Study of natural and traffic-producing turbulences analysing full-scale data from four street canyons

N.A. Mazzeo* and L.E. Venegas

National Scientific and Technological Research Council (CONICET),
Avellaneda Regional Faculty,
Department of Chemical Engineering,
National Technological University,
Av. Ramón Franco 5050 (1874)-Avellaneda,
Prov. Buenos Aires, Argentina
E-mail: nmazzeo@fra.utn.edu.ar
E-mail: lvenegas@fra.utn.edu.ar
*Corresponding author

Abstract: Parameters related with natural and traffic producing turbulences are estimated for four street canyons considering all wind directions. Available data include air pollution concentrations measured in Göttinger Strasse (Hannover, Germany), Schildhornstrasse (Berlin, Germany), Jagtvej (Copenhagen, Denmark) and Hornsgatan (Stockholm, Sweden), background pollution, wind speed and direction measured on the roof of a nearby building and information of traffic flow. Results show that coefficients *a* and *b*, related to natural- and traffic- produced turbulences, vary with wind direction. The variation of critical wind speed with traffic density and wind direction is also studied for each street canyon.

Keywords: urban street canyon; natural turbulence; traffic-produced turbulence.

Reference to this paper should be made as follows: Mazzeo, N.A. and Venegas, L.E. (2011) 'Study of natural and traffic-producing turbulences analysing full-scale data from four street canyons', *Int. J. Environment and Pollution*, Vol. 47, Nos. 1/2/3/4, pp.290–301.

Biographical notes: N.A. Mazzeo completed his PhD in Atmospheric Sciences at the University of Buenos Aires. He is a Senior Researcher of the National Scientific and Technological Research Council (CONICET) and Director of the post-grade career in Environmental Engineering Master at the National Technological University. His main research interest is air pollution and atmospheric dispersion on local and urban scales.

L.E. Venegas did her PhD in Atmospheric Sciences at the University of Buenos Aires. She is a Senior Researcher of the National Scientific and Technological Research Council (CONICET). Her area of research is micrometeorology and atmospheric dispersion modelling.

1 Introduction

The air quality in urban areas can represent a serious health risk to occupants of buildings and pedestrians, because air pollutants from motor vehicle exhausts are confined between tall buildings or in street canyons under unfavourable wind conditions. High air pollutant concentrations at pedestrian level may occur during low wind speed and high traffic volume. 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. Several 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; Hirtl and Baumann-Stanzer, 2007; Kastner-Klein et al., 2000, 2003, 2004; Mazzeo and Venegas, 2005, 2010; Mensink and Cosemans, 2008; Mensink et al., 2002; Solazzo et al., 2007, 2008; Vardoulakis et al., 2007). Di Sabatino et al. (2003), Kastner Klein et al. (2003) and Vachon et al. (2002) addressed the problem of the parameterisation of traffic-induced turbulent motion in urban dispersion models based on scaling considerations. 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 and traffic velocity.

This study evaluates the proportionality coefficients of the linear combination mentioned earlier related with natural and traffic-produced turbulences for four different street canyons. Full-scale data collected during field measurements at: Göttinger Strasse (Hannover, Germany), Schildhornstrasse (Berlin, Germany), Jagtvej (Copenhagen, Denmark) and Hornsgatan (Stockholm, Sweden) are used. Results are analysed considering all wind directions. 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 also evaluated for different traffic densities and wind direction at the four street canyons. Results constitute the starting point of a project whose final objective includes obtaining a parameterisation of the proportionality coefficients mentioned earlier including different features of the street canyon (e.g., the aspect ratio, the existence of trees or balconies, different building heights at each side of the street, crossing streets near the monitoring station, vehicle fleet composition) and wind direction dependence. At this stage, the task is to explore the differences in the proportionality coefficients related to natural- and traffic-produced turbulence when considering different street canyons, varying wind direction and traffic density.

2 Overview of the relation between concentrations and wind and traffic produced turbulences inside a street canyon

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 1.5–2.0 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.

