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Air pollution dispersion inside a street canyon of Göttinger Strasse (Hannover, Germany): new results of the analysis of full scale data

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Abstract: This study analyses the interactions between pollutant concentrations inside a street canyon, and wind and traffic dispersive air motions. Air pollutant concentrations, meteorological parameters and traffic flow continuously measured in Göttinger Strasse (Hannover, Germany) were used in calculations. Parameters included in the inverse proportionality between concentration and a dispersive velocity scale were evaluated using statistical methods, for windward and leeward conditions. For leeward conditions, a 'critical wind speed' is defined as the roof-level wind speed at which traffic and wind induced turbulences inside the street canyon are equal. It varies with traffic density between 2 m s^{-1} and 4.5 m s^{-1}.

Keywords: urban air pollution; street canyon; traffic pollution; local pollution; TPT; traffic-produced turbulence.

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1 Introduction

The concentration of air pollutants in urban areas due to motor vehicles has become of increasing concern. Much work and monitoring have been focused on the background level of substances. However, arguably it is at kerbside locations where the public suffers common exposure to the highest concentrations of pollutants. This is particularly true in a street canyon, a relatively narrow street with buildings lined up continuously along both sides (Nicholson, 1975). The combined of large vehicle emissions and reduced dispersion in these circumstances can lead to high level of pollution.

Wind flow at roof-level (or ambient wind) is disturbed by buildings with different shapes and sizes, and mechanically produced turbulent eddies can stream into a street canyon. Depending on ambient wind speed, three main dispersion conditions can be identified:

- low wind conditions (ambient wind speed lower than 1.5 m s^{-1})
- perpendicular or near perpendicular flow for ambient wind speed over 1.5 m s^{-1} blowing at an angle of more than 30° to the canyon axis
- parallel or near-parallel flow for winds over 1.5 m s^{-1} blowing from all other directions.

When the roof-level wind is perpendicular to the canyon and the wind speed is greater than 1.5–2.0 m s^{-1}, internal flow within the street canyon may be described in terms of three regimes, depending on the dimensions of the street (Oke, 1988). The geometry of a street canyon is usually expressed by its aspect ratio (H/W), where H is the average building height and W is the canyon width. For widely spaced buildings ($H/W < 0.3$), the flow fields associated with buildings do not interact, which results in the 'isolated roughness' flow regime. At closer spacing ($0.3 < H/W < 0.7$) the wake created by the upwind building is disturbed by the downwind building, originating a downward flow along the windward face of the latter. This is the 'wake interference' flow regime. Even closer spacing ($H/W > 0.7$) results in the 'skimming' flow regime. This regime results in a stable circulatory vortex in the canyon and the flow above roof level is decoupled from the street flow (Hunter et al., 1992).

From a three-dimensional point of view, a reflection of the wind off the windward wall of the canyon should be ideally observed in the case of skimming flow (Nakamura and Oke, 1988). For oblique ambient wind, this reflection may induce a spiral wind flow through the canyon. Other complex channelling effects might be produced for winds parallel to the street axis. The strength of the wind vortices inside the canyon mainly depends on roof-level wind speed. Furthermore, the shape and strength of the wind vortices might also be affected by atmospheric stability and other thermal effects induced by differential heating of the wall and/or the bottom of the canyon (Louka et al., 2002).

In addition, Traffic-Produced Turbulence (TPT) can be expected to play a very important role in the air turbulence inside the urban canyons (Vachon et al., 2002; Kastner-Klein et al., 2000, 2003).

The most extensive investigations of flow and dispersion regimes in street canyons have been performed in wind tunnels (Pavageau and Shatzmann, 1999; Kastner-Klein and Plate, 1999; Kovar-Panskus et al., 2002). Also, several studies have been done using full-scale data (Louka et al., 2000; Vachon et al., 2002; Ketzel et al., 2002a; Kastner-Klein et al., 2003; Vardoulakis et al., 2002, 2005).

There are several dispersion models specially developed for simple use in street canyon applications (Johnson et al., 1973; Benson, 1984; Yamartino and Wiegand, 1986; Berkowicz et al., 1997; Buckland, 1998; Mensink et al., 2002; Sahm et al., 2002; Ketzel et al., 2002a, 2002b). They can be useful in air quality and traffic management, urban planning, interpretation of monitoring data, pollution forecasting, population exposures studies, etc. According to their level of complexity, these models might be classified into parametric (operational) models and numerical models.

The present study focuses on the interactions between pollutant concentrations inside a street canyon and wind and traffic dispersive air motions, for all roof-level wind directions. For windward conditions, we obtain the values of parameters involved in two different forms of the inverse proportionality between concentration and roof-level wind speed. For leeward and parallel cases, we evaluate parameters included in the inverse proportionality between concentration and the dispersive velocity scale proposed by Kastner-Klein et al. (2003). We apply statistical methods to CO and NO_x concentrations, meteorological parameters and traffic flow data measured continuously during 1994 in a street canyon of Göttinger Strasse (Hannover, Germany) to obtain the values of parameters of concern.

