reference wind speed in this paper. During the four experimental periods the mean wind speed was $5\,\text{m}\,\text{s}^{-1}$ and the wind direction was mostly southerly, leading to flow perpendicular to the canyon.

The city centre has distinct peaks in weekday traffic flow that occur at 7–9 and 16–18 h local time, as indicated by automated traffic counts from the Mancunian Way, Manchester's inner-city motorway (Fig. 3). Traffic in Princess Street is regulated by signals at both ends of the canyon. Automatic traffic flow measurement was not available but flow rates have been derived from manual observations. Observation was not continuous, but occurred over blocks of about an hour at various periods throughout the experiment. A representative diurnal cycle has been fitted to this data (Fig. 3), which shows that traffic flow varied between $30\,\text{h}^{-1}$ in the early morning periods to $1100\,\text{h}^{-1}$ during the evening peak. In the analysis below this representative traffic data has been applied to every day and day-to-day variations disregarded. It is estimated that speeds rarely exceed $50\,\text{km}\,\text{h}^{-1}$.

2.3. *Salfex, Salford*

The selected experimental site was in Thursfield Street, a straight, simple and very regular canyon. In this residential area there is one parallel road to the NE and five to the SW, which are all effectively identical. It is lined on both sides by continuous, simple and uniform terraced houses with continuous pitched roofs. The houses are low (8 m to the top of the pitched roof) and the street is narrow (11 m). The experimental section is 92 m long and is aligned at 107° to North. Measurements were made across 3 weeks between 22 April and 9 May 2002 within the hours of 10:00–17:00 local time. Traffic was blocked from using the street during the measurements.

Four ultrasonic anemometers were mounted on a single telescopic mast with the sensor heads at heights of 2, 3, 6 and 8 m above the road. The mast was located on the centre-line of the road at the mid-point of the canyon's length. The anemometers were placed on the upwind side of the mast, which in turn was sited upwind of the van used to site equipment. The anemometers used were all RM Young Model 81000. Data was logged from each anemometer at 20 Hz.

For both campaigns the raw data was de-spiked and 10-min means and other statistics were calculated using both EdiRE (part of the EdiSol suite) and tools developed at UMIST using LabView (National Instruments Corp., USA). Unlike some previous studies, measurements of very low wind speed were not discarded.

3. Results

3.1. *Mean flow—Manchester*

3.1.1. *Flow patterns*

With H/W varying from 0.6 to 1.6, and $L/W > 8$, a single vortex would be expected in perpendicular flow (e.g. Hunter et al., 1992; Sini et al., 1996), although modelling studies to date are not sophisticated or specific enough to indicate how the complexity of this asymmetric canyon may influence the mean flow patterns. The principal features of the measured mean flow are illustrated in Figs. 4–6. All wind directions are described with respect to a frame of reference based on the canyon axis, so that a parallel down-canyon flow is 0° (see Fig. 2). The reference wind direction is described as γ, whereas within the canyon, wind direction is specified by η based upon the same frame of reference. It should be noted that γ, like U_{ref}, is measured at the reference location at the UMIST Building, and is therefore only indicative of the wind direction directly above the canyon. The vertical wind angle within the canyon is specified by θ, which is positive for upward flow and negative for downward flow.

Data from the ultrasonic anemometers indicated that the mean flow pattern within the canyon could be divided into four distinct regimes (see Fig. 2):

