EVALUATION OF NATURAL AND TRAFFIC-PRODUCING TURBULENCES USING FULL SCALE DATA FROM FOUR STREET CANYONS

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Abstract: In urban areas, high air pollutant concentrations may be observed, mostly within street canyons, where buildings and other obstacles disturb the airflow and turbulence. Air motions inside the street canyons are influenced by aerodynamic and thermal effects and by the movements of the vehicles. Parameters related with natural and traffic produced turbulences are estimated for four street canyons considering all wind directions. Available data used include air pollution concentrations measured in Göttinger Strasse (Hannover, Germany), Schildhornstrasse (Berlin, Germany), Jagtvej (Copenhagen, Denmark) and Hornsgatan (Stockholm, Sweden), and background pollution, wind speed and direction measured on the roof of a nearby building and information of traffic flow. For each street canyon, the variation with traffic density of critical wind speed (that equals the contributions of turbulent motions related to wind and traffic to the effective velocity variance inside the street canyon) is also studied.

Key words: *Urban air pollution, urban canyons, traffic pollution, natural and traffic-produced turbulences.*

1. INTRODUCTION

Vehicular emission is one of the major sources of anthropogenic pollutants in urbanized cities. Because of surrounding high-rise buildings and narrow streets, building geometry complicates wind flow and pollutant transport in street canyons, unlike the free stream over the buildings. A vortex-like circulation is a typical feature of the flow pattern in narrow long street canyons for wind directions perpendicular to the street (Oke, 1988). Under such conditions, the street ventilation is primarily controlled by the interaction between the in-canyon vortex and the boundary-layer flow above the urban canopy. Vortex-like flow patterns are typically observed for roof level wind speed larger than 1.5 to 2 ms^{-1} (Oke, 1988). Under low wind speed conditions turbulent motions mechanically generated by traffic become an important factor for dilution of pollutants in streets. Thus, accounting for Traffic-Produced Turbulence (TPT) in applied atmospheric dispersion models will lead to a significant improvement in concentration predictions at street level. Theoretical, wind tunnel and full-scale experimental studies have investigated the influence of the vehicles motion on the airflow and dispersion conditions inside street canyons (Berkowicz et al., 2002, 2006; Mensink et al., 2002; Kastner-Klein et al., 2000; 2003; 2004; Hirtl et al., 2007; Solazzo et al., 2007; Vardoulakis et al., 2007; Mensink and Cosemans, 2008).

The objective of this paper is to evaluate the parameters related to natural- and traffic- produced turbulence at four different street canyons. Available air pollutant concentrations and traffic flow from full-scale data registered at: Göttinger Strasse (Hannover, Germany), Schildhornstrasse (Berlin, Germany), Jagtvej (Copenhagen, Denmark) and Hornsgatan (Stockholm, Sweden) are used along with wind speed and direction data registered nearby. Results are analysed considering all wind directions, for leeward and windward situations. Critical wind speed (defined as the wind speed that equals the contributions of turbulent motions related to wind and traffic to the effective velocity variance inside the street canyon) is evaluated for different traffic densities and wind direction at the four street canyons.

2. THE SITES AND DATA

Traffic pollution measurements in Göttinger Strasse have provided very complete datasets of airflow conditions, pollutant concentrations and traffic volume in an urban street canyon. Concentration data have been obtained by a monitoring station located in this street canyon with a traffic volume of approximately 30,000veh/day. Automatic traffic counts provide the vehicle flow in the street. Ambient wind speed and direction data are measured at a 10m mast on top of a nearby building and background concentration sampler is located on the roof of this building. The aspect ratio (H/W) of this street canyon is 0.8.

Another set of representative street canyon concentration data has been obtained by a monitoring station in Schildhornstrasse. In this case, urban background measurements are registered at a monitoring site located about 1.5km away from Schildhornstrasse. Meteorological data have been obtained 10m above the rooftop level at a nearby location. Traffic intensity is about 45,000veh/day and the aspect ratio of this street canyon is 0.93.