2 Brief description of the parameterisation of the interaction between air pollutant concentration inside a street canyon, wind and traffic produced turbulence

In numerical modelling of street canyon pollution, an inverse proportionality between street level concentration and wind speed (U) measured above roof-level is commonly assumed. It is argued that in many instances (particularly when U is greater than 2–3 m s^{-1}) street ventilation is controlled by the interaction between the micro-scale flow structures and the urban boundary layer flow above roof-level. In these situations, both buoyancy-related and TPT are considered secondary street-ventilation mechanisms compared to the main wind-induced mechanism. In this way, considering the specific emission per length (E) and the width (W) of the canyon, the normalised concentration (C^*) (the background concentration, C_b, has been subtracted from the values of pollutant concentrations measured inside the street, C_i) would be (Kastner-Klein et al., 2003):

$$C^* = (C_i - C_b)\, W / E \propto U^{-1}. \tag{1}$$

Considering E expressed in (mg m^{-1} s^{-1}), W in (m), C_b in (mg m^{-3}) and C_i in (mg m^{-3}), the normalised concentration, C^*, is in (s m^{-1}) units. This scaling concept produces significant reduction in modelling efforts in operational air quality studies. However, field data analyses have often demonstrated that the above scaling has certain deficiencies

(Ketzel et al., 2002a; Kastner-Klein et al., 2003), since particularly with lower wind speeds TPT effects start to play an important role. For regulatory purposes, an empirical method (VDI, 1998) has been proposed to account for TPT effect, recommending to use $U^{-0.35}$ as velocity scale in equation (1) for situations with wind speed smaller than 3.0 m s^{-1}. Ketzel et al. (2002a) analyse the application of a modified form of equation (1) given by: $C^* \propto U^{-r}$ (in this case, the units of the proportionality coefficient should be $(\mathrm{m\ s^{-1}})^{(r-1)}$). For the windward situation they find that r seems to be even higher than one.

Different authors (Kastner-Klein et al., 2000, 2001, 2003; Berkowicz et al., 2002; Di Sabatino et al., 2003) studied the influence of turbulence created by traffic flow in the street, on air pollutant dispersion inside street canyons. Kastner-Klein et al. (2000, 2003) propose that the turbulent motions related to wind and traffic are mixed inside the canyon so that the effective velocity variance can be taken proportional to a linear combination of the squares of roof-level wind speed (U) (m s^{-1}) and traffic velocity (V) (km h^{-1}). These authors introduce the following expression for the dispersive velocity scale (u_s) (m s^{-1}) (Kastner-Klein et al., 2000):

$$u_s = (\sigma_u^2 + \sigma_v^2)^{1/2} = (aU^2 + bV^2)^{1/2} \tag{2}$$

where σ_u^2 ($\mathrm{m^2\ s^{-2}}$) is the wind speed variance, σ_v^2 ($\mathrm{m^2\ s^{-2}}$) is the traffic-induced velocity variance, a and b are dimensionless empirical parameters. Parameter a is the proportionality coefficient between the wind-induced turbulence and the square of roof-level wind speed. It depends, among other factors, on street geometry, wind direction and sampling position. Parameter b is the proportionality coefficient between the traffic induced velocity fluctuations and the square of traffic velocity (values of b includes the conversion factors from (km h^{-1}) to (m s^{-1})). Parameter b is function of Wind Direction (WD), vehicles characteristics, their average drag coefficient and traffic density. For congested traffic, b does not depend on traffic density (Di Sabatino et al., 2003). For leeward conditions, the normalised concentrations verifies the relationship $C^* \propto (u_s)^{-1}$.

In a previous paper (Mazzeo and Venegas, 2005) we studied the variation of a and b with WD and traffic density for situations close to leeward conditions. The objective of the present work is to study the variation of the parameters included in the mentioned parameterisations of C^*, with all WDs using full-scale experimental data. For this purpose, data are grouped into 'windward' or 'leeward' conditions, according to roof-level wind direction. Cases with ambient wind parallel to street axis have been included in the 'leeward' group. For 'windward' conditions, we propose the following two different parameterisations: $C^* = (a^{1/2}\,U)^{-1}$ and $C^* = (A^{1/2}\,U^r)^{-1}$. It has been considered than TPT plays less important role than wind speed in determination of concentration levels at a receptor located on the 'windward' side. In this way, both proposed parameterisations assume that dispersive velocity scale is mainly given by wind speed variance ($u_s = \sigma_u$). In the first parameterisation, wind induced turbulence is assumed proportional to wind speed ($u_s = \sigma_u = a^{1/2}\,U$). In the second one, a more general form ($u_s = \sigma_u = A^{1/2}\,U^r$) is tested (coefficient A is in $(\mathrm{m\ s^{-1}})^{2(1-r)}$ units and it is an empirical parameter which has a similar meaning as a). For 'leeward' conditions, we consider that $C^* = (aU^2 + bV^2)^{-1/2}$. We evaluate parameters a, b, A and r included in the previous relationships, considering all WDs and using CO and NO_x concentrations, meteorological parameters and traffic flow measured continuously during 1994 in a street canyon of Göttinger Strasse (Hannover, Germany). In addition, we study the variation of the critical wind speed (U_c) (m s^{-1}) (that verifies $aU_c^2 = bV^2$) with traffic density and WD.