For windward situations, Ketzel et al. (2002a) and Mazzeo and Venegas (2005) show that experimental data of local concentration (C) registered at street canyons follow a potential relation, $C \propto U^{-m}$. 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 re-circulating part of the pollutants inside the canyon. In these situations, both buoyancy-related and Traffic-Produced (TPT) Turbulences are considered secondary street-ventilation mechanisms compared with the main wind-induced mechanism. In this way, considering the specific emission per length (E) and the width (W) of the canyon, the concentration C^* would be (Kastner-Klein et al., 2003):

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

where the background concentration, C_b, has been subtracted from the values of pollutant concentrations measured inside the street, C_i. Values C_b and C_i can be expressed in (mg m^{-3}), E in (mg m^{-1} s^{-1}) and W in (m), then C^* is expressed in (s m^{-1}) units.

For leeward conditions, field data analyses have often demonstrated that the above-mentioned scaling has certain deficiencies (Ketzel et al., 2002b; Kastner-Klein et al., 2003), since particularly with lower wind speeds TPT effects start to play an important role. Different authors (Berkowicz et al., 2002; Di Sabatino et al., 2003; Kastner-Klein et al., 2000, 2001, 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(m^2s^{-2}) is the wind speed variance, σ_v^2(m^2s^{-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 ($\sigma_u^2 = aU^2$). 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 ($\sigma_v^2 = bV^2$) (values of b include the conversion factors from (km h^{-1}) to (m s^{-1})). Parameter b is function of wind direction, vehicles characteristics, their average drag coefficients and traffic density. For congested traffic, b does not depend on traffic density (Di Sabatino et al., 2003). For leeward conditions, C^* verifies the relationship $C^* \propto (u_s)^{-1}$.

As mentioned earlier, TPT plays less important role than wind speed in determination of concentration levels at a receptor located on the 'windward' side. In this case, it can be considered that dispersive velocity scale is mainly given by wind speed variance, $u_s = \sigma_u = a^{1/2} U$.

In this study, it is assumed $C^* = u_s^{-1}$, therefore the following expressions are considered

$$\text{for 'windward' conditions } C^* = (a^{1/2}\, U)^{-1} \tag{3}$$

$$\text{for 'leeward' conditions } C^* = (aU^2 + bV^2)^{-1/2} \tag{4}$$

In a previous study (Mazzeo and Venegas, 2005), an empirical expression of the variation of *b* with traffic density (*N*/*V*) for situations close to leeward conditions at Göttinger Strasse have been developed. A recent study (Mazzeo and Venegas, 2010) presents the variation of *a* and *b* with wind direction and traffic density for all roof-level wind directions and traffic flow measured in Göttinger Strasse.

3 The sites and data

The analysis is done using available hourly air pollutant concentrations and traffic flow from full-scale data registered at four street canyons: Göttinger Strasse (Hannover, Germany), Schildhornstrasse (Berlin, Germany), Jagtvej (Copenhagen, Denmark) and Hornsgatan (Stockholm, Sweden) along with wind speed and direction data registered nearby. One year of hourly information is available for each street canyon. Table 1 summarises the street orientation with respect to North, aspect ratio (H/W) (being H the averaged building height) and annual average daily traffic flow for each street canyon.

Table 1 Street orientation with respect to North, aspect ratio (H/W) and annual average daily traffic flow (veh/day) for the four street canyons

Street canyon	*Street orientation with respect to North*	*H/W*	*Veh/day*
Göttinger Strasse	163º	0.8	30,000
Schildhornstrasse	120º	0.73–0.85	45,000
Jagtvej	30º	0.72	22,000
Hornsgatan	66º	1.0	35,000

4 Results and discussion

Parameters *a* and *b* included in equations (3) and (4) are evaluated considering all wind directions and using air pollutant concentrations, meteorological parameters and traffic flow (*N*) measured in the four street canyons described earlier. The estimations of *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

$$E\ (\text{mg s}^{-1}\ \text{m}^{-1}) = \sum_i N_i e_i \tag{5}$$

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

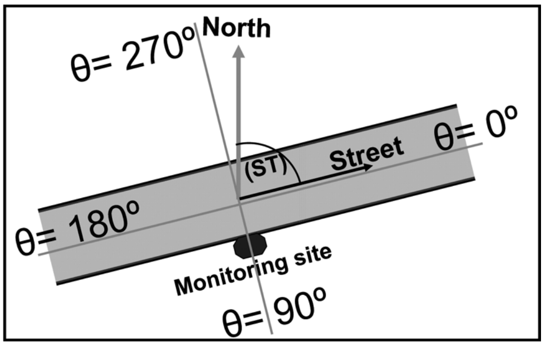
Because of the different orientation of each street canyon, the roof-level Wind Direction (WD) cannot be used as a common indicator of leeward or windward situations for all the canyons. Therefore, to refer the results of the four street canyons to a common value relative to the orientation of the street canyon the parameter θ (Figure 1) is introduced as