There is a permanent air quality monitoring station located on the easterly side of the street Jagtvej. At this site, urban background measurements are conducted on the roof of the Copenhagen University building a few hundred meters North of the street monitoring location. Meteorological data are measured from a 10m meteorological mast located on the roof of this building. Jatgvej is a busy street with about 22,000 vehicles per day and its aspect ratio is 0.72.

Available data at Hornsgatan street canyon include concentrations measured at a monitoring station located on the North-West side of the street and meteorological information registered at a 10m mast above roof level 500m from the air quality monitoring site. Urban background concentrations are available from a monitoring site located at the roof of a nearby building. In this street, traffic volume is of approximately 35,000 veh/day and its aspect ratio is 1.0.

One year of hourly information is available for each street canyon.

3. BRIEF DESCRIPTION OF THE PARAMETERISATION OF INTERACTION BETWEEN AIR POLLUTANT CONCENTRATION INSIDE 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 is commonly assumed. It is argued that in many instances (particularly when U is greater than 1.5-2 ms^{-1}) street ventilation is controlled by the interaction between the micro-scale flow structures and the urban boundary layer flow above roof level.

Ketzel et al. (1999) and Mazzeo and Venegas (2005) show that local concentration (*C*) values for Göttinger Strasse obtained during windward conditions follow a potential relation with wind speed (*U*). Concentrations observed at the windward side of the street do not show evidence of a direct influence of traffic-induced turbulence because they result from the contribution of the recirculating part of the pollutants inside the canyon.

Di Sabatino et al. (2003) have presented a theoretical framework for evaluation of the representative Traffic-Produced Turbulence (TPT) velocity scale in street canyons with different traffic volumes (*N*). Assuming that traffic-induced velocity fluctuations contribute to the dilution of street canyon pollutants in addition to wind-induced dispersive motions, the required scaling velocity must account for both dispersion mechanisms. Kastner-Klein et al. (2000) and Di Sabatino et al. (2003) proposed 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 wind speed (*U*) and traffic velocity (*V*). They defined the following expression for the dispersive velocity scale (u_s):

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

where σ_u^2 is the wind speed variance, σ_v^2 is the traffic-induced velocity variance, *a* is a dimensionless empirical parameter that depends, among other factors, on street geometry, wind direction and sampling position and *b* is a dimensionless empirical parameter that is function of wind direction, vehicles characteristics, their drag coefficient and traffic density (N/V). For congested traffic, *b* does not depend on traffic density (Di Sabatino et al, 2003).

Considering the specific emission per length (*E*) and the width (*W*) of the canyon, a normalised local concentration (C^*) (the background concentration, C_b, is subtracted from the values of pollutant concentrations measured inside the street, C_i) can be expressed as (Kastner-Klein et al., 2003):

$$C^* = (C_i - C_b)W/E \propto U^{-1} \quad (2)$$

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., 2002, Kastner-Klein et al., 2003), since particularly with lower wind velocities TPT effects start to play an important role.

For leeward conditions, the normalised concentrations verifies the relationship $C^* \propto (u_s)^{-1}$. Empirical expressions of the variation of *a* and *b* with wind direction and traffic density (N/V) for situations close to leeward conditions at Göttinger Strasse have been developed in a previous study (Mazzeo and Venegas, 2005).
In this study the following expressions are considered
- for windward conditions, $C^*=(a^{1/2} U)^{-1}$,
- for leeward conditions, $C^*=(aU^2 + bV^2)^{-1/2}$

4. RESULTS AND DISCUSSION

The behaviour of parameters *a* and *b* included in the previous relationships, is studied considering all wind directions and using air pollutant concentrations, meteorological parameters and traffic flow measured in four street canyons: Göttinger Strasse (Hannover, Germany), Schildhornstrasse (Berlin, Germany), Jagtvej (Copenhagen, Denmark) and Hornsgatan (Stockholm, Sweden). Values of the critical wind speed (U_c) (that verifies $aU_c^2=bV^2$) have been estimated for different traffic density and wind direction.