3 Data

Traffic pollution measurements in Göttinger Strasse (Hannover, Germany) have provided one of the most comprehensive datasets of airflow and pollution parameters in a typical urban street canyon. Hourly air quality measurements for CO and NO_x have been obtained by a monitoring station located in this street canyon with a traffic volume of approximately 30,000 vehicles per day (NLÖ, 2000). Automatic traffic counts provide hourly vehicle flow in the street. Ambient wind direction and speed data are taken at a 10 m mast on top of a nearby building. The background concentration samplers are also located on the roof of this building. The aspect ratio (H/W) of this canyon is 0.8. Street orientation is 163° with respect to North.

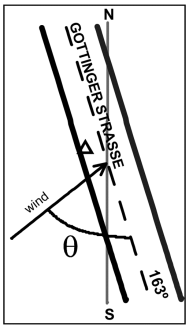
4 Results and discussions

Normalised concentrations, C^*, have been obtained considering emissions (E) calculated based on the number of vehicles (N_i) per hour in a class i (e.g., short, long) and emission factor (e_i) for vehicles in class i (EMEP/CORINAIR, 2004) as

$$E(\text{mg s}^{-1}\ \text{m}^{-1}) = \sum_i N_i e_i .$$

We define θ (expressed in degree) as roof-level Wind Direction referred to the street canyon orientation (see Figure 1). In this way, for $WD \geq 163^{\circ}$, the value of θ is calculated as $[\theta = WD - 163^{\circ}]$ and for $WD < 163^{\circ}$, $[\theta = WD + (360^{\circ} - 163^{\circ})]$. Data of a specific case are treated as 'leeward' if $0 \leq \theta \leq 180^{\circ}$ (including roof-level wind directions parallel to the street axis) or 'windward' if $180^{\circ} < \theta < 360^{\circ}$. Furthermore, 'leeward cases' are classified according to $\theta = 0^{\circ}$, 22.5°, 45.0°, 67.5°, 90.0°, 112.5°, 135.0°, 157.5° and 180° (e.g., $\theta = 45.0^{\circ}$ if WD is $(208^{\circ} \pm 11.25^{\circ})$ and $\theta = 90^{\circ}$ if WD is $(253^{\circ} \pm 11.25^{\circ})$, perpendicular to the street axis). 'Windward cases' comprise $\theta = 202.5^{\circ}$, 225.0°, 247.5°, 270.0°, 292.5°, 315.0° and 337.5° (e.g., $\theta = 270.0^{\circ}$ if WD is $(73^{\circ} \pm 11.25^{\circ})$, perpendicular to the street axis). Values of θ are expressed in degree.

Figure 1 Definition of θ



Normalised concentrations of both air pollutants, CO and NO_x, have been considered together in calculations. The analysis has been done using statistical methods to obtain the best fits to data.

4.1 *Analysis of 'windward cases' data* ($180° < \theta < 360°$)

Figure 2 shows the variation of C^* vs. U, including CO and NO_x data, for different θ in which 'windward cases' have been grouped. Plotting the variation of C^* with roof-level wind speed (U) we obtain the best fitting curves to the expressions (included in Figure 2):

$$C^* = (a^{1/2}\,U)^{-1} \tag{3}$$

and

$$C^* = (A^{1/2}\,U^{\alpha})^{-1}. \tag{4}$$

For each θ, we obtain the value of a fitting data to equation (3) (dash line in Figure 2) and the values of A and α from the best fit to equation (4) (solid line in Figure 2). Figure 3 shows the variation of the values of a with θ. The parameter a varies from 0.009 ($\theta = 337.5°$) to 0.018 ($\theta = 247.5°$, $\theta = 270°$). Figure 4 presents the variation of parameters $A(\mathrm{m\,s^{-1}})^{2(1-r)}$ and r with $\theta(°)$. The lowest value of $A \approx 0.009\ (\mathrm{m\,s^{-1}})^{2(1-r)}$ has been obtained with $r \approx 0.61$ ($\theta = 202.5°$) and the highest $A \approx 0.019\ (\mathrm{m\,s^{-1}})^{2(1-r)}$ is associated to $r \approx 0.98$ ($\theta = 247.5°$). Values of r range between 0.61 ($\theta = 315°$ and 337.5°) and 1.1 ($\theta = 270°$). Results show that regression coefficients are slightly greater if $C^* = (A^{1/2}\,U^r)^{-1}$ is considered.