$$\theta = \text{WD} - \text{ST} \qquad \text{for WD} \geq \text{ST}$$

$$\theta = \text{WD} + 360^\circ - \text{ST} \qquad \text{for WD} < \text{ST}$$

where ST is the angle between the North and the street axis towards the right side of the monitoring location (facing the street). According to the street orientation and the position of the monitors, the values of ST are: ST (Göttinger Strasse) = 163º; ST (Schildhornstrasse) = 120º; ST (Jagtvej) = 30º and ST (Hornsgatan) = 246º. The value of θ is expressed in degrees. In this way, for example, at every street canyon the strict leeward situation is associated to $\theta = 90^{o}$ and the strict windward situation to $\theta = 270^{o}$.

Figure 1 Definition of θ



Data have been grouped into 'leeward cases' ($0^{o} \leq \theta \leq 180^{o}$) and 'windward cases' ($180^{o} < \theta < 360^{o}$). Statistical methods (Mazzeo and Venegas, 2005, 2010) to obtain the best fits to measurements have been applied to data grouped into 16 wind sectors of 22.5º centred in $\theta = 0^{o}$, 22.5º, 45.0º, 67.5º, 90.0º, 112.5º, 135.0º, 157.5º, 180.0º, 202.5º, 225.0º, 247.5º, 270.0º, 292.5º, 315.0º and 337.5º. Uncertainties in hourly data-points, such as the related to measurements, emission rates considered and the stochastic character of atmospheric turbulence, affect the estimation of parameters a and b. The standard error of each fitting curve (StatSoft, 2001) is evaluated. Results are obtained for each street canyon separately.

4.1 Windward conditions

This analysis includes wind directions associated with ($180^{o} < \theta < 360^{o}$), this is $\theta = 202.5^{o}$, 225.0º, 247.5º, 270.0º, 292.5º, 315.0º and 337.5º at each street canyon. The value of a is estimated using equation (3). Plotting C* with ambient wind speed (U) for each θ, a is obtained from the best fitting curve. Standard errors of the fitting curves give an error estimate for parameter a in windward conditions that varies between 5% and 15%. Larger errors are associated with larger data scatter and fewer cases. Details of the methodology, data and fitting curves for Göttinger Strasse can be found in Mazzeo and Venegas (2010). As an example, Figure 2 shows the result for Hornsgatan (Stockholm), $\theta = 202.5^{o}$. Figure 3 shows the values of a for different θ for each street canyon. Parameter a varies from 0.0021 ($\theta = 202.5^{o}$, Hornsgatan) to 0.0704 ($\theta = 270.0^{o}$, Jagtvej). From Figure 3 differences in a between street canyons increase with wind directions perpendicular to the street. Larger a are obtained for Jagtvej and Schildhornstrasse. In these cases, some particularities in the geometry of the street canyon may affect the natural turbulence in a different way than the observed in the other two canyons. Particularly, near the monitoring site in Jagtvej, there is an open street on the opposite side. In Schildhornstrasse building heights in front of the monitor are lower.

Figure 2 Variation of normalised concentrations (C^*) with ambient wind speed (U) for Hornsgatan (Berlin), $\theta = 202.5^\circ$ ('windward condition'). Fitting curve to equation (3) is included

