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EVALUATION OF AIR POLLUTANT CONCENTRATIONS ESTIMATED INSIDE AN ASYMMETRIC STREET CANYON USING DIFFERENT PARAMETERISATIONS OF VEHICLE-INDUCED TURBULENCE

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Abstract. Leeward air pollutant concentrations (C) are estimated by incorporating different parameterisations of traffic-produced turbulence (TPT) into the scaling of C inside a street canyon. Four cases are evaluated. Three of them consider TPT parameterisations previously introduced in literature by other authors, based on a theoretical formulation of TPT and a semi-empirical approach of the generation of turbulence by moving cars already incorporated in an operational street model. The fourth scheme introduces an empirical expression of TPT derived from four full-scale street canyon data sets. Hourly NO_x concentrations are calculated for an asymmetric street canyon in Buenos Aires, using meteorological observations at local airport and modelled background concentrations. Statistical indicators show that the performance of the four schemes is satisfactory.

***Key words:** street canyon, traffic-produced turbulence, urban air pollution, traffic pollution.*

INTRODUCTION

Street canyons have a significant influence on the dispersion of pollutants near the source, as automotive emissions take place at ground level. The most characteristic feature of a street canyon wind flow is the formation of a wind vortex so that the direction of the wind at street level is opposite to the flow above roof level especially when ambient wind direction is perpendicular to the street. Another feature that plays an important role in the dispersion of near-road pollutants is the traffic-produced flow disturbance. Low wind speed conditions are generally associated with the worst air pollution episodes in urban areas. In these cases the turbulence, mechanically generated by traffic motion, becomes the major factor responsible for the dilution of pollutants in streets. Different authors (Berkowicz, R. et al., 2002; Vachon, G. et al., 2002; Di Sabatino, S. et al., 2003; Kastner-Klein, P. et al., 2000, 2001, 2003; Solazzo, E. et al., 2007, 2008; Kondo, H. and T. Tomizuka, 2009) studied the influence of turbulence created by traffic flow in the street, on air pollutant dispersion in street canyons. Di Sabatino, S. et al. (2003) focused on the parameterisation of the interaction between traffic motions and pollutant transport in street canyons under low wind speed conditions. They presented theoretical considerations to estimate mechanical turbulence induced by traffic in street canyons at low wind speed conditions. Kastner-Klein, P. et al. (2003) analysed and interpreted results from a variety of full-scale and wind-tunnel studies. Solazzo, E. et al. (2008) presented a computational fluid dynamics modelling methodology for the simulation of the flow and turbulence induced by wind and vehicle motion within an idealised street canyon.

The objective of this paper is to evaluate different estimations of air pollutant concentrations (C) at ground level for leeward conditions, in a street canyon located in Buenos Aires city, considering four different parameterisations of traffic-produced turbulence into the scaling of C inside a street canyon.

METHODOLOGY

Kastner-Klein, P. et al. (2000, 2003) propose that 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) ($m\ s^{-1}$). Kastner-Klein, P. et al. (2000) introduce the following expression for the dispersive velocity scale (u_s) ($m\ s^{-1}$):

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

where σ_u^2 ($m^2\ s^{-2}$) is the wind speed variance, σ_v^2 ($m^2\ s^{-2}$) 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 ($\sigma_u^2 = a\ U^2$). 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 ($\sigma_v^2 = b\ V^2$).

For leeward conditions, the scaling of the concentration at street level (C) leads to

$$C = [E\ u_s^{-1}\ W^{-1} + C_b] \qquad (2)$$

where E is the emission rate per length, W is the width of the canyon and C_b is the background concentration.

Air pollutants concentrations C are estimated for leeward conditions using equation (2) considering the following four parameterisations of $[\sigma_v]^2 = bV^2$ in equation (1):

Cases 1 and 2: TPT is evaluated including a theoretical formulation of b

Based on the balance between turbulent kinetic energy production and dissipation, different parameterisations for TPT suitable for different traffic flow conditions were derived by Di Sabatino, S. et al. (2003). Three traffic configurations were distinguished: (i) light traffic conditions (isolated vehicles, non-interacting vehicle wakes); (ii) moderate traffic conditions corresponding to non-isolated (interacting) vehicle wakes; and (iii) heavy (congested) traffic conditions characterised by strongly interacting wakes. The parameterisations for TPT derived for the three traffic regimes are:

- light traffic density:

$$[\sigma_v]^2 = b\,V^2 = c_1\, n_v\, C_D^{2/3}\, h^3\, Sc^{-1}\, V^2 \tag{3}$$

- intermediate traffic density:

$$[\sigma_v]^2 = b\,V^2 = c_2\, (n_v\, C_D)^{2/3}\, h^2\, Sc^{-2/3}\, V^2 \tag{4}$$

- large traffic density:

$$[\sigma_v]^2 = b\,V^2 = c_3\, C_D^{2/3}\, h^{4/3}\, Sc^{-2/3}\, V^2 \tag{5}$$

where c_1, c_2 and c_3 are dimensionless constants, n_v is the traffic density (number of vehicles per unit length), C_D is the average drag coefficient of vehicles, h is the vehicle length scale and $Sc \leq (WH)$ is the cross-section area of the canyon portion affected by TPT with H the depth of the canyon.