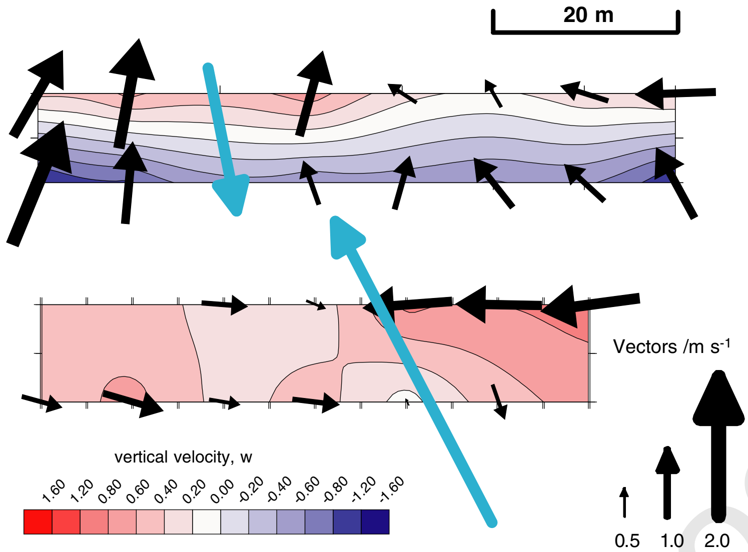

Fig. 4. Data from the mobile system. Plan view of SCAR canyon, SW side at bottom. Smaller arrows indicate vectors of mean horizontal wind component, contours showing vertical wind speed, w (red positive, blue negative). Large arrow indicates mean reference wind direction. Top: 14/5/01, $\bar{\gamma} = 78°$, range = 66–93°, measurements at 4 m height; presented as example of NE perpendicular flow. Bottom: 24/10/01, $\bar{\gamma} = 241°$, range = 226–251°, measurements at 2 m height; showing SW perpendicular flow. Note positive w only and flow reversal.

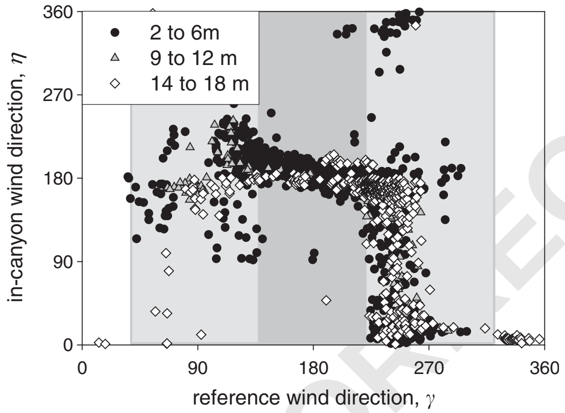

Fig. 5. In-canyon wind direction (η) as a function of above-canyon wind direction (γ) and height. Lightly shaded areas represent perpendicular flow (left NE, right SW), and central shaded area represents up-canyon flow. Includes all data from the measurement site at the mid-length of the SW side of Princess Street, but does not include data from the mobile system.

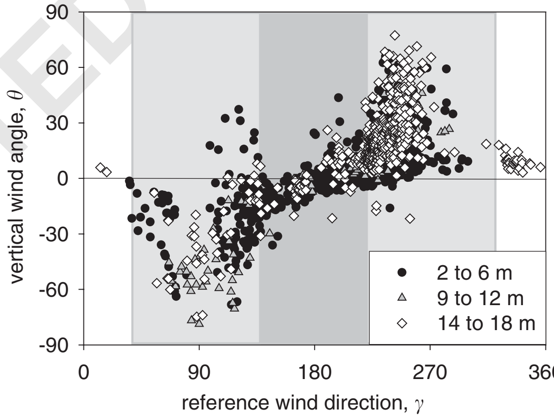

Fig. 6. As Fig. 5, but showing in-canyon vertical wind angle (θ) as a function of above-canyon wind direction (γ) and height.

- ‘Up-canyon’ flow is defined as flow when γ is within $\pm 40°$ of the canyon axis (i.e. 320–40°), blowing against the traffic flow.
- ‘NE perpendicular’ occurred when the wind approached the canyon over the shorter NE wall (40–140°). There was only limited data recorded in this regime.
- ‘Down-canyon’ is the opposite of up-canyon (140–220°). Again, only limited data was captured in this regime, due the lack of north-westerlies during the campaign.
- ‘SW perpendicular’ occurred when the wind approached over the taller wall (220–320°).

It should be noted that this definition of ‘perpendicular’ flow includes diagonal approach, within which a helical vortex flow might be expected within the canyon (Johnson and Hunter, 1999). In both up- and down-canyon flow the wind was channelled along the canyon with very little vertical component, as shown in the dark shaded section of Figs. 5 and 6.