Figure 2 Variation of normalised concentrations, $C^* = (C_i - C_b)W/E$ with ambient wind speed (U) for different θ ('windward cases'). ◊CO, ▲NO_x. Fitting curves to equation (3) (dash line) and equation (4) (solid line) are included

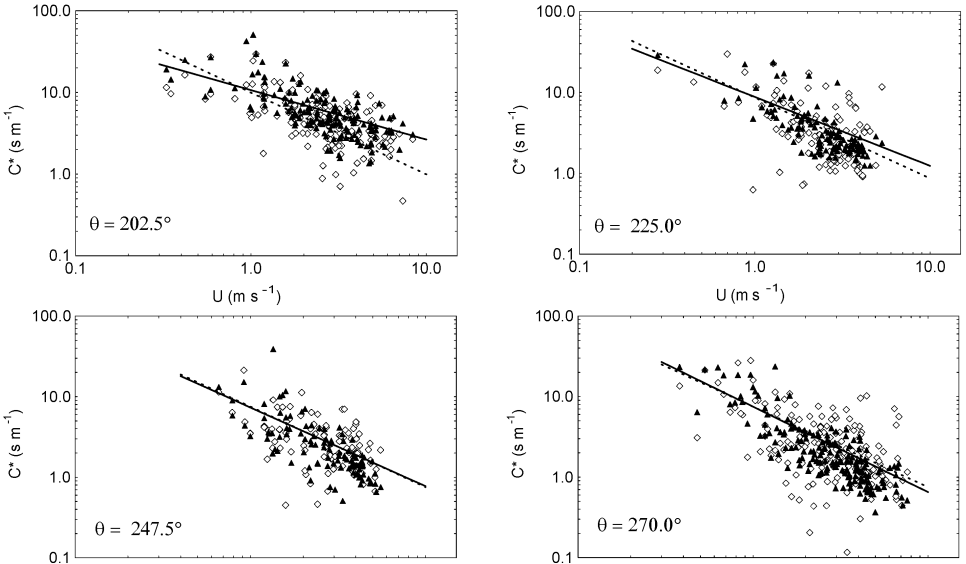
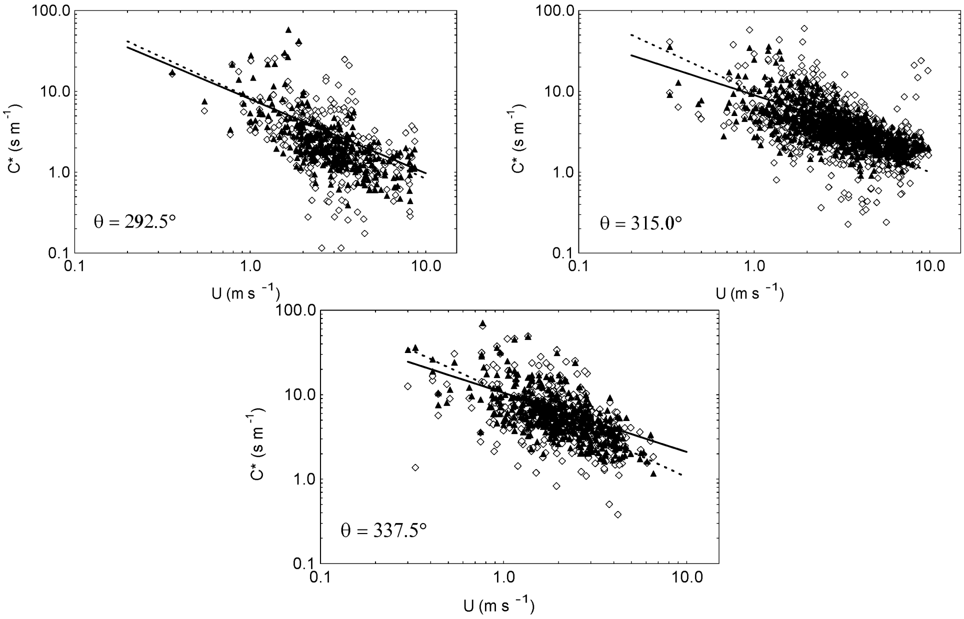


Figure 2 Variation of normalised concentrations, $C^* = (C_i - C_b)W/E$ with ambient wind speed (U) for different θ ('windward cases'). ◊CO, ▲NO$_x$. Fitting curves to equation (3) (dash line) and equation (4) (solid line) are included (continued)



It can be seen a slight asymmetry in the variation of parameters included in Figures 3 and 4 with wind direction, at both sides of the direction perpendicular to the street axis ($\theta = 270°$). A symmetric configuration would be expected in an ideal street canyon structure. The difference between building height at both sides of the street canyon, the existence of street intersections and irregular building structures near the monitoring station could be responsible for the asymmetries mentioned above.