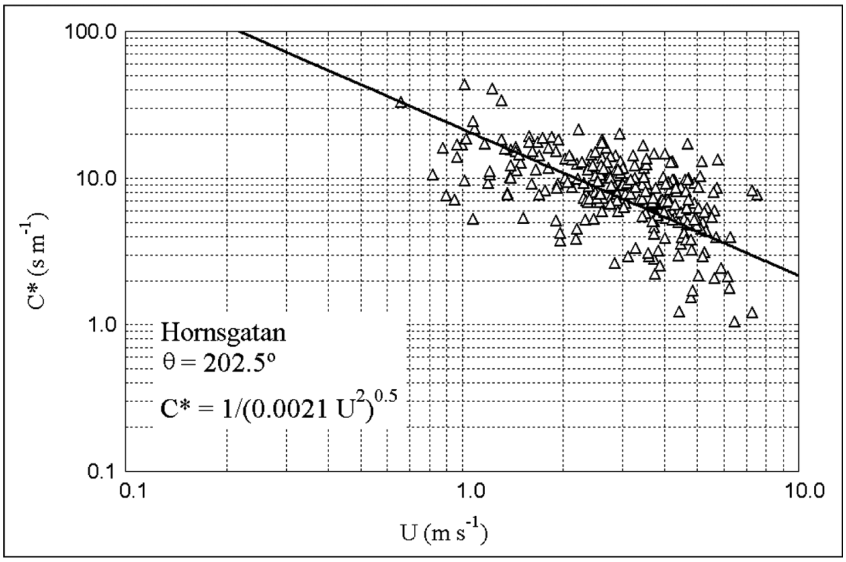
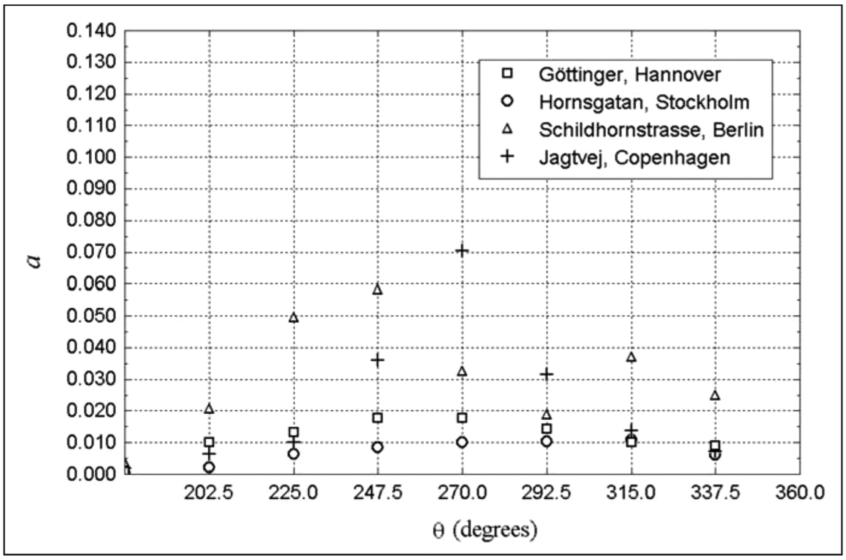


Figure 3 Values of parameter *a* for different θ in windward conditions, for the four street canyons



4.2 Leeward conditions

'Leeward cases' include all cases with ($0^\circ \leq \theta \leq 180^\circ$). For each street canyon, concentrations registered when WD gives $\theta = 0^\circ$, 22.5°, 45.0°, 67.5°, 90.0°, 112.5°, 135.0°, 157.5°, 180.0° are considered in this analysis.