In *NE perpendicular flow* the wind approaches over the shorter wall. Data gathered by the mobile system on the 14 (Fig. 4) and 15 May 2001 clearly indicates downward flow and flow towards the canyon centre-line along the whole length of the SW (downwind) side of the canyon and upward flow and flow away from the centre-line on the NE (upwind) side. This is clearly consistent with a vortex flow within the canyon space. There is also evidence of lateral convergence towards the middle of the canyon length at street level, as predicted by the LES model of Walton and Cheng (2002). Data from the fixed anemometers on the SW (downwind) side of the canyon indicate mostly downward flow (Fig. 6, left). Above 14 m the tall SW wall diverts the flow up-canyon if $\gamma > 90^\circ$ and down-canyon if $\gamma < 90^\circ$. However, lower in the canyon this simple relationship is not apparent, with only up-canyon flow observed.

When the wind approached the canyon over the taller SW wall (*SW perpendicular flow*, Figs. 5 and 6, right) there was similar evidence of channelling and vortex flow, shown by upward flow near the SW (lee) wall. However, this single vortex flow pattern did not always penetrate the full canyon depth. The mobile system observed only positive w, i.e. upward flow, along the whole length of both sides of the canyon (Fig. 4), except at the upwind entrance to the canyon (beyond which is the open space of St. Peter's Square). The lack of measured downward flow on the downwind side would be consistent with the vortex formed in the lee of the taller wall extending over and beyond the shorter downwind wall rather than into the canyon space, as has been predicted in some modelling studies (e.g. Scaperdas and Colville, 1999; Chan et al., 2001). There was no clear evidence on the SW side of the canyon (i.e. the taller wall) of a counter-rotating vortex below the main vortex, as has been predicted by some modelling studies (e.g. Baik and Kim, 1999) in deep canyons.

The horizontal wind direction within the canyon, η, was mostly channelled to within 30° of the canyon axis (Fig. 5). However, occasionally cross-canyon flow was observed, as was reversed-channelled flow when the wind would be diverted by more than 90° relative to the reference direction, flowing against the expected direction. What determined whether the in-canyon flow was channelled, reversed-channelled or cross-canyon could not be clearly determined. However, some insight into the mean flow within the canyon can be gained from data recorded by the mobile turbulence system. Seven of the periods during which this system was operational were during SW perpendicular flow. The data from these periods illustrated that up-canyon approach (around 180°) led to channelled flow in the same direction. As the incident wind direction increased from 180° and exceeded 230° down-canyon (reversed) flow was observed at the NW end of the canyon, which meets the up-canyon flow at some point along the canyon length (an example is shown in Fig. 4). It is at this point that the cross-canyon flow may be observed. This convergence point appears to move towards the upwind end of the canyon as the reference wind direction becomes more perpendicular. Care must be taken with this interpretation, as the data for the various points is not simultaneous, however in the periods selected the reference wind direction changed little within the duration of the mobile system's circuit of the canyon ($\sigma_\gamma < 8^\circ$, $\sigma_{U_{\mathrm{ref}}}/U_{\mathrm{ref}} < 0.1$). However, it does indicate how inflow from the downwind end of the canyon appears to be important. It should be recalled that there is a large open square beyond this end of the canyon, which may be influencing this aspect of the flow within the canyon.

3.1.2. U/U_{ref}

With U_{ref} being measured some distance from the canyon, we may expect the correlation between the wind speed within the canyon, U, and U_{ref} to be weakened relative to the situation had U_{ref} been truly representative of wind speed directly above the canyon. However, U was still linearly related to U_{ref} with $U \approx 0.5 U_{\mathrm{ref}}$, except in the SW perpendicular flow regime. There was a weak positive vertical gradient in U/U_{ref} (Fig. 7). A similar influence of wind direction over in-canyon wind speed was previously highlighted by Rotach (1995).

In SW perpendicular flow, during the day, the value of U/U_{ref} was much more variable, especially closer to street level, being influenced by the magnitude of reference wind speed, traffic flow rate, U_{ref} and the microscale flow pattern within the canyon. In general, sheltering by the tall SW wall made the ratio U/U_{ref} lower than in other regimes. The value of the ratio U/U_{ref} was reduced whenever and wherever there was a localised upward flow. These updraughts were often related to cross-canyon flow and flow reversal, more commonly observed in the daytime (described above).