Figure 3 Variation of a with θ ('windward cases')

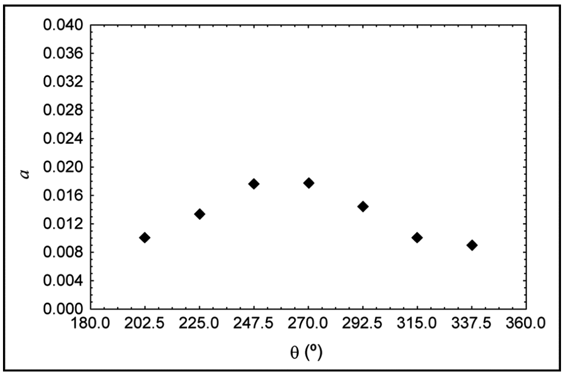
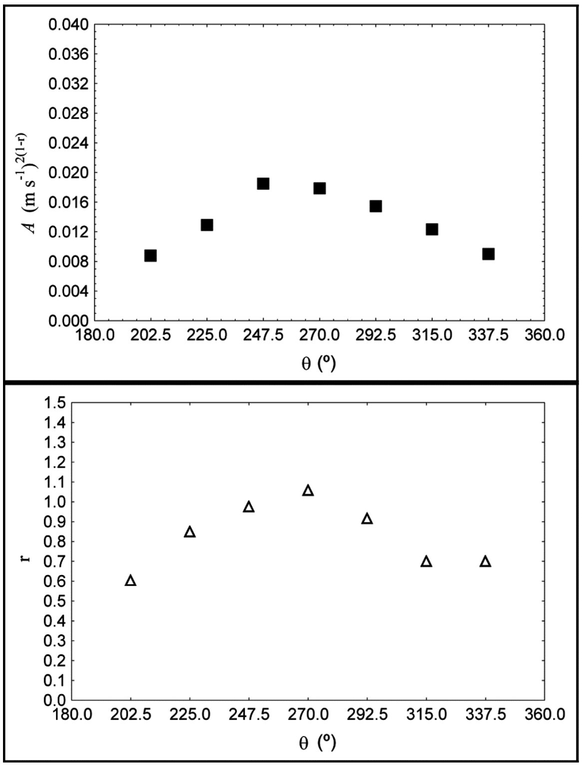


Figure 4 Variation of parameters A and r included in equation (4) with θ



4.2 *Analysis of 'leeward cases' data (0°≤ θ ≤ 180°)*

As already mentioned, for 'leeward cases' it can be assumed that normalised concentrations verifies the relationship $C^* = (u_s)^{-1}$. Several authors (Ketzel et al., 2002a; Kastner-Klein et al., 2001, 2003; Mazzeo and Venegas, 2005) have studied the variation of street level concentration with U for wind directions close to leeward condition (in this study, $\theta = 90°$) and they have found that for wind speeds greater than 5 m s^{-1}, it can be considered that $C^* \propto U^{-1}$ and for lower wind speeds the fitting curve considerable deviates from $C^* \propto U^{-1}$ (representative of the 'without traffic turbulence' condition). The wind speed for the transition between 'with' and 'without' traffic turbulence regimes depends on traffic conditions. Considering the 'leeward cases' ($0° \leq \theta \leq 180°$) with $U > 5$ m s^{-1}, and assuming $C^* = (a^{1/2}\,U)^{-1}$, we obtain the values of a for different θ from the best fitted curves considering CO and NO$_x$ normalised concentrations plotted in Figure 5. Figure 6 shows the variation of the obtained a with θ. Values of a varies from 0.000345 ($\theta = 90°$) to 0.0021 ($\theta = 0°$). The value of a obtained for wind direction perpendicular to the street axis ($\theta = 90°$) is in agreement with $a = 0.00035$ reported by Kastner-Klein et al. (2003). The asymmetric variation of a with wind direction, at both sides of the direction perpendicular to the street axis ($\theta = 90°$) may be because this is not an ideal street canyon. In an ideal street canyon configuration a more symmetric variation of a with θ can be expected.

Figure 5 Variation of normalised concentrations, $C^* = (C_i - C_b)W/E$, with ambient wind speed (U) for different θ ('leeward cases'). ◊CO, ▲NO_x. Solid line is the fitting curve to $C^* = (a^{1/2}\,U)^{-1}$ for $U > 5$ m s^{-1}. Dash line is the extension of solid line for $U \le 5$ m s^{-1}