The expressions (3)-(5) introduced by Di Sabatino, S. et al. (2003) were applied considering two cases:
Case 1: Following Kastner-Klein, P. et al. (2003), light traffic density was assumed when $n_v < 0.04\ m^{-1}$ and equation (3) was applied considering c_1=0.06. For $n_v \geq 0.04\ m^{-1}$, intermediate traffic conditions were considered and equation (4) was applied with c_2= 0.007.
Case 2: Following Solazzo, E. et al. (2007), the three traffic regimes were considered in calculations. Equation (3) was applied for $n_v < 0.037\ m^{-1}$ with c_1=0.03, equation (4) was considered when $0.037\ m^{-1} \leq n_v < 0.05\ m^{-1}$ with c_2=0.0025 and equation (5) was used for $n_v \geq 0.05\ m^{-1}$ with c_3=0.00049.

Case 3: TPT is evaluated using the formulation included in WinOSPM model
Generation of turbulence by moving cars in street canyons is included in the Danish Operational Street Model (WinOSPM) model using the following approach (Berkowicz, R. et al., 1997):

$$[\sigma_v]^2 = b\,V^2 = (C_D^2\, n_v\, S^2\, W^{-1})\, V^2 \tag{6}$$

where S^2 is the planar area of the vehicles.

Case 4: TPT is evaluated including an empirical variation of b with traffic density
Mazzeo, N and L. Venegas (2011) studied the variation of parameters *a* and *b* with wind direction and traffic density using full-scale hourly data collected during field measurements at: Göttinger Strasse (Hannover, Germany), Schildhornstrasse (Berlin, Germany), Jagtvej (Copenhagen, Denmark) and Hornsgatan (Stockholm, Sweden). Figure 1 shows the values of *b* with traffic density obtained by Mazzeo N. and L. Venegas (2011) considering air pollution data registered for wind blowing from the leeward side of the streets.

In this paper, an empirical expression of *b* with n_v is derived using results in Figure 1. As the number of cases of *b* is not uniformly distributed with traffic density, the values of *b* have been sorted on n_v (km^{-1}) into the following bins: <10, 10-20, 20-33, 33-45, 45-55, 75-85 and >120. These bins have been selected taking into account the groups of *b* values that appear in Figure 1. The *b* values for each bin are averaged giving the variation of *b* with n_v used to obtain the fitting curve given by
b= 2.88642E-06 $(n_v)^{0.930771}$ (regression coefficient=0.962) with $[n_v]$ in km^{-1} (Figure 2).

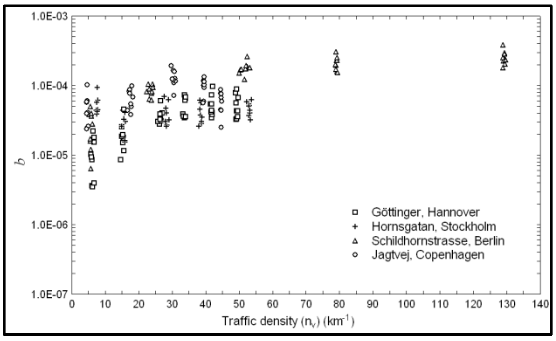

Figure 1. Variation of *b* with traffic density. (Mazzeo, N. and L. Venegas, 2011)

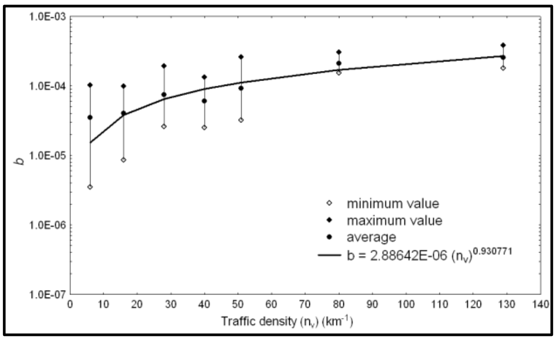

Figure 2. Variation of *b* (averaged for each bin) with traffic density. Fitting curve is included, maximum and minimum values in each bin are indicated.

Therefore, the traffic-produced turbulence is estimated as:

$$[\sigma_v]^2 = b\,V^2 = 2.88642\text{E-}06\, (n_v)^{0.930771}\, V^2 \tag{7}$$

with n_v expressed in km^{-1}

RESULTS

Hourly concentrations of nitrogen oxides (NO_x) are estimated for leeward conditions using equation (2) considering the four different parameterisations of traffic produced turbulence ($b\ V^2$) described in Cases 1, 2, 3 and 4, in an asymmetric street canyon of Córdoba Avenue in Buenos Aires city. This avenue is orientated E-W and it has five lanes. Mean traffic flow is approximately 38,000 veh h^{-1}. The street canyon is irregular and asymmetric. Its width is W= 30 m. Building heights (H) at both sides of the street are very different. On the northern side, buildings are low and quite uniform (approximately 10 m high). On the southern side, building heights show a wide variation from 10 m to 80 m with an average height of approximately 40 m. A NO_x monitoring station is located on the southern side of the street.