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, $\theta \approx 90^{\mathrm{o}}$) and they have found that for wind speeds lower than 5 ms^{-1}, the fitting curve considerably 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 considering only the 'leeward cases' with $U \geq 5$m s^{-1}. In these conditions, wind speed dominates the dilution of concentration inside the street canyon and observed data can be considered as 'without' the influence of traffic turbulence. Therefore, if the term of traffic-induced velocity variance is neglected in equation (4), the form is similar to equation (3). For a detailed description of the applied methodology, including all the figures and fitting curves for Göttinger Strasse the reader is referred to Mazzeo and Venegas (2010). As an example, Figure 4 shows the result for Schildhornstrasse ($\theta = 135^{\mathrm{o}}$). Values of a for different θ for each street canyon are shown in Figure 5. Parameter a varies between 0.00034 ($\theta = 157.5^{\mathrm{o}}$, Hornsgatan) and 0.00365 ($\theta = 135^{\mathrm{o}}$, Schildhornstrasse). The error estimate for parameter a in leeward conditions varies between 5% and 25%. In an ideal canyon, similar values of a are expected to be found for both wind directions parallel to the street ($\theta = 0^{\mathrm{o}}$ and 180º). However, the existence of obstacles inside the street canyon may affect this behaviour. For instance, there is a construction (some columns) to the right of the monitor located in Göttinger Strasse, which may affect atmospheric turbulence. In this way, this construction may explain the increasing values of a for $\theta < 67.5$ in Göttinger Strasse. On the other hand, some trees and building structures (different roofs, heights) located left of the monitoring site in Schildhornstrasse may contribute to rise the value of a for $\theta > 112.5^{\mathrm{o}}$ in this canyon. In Hornsgatan, traffic lights on the right side of the monitors may generate occasional obstacles inside the canyon, which may contribute to larger a for $\theta = 0^{\mathrm{o}}$. On the other hand, in Jagtvej the values of a for $\theta = 0^{\mathrm{o}}$ and 180º appear quite similar. Some of the reasons mentioned earlier (along with error estimate) may explain the different ranges of a obtained in Figure 5. A better knowledge of building structures (balconies, shape of the roofs, heights) and obstacles (trees, traffic queues) at each street canyon may help to a better understanding of the spread of these results.

Knowing a for each θ, parameter b can be obtained for θ = 0º, 22.5º, 45.0º, 67.5º, 90.0º, 112.5º, 135.0º, 157.5º, 180.0º, plotting C^* vs. U and obtaining the best fitting curve to equation (4), considering different traffic densities. Standard errors of the fitting curves give an error estimate for parameter b varying between 7% and 35%. The values of b for different traffic density (N/V) for each urban street canyon are shown in Figure 6. In this figure, results for each street canyon are identified with a different mark. Large spread is observed for low traffic density, when the variability in the emission rate is greater. However, the spread in b comes not only from the uncertainties in data and fitting curves but also because of the possible influence of wind direction. The values of b for different θ and traffic density (N/V) ranges are included in Figure 7. The spread of b values decreases from $\theta = 0^{\mathrm{o}}$ to $\theta = 90^{\mathrm{o}}$ and increases between 90º and 180º.

Figure 4 Variation of normalised concentrations (C^*) with ambient wind speed (U) for Schildhornstrasse (Berlin), $\theta = 135°$ ('leeward condition'). 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 $U \leq 5$ m s^{-1}

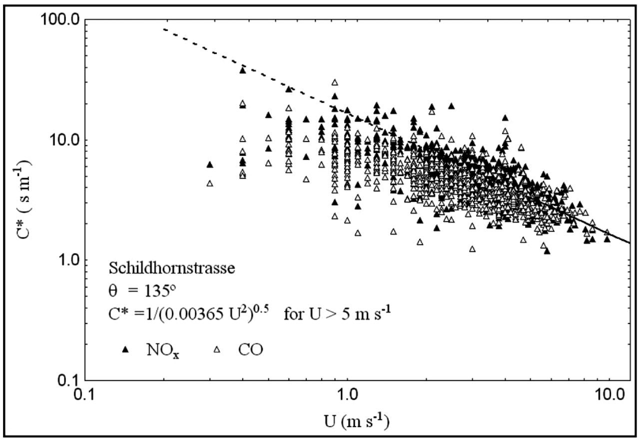


Figure 5 Values of parameter a for different θ in leeward conditions, for the four street canyons

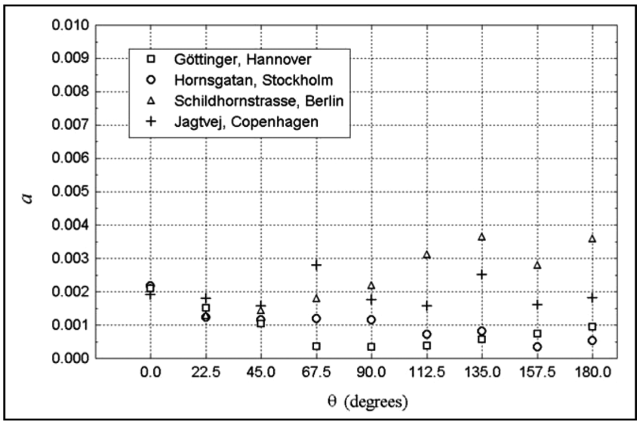


Figure 6 Values of parameter b for different traffic density (N/V), for the four street canyons