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

$$E(\mathrm{mg\,s^{-1}\,m^{-1}}) = \sum_i N_i e_i \quad (3)$$

and emission information reported in Berkowicz et al. (2006).

In order to refer roof level wind direction (WD) at all street canyons to a common value relative to the orientation of the street canyon, parameter θ is defined as (θ =WD–ST) if WD≥ST and (θ =WD+360º-ST) if WD<ST. ST is the angle between the street axis towards the right side of the monitoring location (facing the street) and the North. The value of θ is expressed in degrees. Data have been grouped into "leeward cases" (0º≤ θ ≤180º) and "windward cases" (180º<θ<360º). Statistical methods to obtain the best fits to measurements have been applied to data grouped into 16 wind sectors of 22.5º centred in θ=0º, 22.5º, 45.0º, 67.5º, 90º, 112.5º, 135.0º, 157.5º, 180.0º, 202.5º, 225.0º, 247.5º, 270.0º, 292.5º, 315.0º and 337.5º.

Windward conditions

Plotting the variation of *C** with ambient wind speed (*U*), for each direction in each urban canyon, we obtain the best fitting curves to the expression:

$$C^* = (a^{1/2}\,U)^{-1} \qquad (4)$$

Considering all cases 180º<θ<360º, the values of *a* are obtained from Equation (4). Figure 1 shows the variation of *a* with θ for each street canyon. The parameter *a* varies from 0.0021 (θ=202.5º, Göttinger Strasse) to 0.0704 (θ=270.0º, Jagtvej). Shaded area is confined between the following curves: *a*(min)= 5.5685E-04 – 9.794E-03 sin(π θ/180) and *a*(max)=0.0038 – 0.05951 sin(π θ/180) (valid for 180º ≤ θ < 360º)

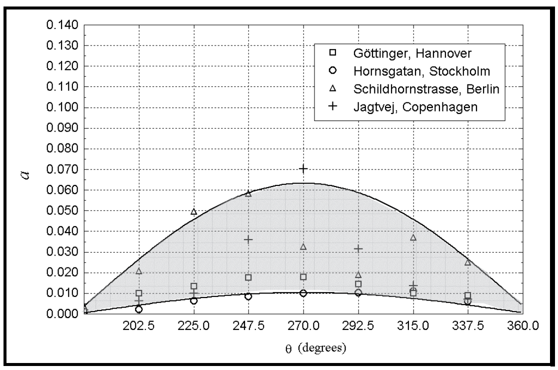

Figure 1. Parameter *a*. Windward conditions.

Leeward conditions

In these cases it can be assumed that normalised concentrations verifies the relationship $C^* \propto (u_s)^{-1}$. Several authors (Ketzel et al., 2002, Kastner-Klein et al., 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, θ≈90º) and they have found that for wind speeds lower than 5 m s^{-1}, 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 the traffic conditions. The variation of *a* with θ can be obtained from Expression (4) when considering the "leeward cases" (0º≤ θ ≤180º) with *U* 5m s^{-1}. The values of *a* are shown in Figure 2 and varies from 0.00034 (θ=157.5º, Hornsgatan) to 0.00365 (θ=135º, Schildhornstrasse). Shaded area is bounded by the following curves: *a*(min)=0.001854-1.50E-03(πθ/180)-3.461E-04$(\pi\theta/180)^2$ and *a*(max)=0.002113+5.049E-04(π θ/180) +1.03E-05$(\pi\,\theta/180)^2$ (valid for 0º≤ θ ≤ 180º).

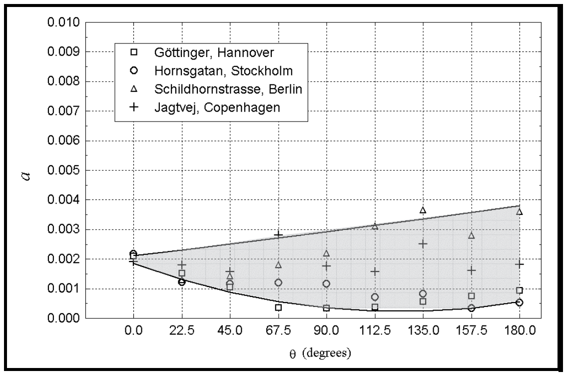

Figure 2. Parameter *a*. Leeward conditions.