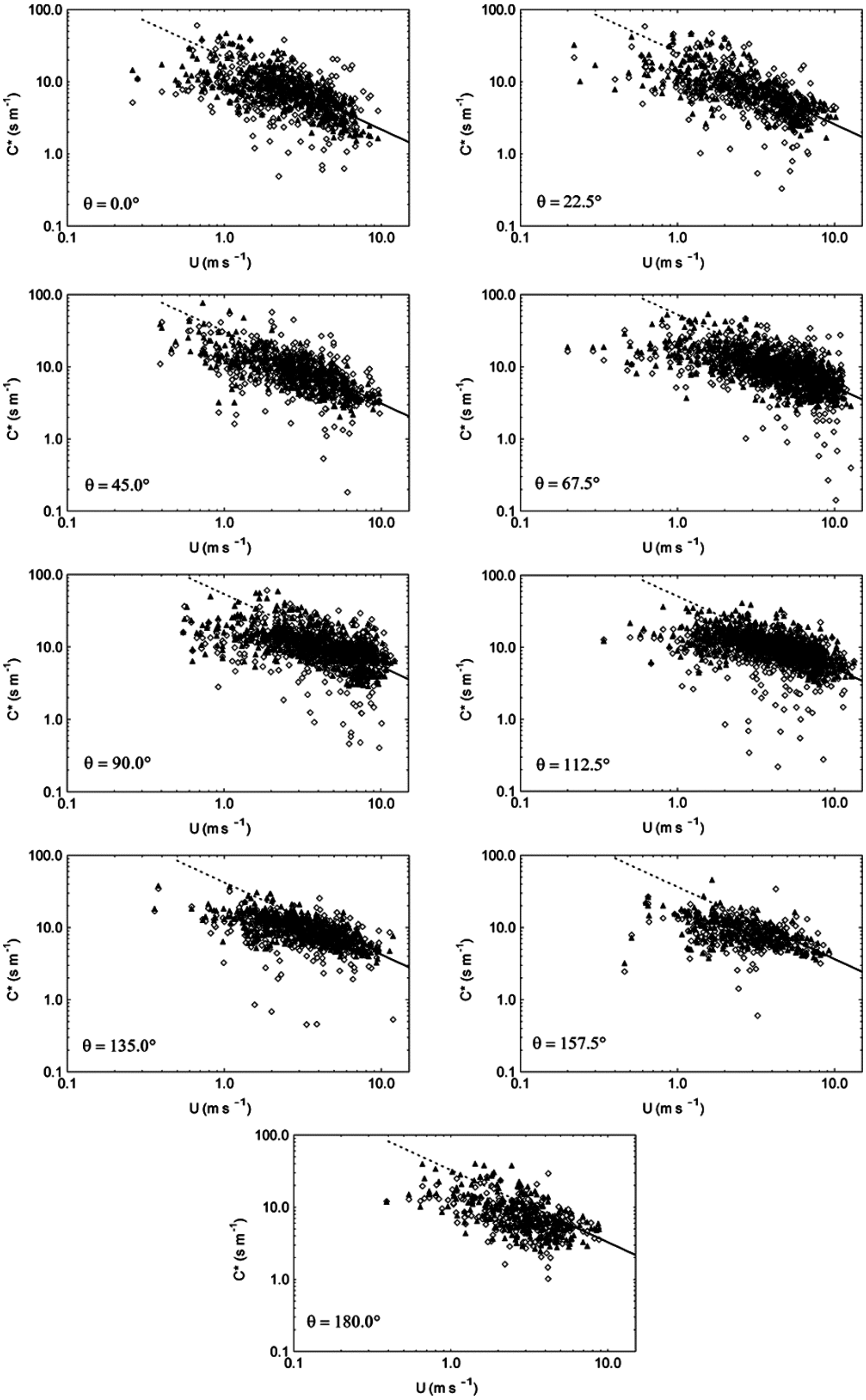
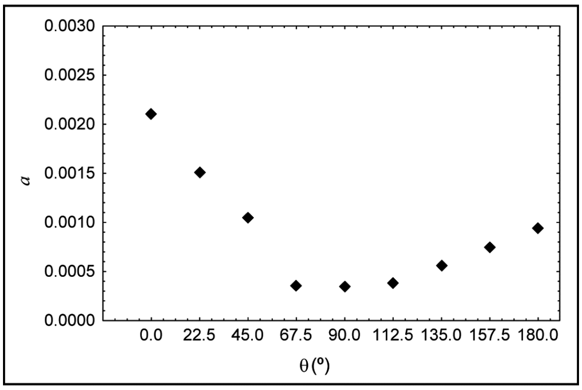


Figure 6 Variation of a with θ (‘leeward cases’)