3.1.3. *Traffic-induced flow*

When the reference wind direction was between 90° and 270°, one may expect up-canyon channelling within the canyon, with the wind opposing the direction of traffic. However, during such conditions a flow reversal was often observed with down-canyon channelling. The lower fixed anemometers on the south side of the canyon, as well as the mobile anemometer observed such reversal, most often during SW perpendicular flow. It only occurred in this regime when the traffic flow rate was above $200\,\mathrm{h}^{-1}$, and in the other flow regimes it only occurred between 11:35 and 17:55.

Thus, the increased occurrence of cross-canyon and reversed flow with increasing traffic, and the consequent breakdown of the linear relationship between U and

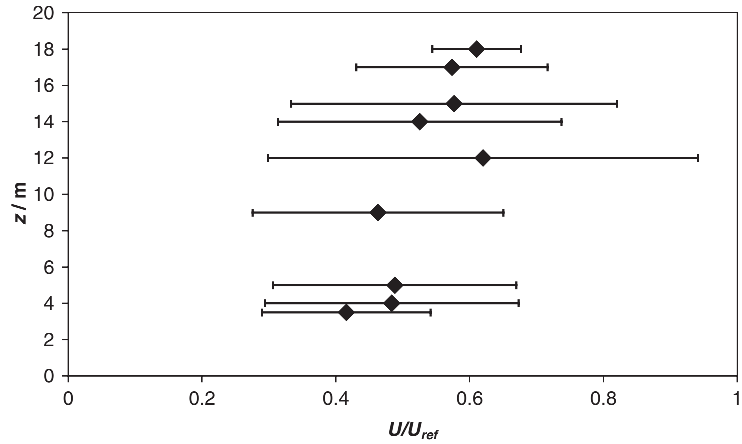

Fig. 7. Vertical profile of mean U/U_{ref} (and standard deviations) (SW perpendicular data excluded).

U_{ref}, together indicate that traffic may disrupt a simpler flow pattern. A weak wind may be directly attributable to the momentum transfer from the vehicles moving down-canyon, with the effect being stronger in SW perpendicular flow due to the greater isolation of flow from the flow above the canyon.

3.2. Turbulent intensities

3.2.1. A simple model

Within the canyon, we may expect turbulent variances to depend at least partly upon wind speed and hence studies often present variances as standard deviations normalised by a reference wind speed measured above the canyon (e.g. Nielsen, 2000). As such a reference was not available in this study the turbulent intensity, the ratio of standard deviation to the local in-canyon wind speed, U, from the same anemometer (i.e. $\sigma_{u,v,w}/U$) is discussed.

All of the turbulent intensities (longitudinal, transverse and vertical) were found to have a similar relationship with wind speed, allowing a model to be fitted to the data (e.g. Fig. 8). The general model was

$$\sigma_i^2 = \sigma^2_{\mathrm{primary},i} + \sigma^2_{\mathrm{secondary},i}\ (i = u, v, w),$$

where

$$\sigma^2_{\mathrm{primary},i} = (A_i U)^2$$

and

$$\sigma^2_{\mathrm{secondary},i} = (B_i T/3600) + C_i$$

$$(T = \text{traffic flow rate (vehicles h}^{-1})).$$

The primary term represents mechanical production of turbulence related to *local* wind speed. The coefficients A_u, A_v and A_w correspond to the near-neutral limit, i.e. the values towards which the turbulent intensities tend at high wind speeds when the primary term dominates. At lower wind speeds the turbulent

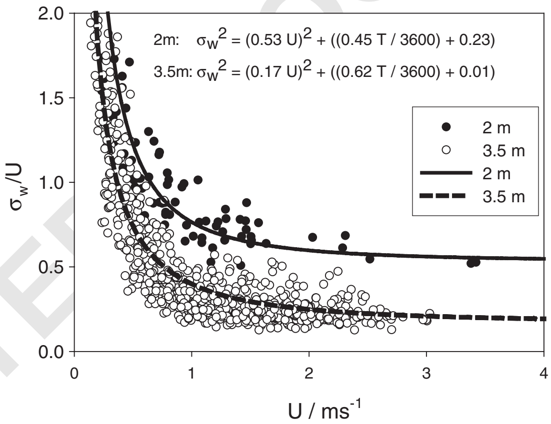

Fig. 8. Variation of σ_w/U with local wind speed, above and within traffic-layer at SCAR site showing model for typical traffic flow rate ($T = 600\,\text{vehicles}\,\text{h}^{-1}$).