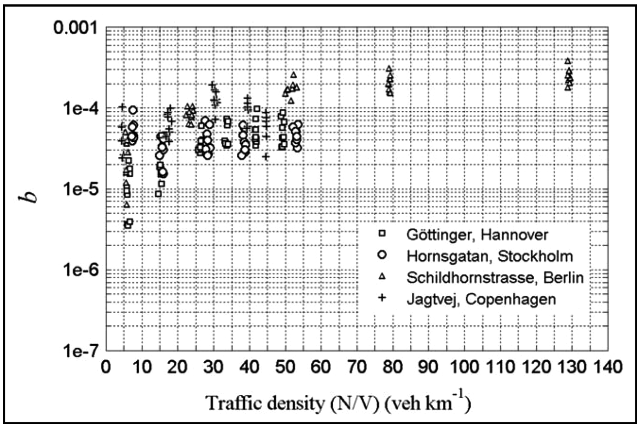
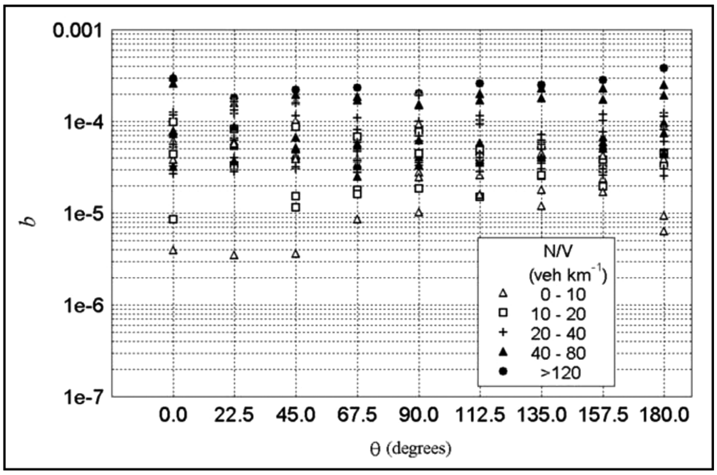


Figure 7 Values of parameter b for different θ and traffic density (N/V)



4.3 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 and Venegas, 2010). For each combination (θ, N/V), U_c is estimated from values of a and b. The error estimate for U_c is evaluated considering the error estimate for parameters a and b in each case. The error estimate for U_c varies between 10% and 25%. The values of U_c for different (N/V) estimated for each street canyon are shown in Figure 8. For the street canyons considered, U_c ranges between 0.6 m/s and 5.0 m/s. Following the behaviour of b, the spread of U_c decreases with traffic density. Considering the results of U_c for the four street canyons, U_c does not show a clear dependence on wind direction (Figure 9). Given a wind sector, the estimated values of U_c show a greater spread when wind blows parallel to the street ($\theta = 0°$ and 180°).

Figure 8 Values of the critical wind speed (U_c) for different traffic density (N/V), for the four street canyons

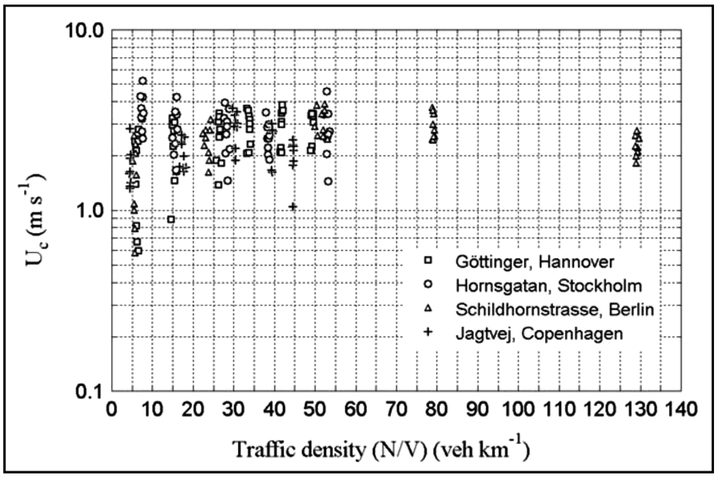
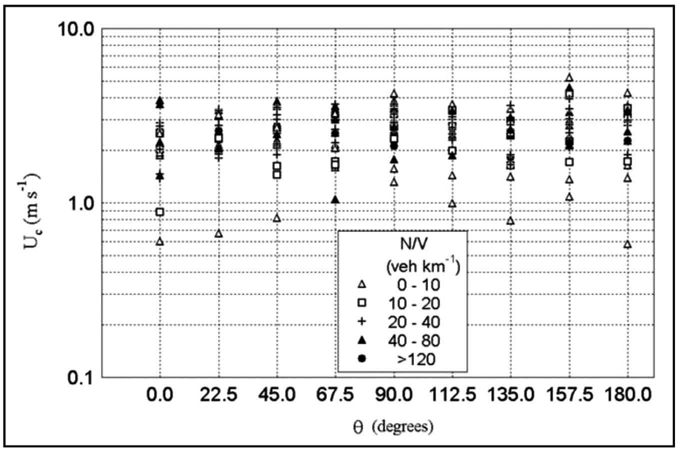