Knowing the value of a, parameter b can be obtained by means of a regression analysis applied to equation (2). Parameter b is directly related to TPT, therefore for a given θ, it varies with traffic volume. We consider the following traffic volumes (N): (0–600) veh h^{-1}, (600–900) veh h^{-1}, (900–1200) veh h^{-1}, (1200–1500) veh h^{-1}, (1500–1800) veh h^{-1} and >1800 veh h^{-1} and we assume traffic velocity (V) equal to 50 km h^{-1} for $N < 900$ veh h^{-1} and 40 km h^{-1} for $N \geq 900$ veh h^{-1} (Kastner-Klein et al., 2003). In this way, considering normalised concentrations of both pollutants for a given θ, the value of b for each traffic volume class, is estimated from the best fitted function $C^* = (u_s)^{-1}$, knowing the value of a for that θ. The variation of dimensionless parameter $b(N/V;\ \theta)$ with traffic density (N/V) (N is traffic volume, veh h^{-1}, V is traffic velocity, km h^{-1}, N/V is expressed in veh km^{-1}) for different θ (°) (expressed in degree) is shown in Figure 7. The curves included in Figure 7 are the best fitted functions of the form:

$$b(N/V;\theta) = m(N/V)n. \tag{5}$$

The values of m and n in equation (5) obtained from each regression curve, are shown in Figure 8. Being b a dimensionless parameter, units of m are (veh^{-n} km^{n}) and n is dimensionless. Fitting curves in Figure 8 suggest the following forms:

$$m = 9.861E-07 + 2.989E-08\,\theta + 3.493E-10\,\theta^2 - 2.311E-12\,\theta^3 \tag{6}$$

where units of the each numerical coefficient are such that, expressing θ in degree (°), m is obtained in (veh^{-n} km^{n}), and

$$n = 2.7542\,(\theta + 14.1)^{-0.3098} \tag{7}$$

where units of numerical coefficients correspond to θ expressed in degree (°). These expressions are valid for 5 veh $km^{-1} \leq (N/V) \leq 50$ veh km^{-1}.

Finally, we study the variation of the critical wind speed (U_c) (that verifies $aU_c^2 = bV^2$) with traffic density and wind direction. It should be noticed that, as the values of b include the necessary factors to convert (km h^{-1}) to (m s^{-1}), the product bV^2 is in $(m\ s^{-1})^2$ units the same as aU_c^2. Results of U_c are included in Figure 9, along with the curves obtained fitting to

$$U_c(N/V;\theta) = p\exp[q(N/V)]. \tag{8}$$

Figure 7 Variation of *b* with traffic density (*N*/*V*) for different *θ*. The curves are obtained fitting equation (5) to data

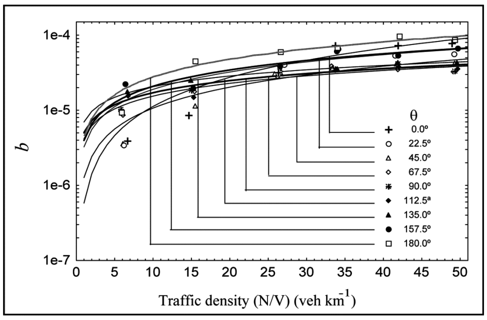
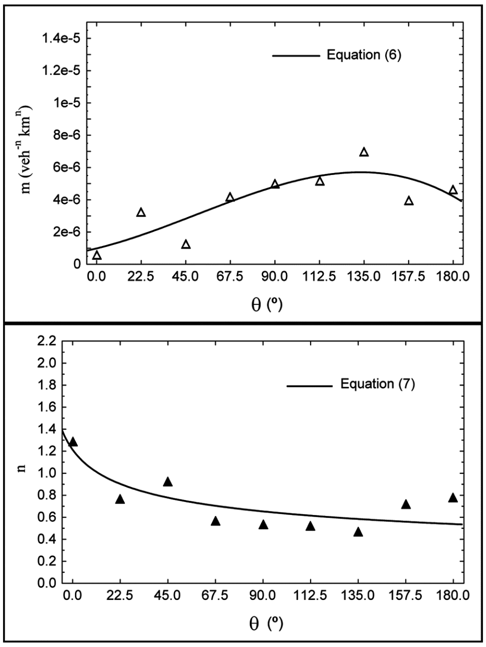


Figure 8 Variation of parameters *m* and *n* included in equation (5) with *θ*. Fitting curves given by equations (6) and (7) are shown



The values of $p(\mathrm{m\,s^{-1}})$ and q $(\mathrm{veh^{-1}\,km})$ in equation (8) are plotted against θ (°) (Figure 10) and the following expressions have been obtained:

$$p = (1.73484 + 3.3811E - 03\,\theta + 1.1765E - 04\,\theta^2 - 5.2263E - 07\,\theta^3) \tag{9}$$

$$q = (0.02604 - 3.5276E - 04\,\theta + 1.5321E - 06\,\theta^2). \tag{10}$$

According to fitting curves, coefficients in equations (9) and (10), are valid only if θ (°) is expressed in degree. Critical wind speed U_c is given in $(\mathrm{m\,s^{-1}})$, N in $(\mathrm{veh\,h^{-1}})$, V in $(\mathrm{km\,h^{-1}})$ and θ (°) in degree. Values of U_c are within $2.0\ \mathrm{m\,s^{-1}}$ ($N/V = 5\ \mathrm{veh\,km^{-1}}$) and $4.5\ \mathrm{m\,s^{-1}}$ ($N/V = 50\ \mathrm{veh\,km^{-1}}$).