intensities measured were raised above the values of A_i, indicating other sources of turbulence, represented by the secondary term. The extra sources of turbulence would include a traffic-induced mechanical turbulence. There could also be thermal turbulence, not only from canyon heating, but also from vehicle exhausts and engines. Most of these sources would be expected to vary in a diurnal cycle encompassing the cycles of solar heating, anthropogenic heating and traffic flow. Traffic flow rate, T, was used as a surrogate of these diurnal cycles. Constants were fitted to A_i, B_i and C_i. The shortcomings of the simplicity of the model, particularly in specifying the secondary terms, are exposed by the appearance of negative values for C_i, which are unlikely to be physically realistic.

3.2.2. Results

The turbulence measurements made during SCAR were measured at different heights at different times, albeit during periods of similar meteorology. Only those datasets spread over several days, with both day-time and night-time data have been used in this analysis.

There was a weak positive gradient in the turbulent intensities with height (Fig. 9). Some datasets fitted the model better than others but general patterns did emerge (Table 1). Above 3 m, the values of A_u, A_v and A_w were approximately 0.4, 0.2 and 0.2, respectively, and there was no major vertical gradient in either of these coefficients (Fig. 10). With $U/U_{\rm ref}$ of the order of 0.5 in the canyon, this corresponds to a high-wind value of $\sigma_{\rm w}/U_{\rm ref}$ of $\sim$0.1, similar to that noted in a much longer field study by Nielsen (2000). There was generally a near-zero gradient in the secondary terms above 3 m in low traffic/heating conditions and a positive gradient in high traffic/heating conditions.

In the 3–5 m layer the strongest effect of variation in T on the secondary terms, indicated by the magnitude of B_i, seemed to have been on longitudinal turbulence, σ_u (Table 1) with B_u typically double the magnitude of B_v, which was also double the magnitude of B_w. Using the model, at a typical in-canyon wind speed of $2\,{\rm m\,s^{-1}}$, a five-fold increase in traffic from 200 to $1000\,{\rm h^{-1}}$ would increase σ_u and σ_v at 3–5 m by approximately 30% and σ_w by 10–20%. At night, secondary terms dominate the turbulent intensity only when $U<1.5\,{\rm m\,s^{-1}}$, whereas during the hours of busiest traffic secondary terms dominate up to around $2.5\,{\rm m\,s^{-1}}$. A more specific parameterisation cannot be confidently presented due to the lack of reliable automated traffic counting observations and a fuller turbulence dataset with assured spatial representativeness.

3.2.3. Traffic influence on turbulence

Perhaps the most striking aspect of this analysis is the sharp inflection in the profile of parameter A_w at 2 m height (Fig. 10) leading to an approximate doubling of σ_w/U at higher wind speeds (Fig. 8). This data is from the mobile anemometer and thus relates to 18 different pavement locations on both sides of the canyon. The anemometers were typically 1–3 m from the traffic lanes, closer than in any other of the datasets. These measurements were only made during day-time and will thus be biased towards higher-turbulence conditions. The effect is mostly restricted to vertical turbulence as the primary coefficients A_u, A_v and A_w increase at 2 m, relative to 3.5 m, by 12%, −20% and 205%, respectively. At street level the wind is mostly channelled along the canyon so that the u vector is usually parallel to the traffic flow, so the simplest explanation for the enhanced turbulence would be that traffic-induced turbulence is related to wind speed, U, and is making a significant contribution to turbulence in this shallow layer below 3 m. One may expect that the speed of the wind relative to the vehicles would be the crucial parameter here. However, vehicle speed data is not available in this