Figure 9 Values of the critical wind speed (U_c) for different θ and traffic density (N/V)



5 Conclusions

This study explores the existence of differences in the parameters related with natural and traffic produced turbulences in different street canyons. One year of hourly traffic pollution data, wind data and traffic flow registered in four different street canyons located in: Göttinger Strasse (Hannover, Germany), Schildhornstrasse (Berlin, Germany), Jagtvej (Copenhagen, Denmark) and Hornsgatan (Stockholm, Sweden) are used. 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.

The parameter a (related with natural turbulence) varies from 0.0021 ($\theta = 202.5$º, Hornsgatan) to 0.0704 ($\theta = 270.0$º, Jagtvej) for 'windward cases'. The error estimate for a in windward cases ranges 5–15%. For "leeward cases" (including wind directions parallel to the street), this parameter is obtained considering the cases with $U \geq 5$ m s^{-1}. In these situations, values of a vary between 0.00034 ($\theta = 157.5$º, Hornsgatan) and 0.00365 ($\theta = 135$º, Schildhornstrasse) and its error estimate is between 5% and 25%.

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 for 'leeward cases'. The error estimate for b ranges between 7% and 35%. 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 θ has a great spread in all directions with a minimum at $\theta = 90$º (perpendicular to the street).

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 m/s and 5.0 m/s with an error estimate of 10–25%.

Uncertainties in hourly data-points, such as those related to measurements, emission rates considered and the stochastic character of atmospheric turbulence, affect the estimation of parameters a, b and U_c. Other factors responsible for the observed spread in the estimated values of parameters a, b and U_c are related with different features of each street canyon (e.g., the aspect ratio, the existence of trees or balconies, different building heights at both sides of the street, crossing streets near the monitoring station, vehicle fleet composition).

Future work, including other street canyon data sets, will consider exploring alternative parameterisations of a and b with the aim of minimising the cross-site parameter variations, for example by incorporating geometric information (presence of balconies and trees, building distribution and density along the street canyon) to be incorporated in simple operational street canyon models.

Acknowledgements

Traffic pollution data have been provided by the European Research Network on Optimisation of Modelling for Traffic Pollution in Streets (TRAPOS). The financial support of the National Scientific and Technological Research Council of Argentina (CONICET) is also gratefully acknowledged.

References

Berkowicz, R., Ketzel, M., Vachon, G., Louka, P., Rosant, J.M., Mestayer, P.J. and Sini, J.M. (2002) 'Examination of traffic pollution distribution in a street canyon using the Nantes'99 experimental data and comparison with model results', *Water, Air and Soil Pollution, Focus,* Vol. 2, pp.311–324.

Berkowicz, R., Winther, M. and Ketzel, M. (2006) 'Traffic pollution modelling and emission data', *Environmental Modelling & Software*, Vol. 21, pp.454–460.

Di Sabatino, S., Kastner-Klein, P., Berkowicz, R., Britter, R.E. and Fedorovich, E. (2003) 'The modelling of turbulence from traffic in urban dispersion models- Part I. Theoretical considerations', *Environmental Fluid Mechanics*, Vol. 3, pp.129–143.