Knowing *a*, the values of *b* can be obtained from expression $C^{*}= (aU^{2} + bV^{2})^{-1/2}$. The variation of *b* with traffic density (N/V) for each urban street canyon is shown in Figure 3. Maxima and minima values in this Figure have been fitted to $b(\text{min})=5.2981\text{E-}08(N/V)^{1.66956}$ and $b(\text{max})=3.9545\text{E-}05(N/V)^{0.4655}$ valid for $5\text{veh.km}^{-1} \leq (N/V) \leq 130\text{veh.km}^{-1}$. The relative variation of *b* decreases with traffic density.

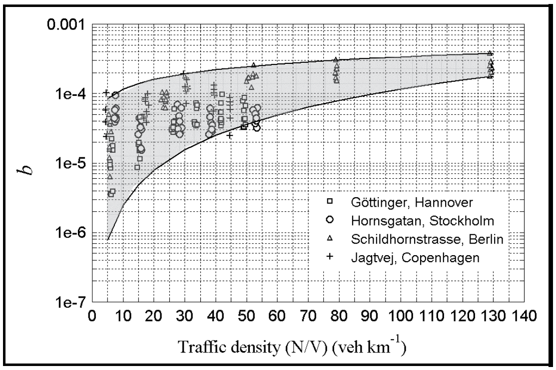

Figure 3. Values of parameter *b* with traffic density.

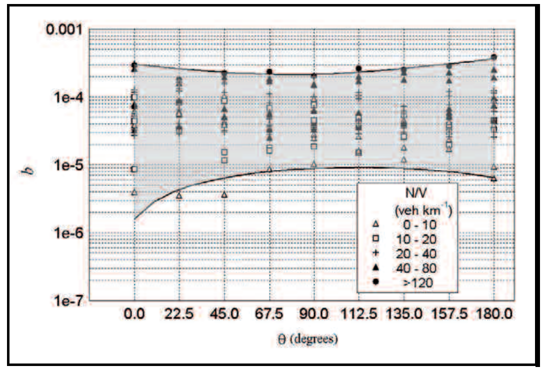

Figure 4. Values of parameter *b* with *Θ*.

The variation of *b* with θ for different ranges of traffic density (N/V) is included in Figure 4. The spread of *b* values decreases from θ= 0º to θ= 90º and increases between 90º and 180º. The expressions of the boundaries of the upper and lower values of *b* are given by: $b(\text{min})= 1.608\text{E-}06 + 7.707\text{E-}06(л\theta/180) - 1.964\text{E-}06(л\theta/180)^{2}$ and $b(\text{max})= 3.052\text{E-}04 - 1.327\text{E-}04(л\theta/180) + 4.85\text{E-}05(л\theta/180)^{2}$.

Critical wind speed

The critical wind speed (U_c) (that verifies $aU_c^{2}=bV^{2}$) varies with traffic density (N/V) and wind direction (Mazzeo et al. 2007). The variation of U_c with (N/V) estimated for the four street canyons, is shown in Figure 5. The shaded area in this Figure is bounded by the fitting curves to minima and maxima values, given by $U_c(\text{min})=0.30715(N/V)^{0.365}$ and $U_c(\text{max})=7.0104(N/V)^{-0.1566}$ valid for 5veh.km^{-1} (N/V) 130veh.km^{-1}. For the street canyons considered, U_c ranges between 0.6–5.0 m/s. Results show that U_c decreases with traffic density.