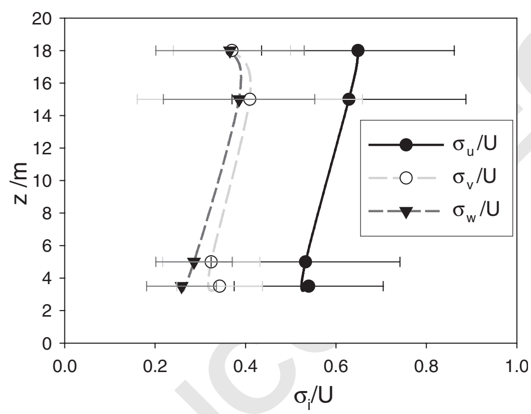

Fig. 9. Vertical profiles of means of $\sigma_{u,v,w}/U$ in SCAR-4 when $U>1\,{\rm m\,s^{-1}}$.

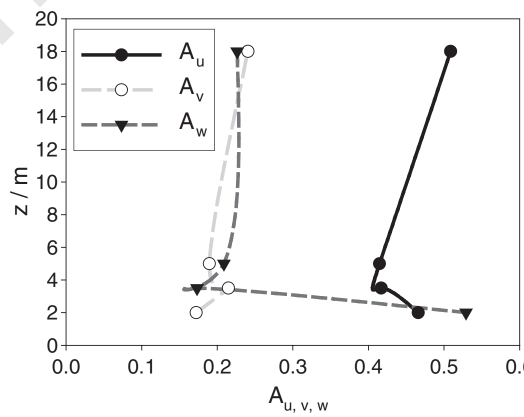

Fig. 10. Vertical profiles of model coefficient A_i applied to Manchester data.

Table 1
Parameters describing turbulent variances in SCAR, Manchester

z (m)	A_u	A_v	A_w	B_u ($m^2 s^{-1}$)	B_v ($m^2 s^{-1}$)	B_w($m^2 s^{-1}$)	C_u($m^2 s^{-2}$)	C_v($m^2 s^{-2}$)	C_w ($m^2 s^{-2}$)
18	0.51	0.24	0.23	3.6	2.1	0.85	−0.11	−0.01	0.11
5	0.41	0.19	0.21	2.4	0.71	0.36	−0.04	0.12	0.05
3.5	0.42	0.21	0.17	2.4	0.95	0.62	−0.04	0.05	0.01
2	0.47	0.17	0.53	1.2	1.9	0.45	0.37	−0.20	0.23

study, and it may be noted that casual observations suggest that there is little variation in vehicle speed averaged over 10-min period at this particular site. Increased turbulence related to the wind blowing past fixed obstacles in the canyon may also cause the enhanced turbulence at 2 m. There is also a significant increase in the secondary terms at this level. If $T = 1000$ vehicles h^{-1} then the secondary terms $((B_iT)/3600) + C$ at 2 m increase by 12% (u), 9% (v) and 97% (w) relative to 3.5 m.

This observation may be contrasted with the data from the Salfex measurements in the traffic-free canyon (Fig. 11). Broadly similar patterns in turbulent intensity were seen above the lowest level, although one difference between Manchester and Salford was the reduced σ_v/U in the asymmetrical Manchester canyon (H/W varies from ~0.6 to ~1.6) compared to the regular Salford canyon ($H/W = 0.73$). As the Salford data generally covered similar afternoon periods of a few hours within a 3-week campaign, there was little variation in thermal conditions, and in the absence of traffic, constants were fitted to the secondary term. All three of the primary parameters A_u, A_v and A_w, plus $\sigma^2_{\text{secondary},v}$ and $\sigma_{\text{secondary},w}$ peak at 6 m, but $\sigma^2_{\text{secondary},u}$ has a minimum at 6 m (Table 2). In each case the secondary term became larger than the primary when $U < 1.5-2\,\text{m s}^{-1}$.