EMEP/CORINAIR (2004) *Emission Inventory Guidebook*, 3rd ed., Update, Technical Report No. 30, European Environ, Agency (www.reports.eea.eu.int/ EMEPCORINAIR4/en).

Hirtl, M. and Baumann-Stanzer K. (2007) 'Evaluation of two dispersion models (ADMS-Roads and LASAT) applied to street canyons in Stockholm, London and Berlin', *Atmospheric Environment*, Vol. 41, pp.5959–5971.

Kastner-Klein, P., Berkowicz, R. and Plate, E.J. (2000) 'Modelling of vehicle induced turbulence in air pollution studies for streets', *International Journal of Environment and Pollution*, Vol. 14, pp.496–507.

Kastner-Klein, P., Berkowicz, R. and Fedorovich, E. (2001) 'Evaluation of scaling concepts for traffic-produced turbulence based on laboratory and full-scale concentration measurements in street canyons', *Proceedings of The Third International Conference on Urban Air Quality*, Loutraki, Greece, Institute of Physics, London, CD-Rom, Paper RAQ.3.3.

Kastner-Klein, P., Fedorovich, E., Ketzel, M., Berkowicz, R. and Britter, R.E. (2003) 'The modelling of turbulence from traffic in urban dispersion models- Part II. Evaluation against laboratory and full-scale concentration measurements in street canyons', *Environmental Fluid Mechanics*, Vol. 3, pp.145–172.

Kastner-Klein, P., Berkowicz, R. and Britter, R.E. (2004) 'The influence of street architecture on flow and dispersion in street canyons', *Meteorology Atmospheric Physics*, Vol. 87, pp.121–131.

Ketzel, M., Berkowicz, R., Müller, W. and Lohmeyer, A. (2002a) 'Dependence of street canyon concentrations on above roof wind speed – Implications for numerical modelling', *International Journal of Environment and Pollution*, Vol. 17, pp.356–366.

Ketzel, M., Louka, P., Sahm, P., Guilloteau, E., Sini, J.F. and Moussiopoulos, N. (2002b) 'Intercomparison of numerical urban dispersion models – Part II: street canyon in Hannover, Germany', *Water, Air and Soil Pollution, Focus*, Vol. 2, pp.603–613.

Mazzeo, N.A. and Venegas, L.E. (2005) 'Evaluation of turbulence from traffic using experimental data obtained in a street canyon', *International Journal of Environment Pollution*, Vol. 5, pp.164–176.

Mazzeo, N.A. and Venegas, L.E. (2010) 'Air pollution dispersion inside a street canyon of Göttinger Strasse (Hannover, Germany): new results of the analysis of full scale data', *International Journal of Environment Pollution*, Vol. 40, pp.195–209.

Mensink, C., Lewyckyj, N. and Janssen, L. (2002) 'A new concept for air quality modelling in street canyons', *Water, Air and Soil Pollution: Focus*, Vol. 2, pp.339–349.

Mensink, C. and Cosemans, G. (2008) 'From traffic flow simulations to pollutant concentrations in street canyons and backyards', *Environmental Modelling & Software*, Vol. 23, pp.288–295.

Solazzo, E., Vardoulakis, S. and Cai, X. (2007) 'Evaluation of traffic-producing turbulence schemes within operational street pollution models using roadside measurements', *Atmospheric Environment*, Vol. 41, pp.5357–5370.

Solazzo, E., Cai, X. and Vardoulakis, S. (2008) 'Modelling wind flow and vehicle-induced turbulence in urban streets', *Atmospheric Environment*, Vol.42, pp.4918–4931.

StatSoft, Inc. (2001) *STATISTICA (data analysis software system)*, version 6, www.statsoft.com

Vachon, G., Louka, P., Rosant, J.M., Mestayer, P.G. and Sini, J.F. (2002) 'Measurements of traffic-induced turbulence within a street canyon during the Nantes'99 experiment', *Water, Air and Soil Pollution: Focus*, Vol. 2, pp.12–140.

Vardoulakis, S., Valiatins, M., Milner, J. and ApSimon, H. (2007) 'Operational air pollution modelling in the UK- street canyon applications and challenges', *Atmospheric Environment,* Vol. 41, pp.4622–4637.