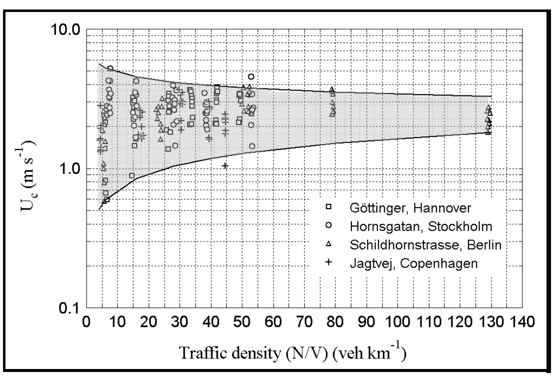

Figure 5. Values of the critical wind speed (U_c) with traffic density

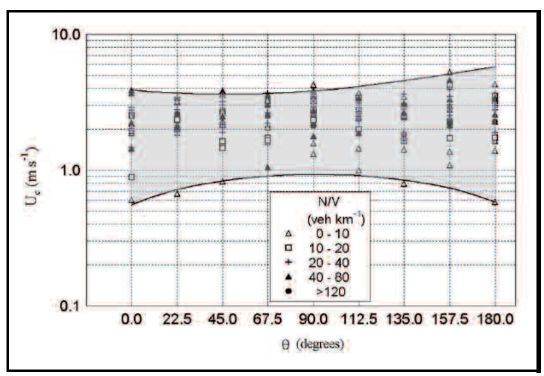

Figure 6 Values of the critical wind speed (Uc) with θ.

Considering the results of U_c for the four street canyons, they do not show a clear dependence on wind direction (Fig. 6). Given a wind sector, the estimated values of U_c show a greater spread when wind blows parallel to the street (θ= 0º and 180º). The empirical expressions that bound the shaded area in Figure 6 are $U_c(\text{min})= 0.5577 + 0.4672(л\theta/180)-0.1463(л\theta/180)^{2}$ and $U_c(\text{max})=3.8922-0.6849(л\theta/180)+0.4081(л\theta/180)^{2}$.

5. CONCLUSIONS

Parameters related with natural and traffic produced turbulences have been studied using hourly traffic pollution data, wind data and traffic flow registered in four street canyons located in: Göttinger Strasse (Hannover, Germany), Schildhornstrasse (Berlin, Germany), Jagtvej (Copenhagen, Denmark) and Hornsgatan (Stockholm, Sweden). Data for all wind directions have been grouped into wind sectors of 22.5º. Results are referred to a common angle (θ) for all street canyons. This parameter is defined taken into account the street canyon orientation. For "windward cases", the parameter *a* (related with natural turbulence) varies from 0.0021 (θ=202.5º, Göttinger Strasse) to 0.0704 (θ=270.0º, Jagtvej). For "leeward cases" (including wind directions parallel to the street) parameter *a* is obtained considering the cases with $U \geq 5\ \text{ms}^{-1}$. In these situations the values of *a* vary between 0.00034 (θ=157.5º, Hornsgatan) and 0.00365 (θ=135º, Schildhornstrasse). Considering the results of the four street canyons, expressions to estimate the lower and upper expected values of *a* with wind direction have been obtained.

For "leeward cases", the values of *b* (parameter related with traffic produced turbulence) are obtained using the expression $C^{*}=(aU^2+bV^2)^{-1/2}$ and the estimated values of *a.* Results for the four street canyons, show the growth of *b* and the decrement of the spread of its values with traffic density. The plot of *b* with wind direction has a great spread in all directions with a minimum at θ =90º (perpendicular to the street). Empirical expressions of the lower and upper values of *b* for a given traffic density have been obtained, valid for traffic density in the interval 5–130 veh km^{-1}.

Data of the four street canyons show that the critical wind speed (U_c) (that verifies $aU_c^2=bV^2$) for "leeward" cases (including wind parallel to the street) varies between 0.6–5.0 ms^{-1}. For these canyons, empirical expressions to estimate expected U_c(min) and U_c(max) as a function of traffic density have been obtained.

Some of the main factors responsible for the observed spread in the estimated values of parameters *a*, *b* and U_c are the different features of each street canyon (e.g. the presence of trees or balconies, different building heights at both sides of the street, crossing streets near the monitoring station) and the uncertainty in the estimation of the emission rates used in calculations.

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