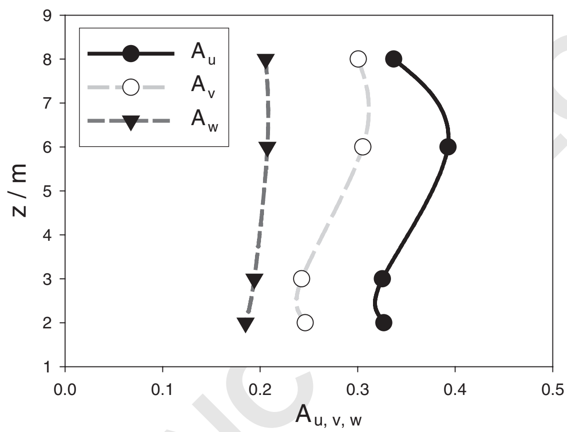

Fig. 11. Vertical profiles of model coefficient A_i applied to Salford data.

The crucial difference between the Salford data and the Manchester data is the total absence of the enhancement at the lowest level of 2 m. The sharp change in the nature of the turbulence in the trafficked canyon at 2 m is also indicated in quadrant analysis plots. The 20 Hz instantaneous raw data was rotated in two dimensions in 1-h sections and a 2-dimensional (u' and w') frequency distribution matrix of the average of all available data for the 23 October 2001 (chosen as typical as little day-to-day variation was seen) has been plotted (Fig. 12). In the Manchester canyon there is little variation in the shape of the plot at 5 m and above. However, there is a distinct difference at the 2 m level, consistent with the description of turbulent variances above. The Salford 2 m plot (Fig. 12c) is little different to those above it, but a distinctive 'C'-shaped plot is apparent at 2 m in Manchester (Fig. 12b). This plot indicates that a more organised turbulence structure existed with positive u' associated with much larger vertical gusts (w'), both positive (upwards) and negative (downwards), than was the case in Salford or at 5 m and above in Manchester. There is an increase in the time fraction of outward interactions ($+w'$, $+u'$) at the expense of sweeps ($-w'$, $+u'$), and the net momentum flux is upwards compared to downwards at 5 m and in the Salford data. As the principal difference between the Salford and Manchester canyons that would have an effect at this level only was the traffic, it is suggested that moving traffic was responsible for the occasional extra large positive and negative momentum fluxes.

4. Conclusions

This study has indicated that the simple vortex predicted by most modelling studies does not represent the complexity of flow in real canyons. In both of the canyons studied channelling along the canyon was the principal feature of the mean flow, with some evidence of a super-imposed vortex flow. The relationship between wind direction above the canyon and within the canyon was more complex than the sinusoidal relationship discussed by Johnson and Hunter (1999). Other complexities included reversal of this channelled flow and the non-penetration of the main vortex into the full canyon space. A major difference between the

Table 2
Parameters describing turbulent variances in Salfex, Salford

z (m)	A_u	A_v	A_w	$\sigma^2_{\text{secondary},u}$ ($\text{m}^2\,\text{s}^{-2}$)	$\sigma^2_{\text{secondary},v}$ ($\text{m}^2\,\text{s}^{-2}$)	$\sigma^2_{\text{secondary},w}$ ($\text{m}^2\,\text{s}^{-2}$)
8	0.34	0.30	0.21	0.39	0.15	0.04
6	0.39	0.60	0.21	0.25	0.21	0.15
3	0.33	0.24	0.19	0.35	0.11	0.11
2	0.33	0.25	0.19	0.31	0.13	0.07