Figure 9 Variation of U_c with traffic density (*N*/*V*) for different *θ*. The curves are obtained fitting equation (8) to data

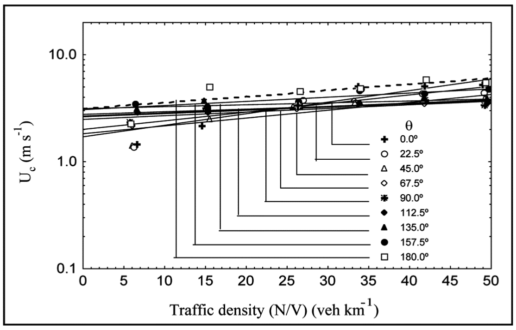
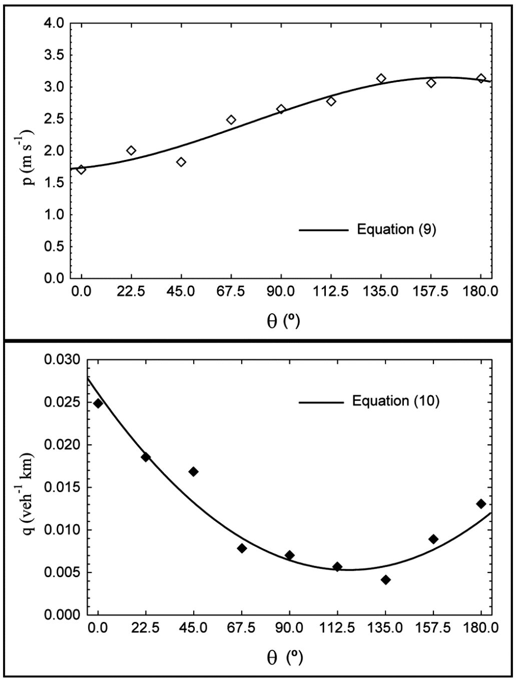


Figure 10 Variation of parameters *p* and *q* included in equation (8) with *θ*. Fitting curves given by equations (9) and (10) are shown.



Fitting curves to data on Figures 7 and 8, showing the variation of *b* and U_c with traffic density for different *θ*, cross each other. This behaviour may be consequence of several factors including scatter in experimental data and the fact that this is not an ideal canyon.

5 Conclusions

We study parameterisations of normalised concentration [$C^* = (C_i - C_b)W/E$] (C_i is the concentration inside the street, C_b is the background concentration, W is the street canyon width, E is the emission per length) combining traffic and wind induced dispersive motions, considering all roof-level wind directions. We use hourly traffic pollution data (CO and NO_x concentrations, wind data and traffic flow) registered in a street canyon of Göttinger Strasse (Hannover, Germany).

For 'windward cases', we consider the expressions: $C^* = (a^{1/2}\,U)^{-1}$ and $C^* = (A^{1/2}\,U)^{-r}$. The variation of parameters a, A and r with wind direction is obtained. Results show that: $0.009 \le a \le 0.018$, $0.009\ (\mathrm{m\,s^{-1}})^{2(1-r)} \le A \le 0.019\ (\mathrm{m\,s^{-1}})^{2(1-r)}$ and $0.61 \le r \le 1.1$.

For 'leeward cases' (including wind directions parallel to the street), we consider the expression $C^* = (aU^2 + bV^2)^{-1/2}$. Considering the approach that when $U > 5\ \mathrm{m\,s^{-1}}$ the influence of traffic produced turbulence in the dispersion of street-canyon pollutants is smaller that wind turbulence, previous expression becomes $C^* = (a^{1/2}\,U)^{-1}$. For these cases we obtain the values of a varying with roof-level wind direction. Values of a vary from 0.000345 ($\theta = 90°$, wind perpendicular to the street axis) to 0.0021 ($\theta = 0°$, wind parallel to the street axis). Knowing a, and considering all 'leeward cases' data, we estimate b, for different traffic density (N/V) and WD (θ). Parameter b varies between ~3.0E–06 and ~1.0E–04. We obtain an empirical expression for b as a function of θ and (N/V). In addition, we estimate the values of the critical wind speed (U_c) (that verifies $aU_c^2 = bV2$) for all 'leeward' cases (including wind parallel to the street). Values of critical wind speed mainly vary with traffic density (N/V) and show less variation with roof level wind direction. U_c varies from $2.0\ \mathrm{m\,s^{-1}}$ ($N/V = 5$ veh km^{-1}) to $4.5\ \mathrm{m\,s^{-1}}$ ($N/V = 50$ veh km^{-1}). We obtain an empirical form of $U_c = f(N/V; \theta)$ that estimates the value of wind speed at which traffic induced turbulence and wind induced turbulence inside the street canyon are equal.

Further evaluation of all these parameters and their variation with wind direction using other field data sets is necessary. These data sets should include measurements from several street canyons with different street geometry, traffic densities, roof-level wind speed ranges and other pollutants.

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