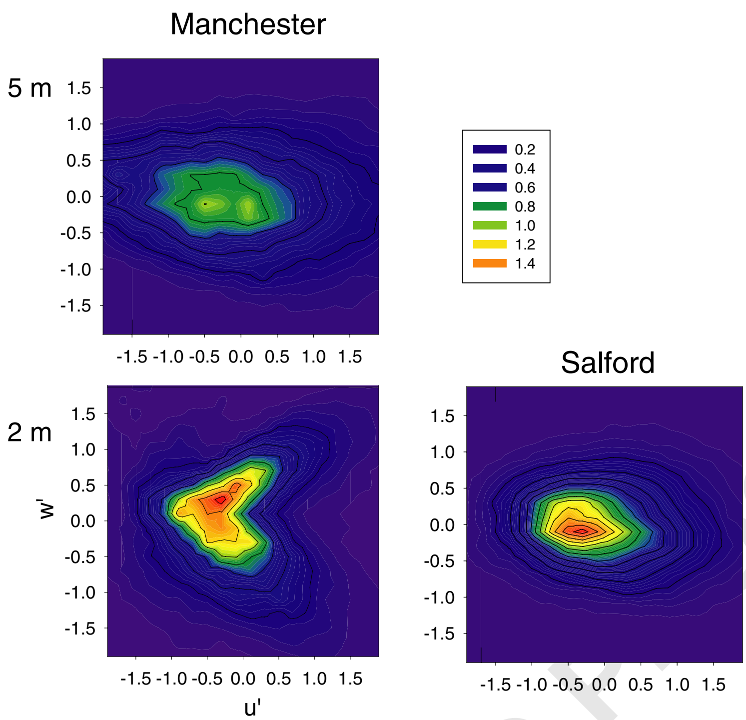

Fig. 12. Quadrant plots of w' versus u'. (a) Top left: Manchester, 5 m, (b) bottom left: Manchester, 2 m, (c) right: Salford, 2 m. Contours represent probability densities.

Manchester study and modelling studies was the variation in building geometry along the length of the canyon, plus the influence of the urban topography beyond the ends of the canyon. These differences will have made vortices in all directions very influential on the mean flow (compared to the dominance of vortices with about axes parallel to the canyon axis assumed in many street canyon vortex models) and were responsible for considerable spatial variation including localised convergence and updraughts. This could have major consequences for dispersion pathways of pollutants. A major feature of flow in this canyon was the sheltering provided by the taller canyon wall in perpendicular flow, which allowed a degree of de-coupling of the flow at street-level from that aloft.

There was limited evidence of an effect of traffic flow on advection. High traffic flow rates in the one-way Manchester canyon were associated with a higher frequency of flow reversal in which momentum transfer from vehicles appears to have reversed the direction of flow within the canyon. This effect has been predicted in both numerical and physical modelling studies. In a 3-d numerical model Jicha et al. (2000) found that one-way traffic enhanced ventilation of a canyon in perpendicular winds by enhancing the circulation in the canyon. Small but significant net longitudinal winds induced by moving vehicles were also measured in a wind tunnel simulation (Kastner-Klein et al., 2001).

A limited model was presented describing turbulent variances using in-canyon wind speed and traffic flow rate. At low wind speeds, local generation of turbulence (not related to the wind speed) dominated. The de-coupling of in-canyon flow in perpendicular winds prevented basing the model on a more readily available roof-top wind speed. Any future study of this nature would strongly benefit from a much closer reference wind speed measurement made at a point unaffected by local distortion. Nevertheless, it is felt that the model qualitatively describes real processes and relationships that should be of use to the urban meteorology community.

The effect of traffic on vertical turbulence was strikingly increased at 2 m relative to 3 m and higher. Increases in longitudinal and lateral turbulence on the leeward side of the canyon were observed in the wind tunnel by Kastner-Klein et al. (2001) in both one- and two-way traffic, but vertical turbulence was not reported. In a recent field study, Vachon et al. (2000) noted a traffic-induced turbulence in a layer up to 4 m above the road, especially at the leeward side. Turbulent kinetic energy (TKE) was associated with both the number of vehicles and vehicle velocity, albeit with reduced TKE in congested conditions. In SCAR, the relative importance of traffic-related turbulence increased in perpendicular flow because of sheltering and de-coupling of flow from aloft, and the consequent fall in in-canyon wind speed.

This short study has indicated that although making observations in real street canyons may be logistically complicated and less controllable than a model, a genuine qualitative insight may be gained into how flow, turbulence and dispersion in the real world agrees or deviates from the predictions of a model. Longer studies are required covering a wider range of meteorological conditions. Previous studies have shown a strong influence of stability on flow in the roughness sublayer and street canyons (Rotach, 1995; Uehara et al., 2000). The effect of atmospheric stability was not considered in this work due to insufficient variation. Further studies covering other locations, can only help to improve this description and, in parallel with model development, aid progress towards a more quantitative description. In particular, this study has shown how traffic can be a major factor that needs to be incorporated into any street canyon model that aims to represent real-world conditions.

Acknowledgements

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