Information on traffic flow, average road traffic speed and composition of road traffic is obtained from several reports elaborated by local authorities (GCBA, 2006, GCBA-ACOM, 2006). Emission factors similar to the ones used in the application of the WinOSPM in this street canyon (Venegas, L. and N. Mazzeo, 2011) and in the development of the NO_x emission inventory for the city (Mazzeo, N. and L. Venegas, 2003; Venegas, L. et al., 2011) are used. This emission inventory is used in the estimation of urban background concentrations (C_b) using the urban DAUMOD model (Mazzeo, N. and L. Venegas, 2010). Due to lack of available information on ambient wind at the monitoring site, hourly measurements observed at the domestic airport located approximately 3.5 km from the site have to be considered as ambient wind conditions (U).

The application of equation (2) requires the value of parameter a for this street canyon. Parameter a can be obtained considering only the leeward cases with U> 4m 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 (1), the scaling of C is given by

$$C^* = (C - C_b)W/E = a^{-1/2}\ U^{-1} \qquad (8)$$

Considering the variation of C* for hourly NO_x concentrations measured in the street canyon during leeward conditions (wind directions SSE, S and SSW) for U> 4 m s^{-1}, parameter a results 0.00025 (Figure 3). This value of a is considered in calculations of all Cases.

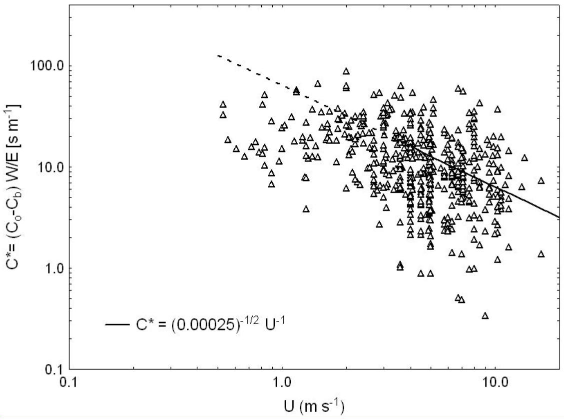

Figure 3. Variation of normalised concentrations (C*) with ambient wind speed (U) for leeward conditions (SSE, S and SSW) in Córdoba Ave. (Buenos Aires). Fitting curve to equation (8) is included.

In this study drag coefficient C_D is assumed 0.3 for passenger cars and 0.9 for heavy-duty vehicles, the vehicle length scale (h) is considered 1.4m for passenger cars and 3.0m for heavy duty vehicles and the planar area of the vehicles S^2 is 2.0m^2 for passenger cars and 16.0m^2 for heavy-duty vehicles (Kastner-Klein, P. et al., 2003; Solazzo, E. et al., 2007). The value of Sc is assumed 150 m^2 (= 0.5 WH) obtained considering the mean building height (H=10m) of the lowest side of the street.

Estimated hourly NO_x concentrations are compared with observations inside the canyon for the period June to December 2009. Scatter plots of estimated (C_e) and observed (C_o) hourly concentrations for the four Cases are shown in Figure 4. The data have been categorised into two ambient wind speed classes, U> 2 m s^{-1} and U≤ 2 m s^{-1}.

Results for all Cases show wider scatter of data for light ambient wind speeds (U≤ 2 m s^{-1}) than for higher ambient wind speeds. Comparing the results obtained for Cases 1 and 2 for this street canyon, it can be seen that the theoretical parameterisation of TPT proposed by Di Sabatino, S. et al. (2003) when applied considering constants and traffic conditions defined in Kastner-Klein, P. et al. (2003) (Case 1) provides better estimations than the obtained following the assumptions used in Solazzo, E. et al. (2007) (Case 2). Case 2 overestimates observed concentrations. On the other hand most of concentrations estimated with TPT parameterisation of Case 3 are lower than the observed values. Finally, proposed Case 4 tends to underestimate higher concentration values.

A summary of statistical indicators of the agreement between observed and modelled hourly concentrations are included in Table 1. The statistics included in this Table are the number of values (N), mean, sigma, bias, normalised mean square error (NMSE), correlation coefficient (Corr), fraction of modelled values between a factor 2 of observations (FA2), fractional bias (FB) and the under-predicting (FBfn) and over-predicting (FBfp) components of FB (Chang, J. and S. Hanna, 2004).

In general, the performance of all schemes is satisfactory. Results of all schemes show greater errors for light wind speeds (U≤ 2 m s^{-1}). Estimated C considering the parameterisations of Cases 1 and 4 show lower errors than the obtained for Cases 2 and 3. Case 1 slightly overestimates while Case 4 slightly underestimates observed concentrations.

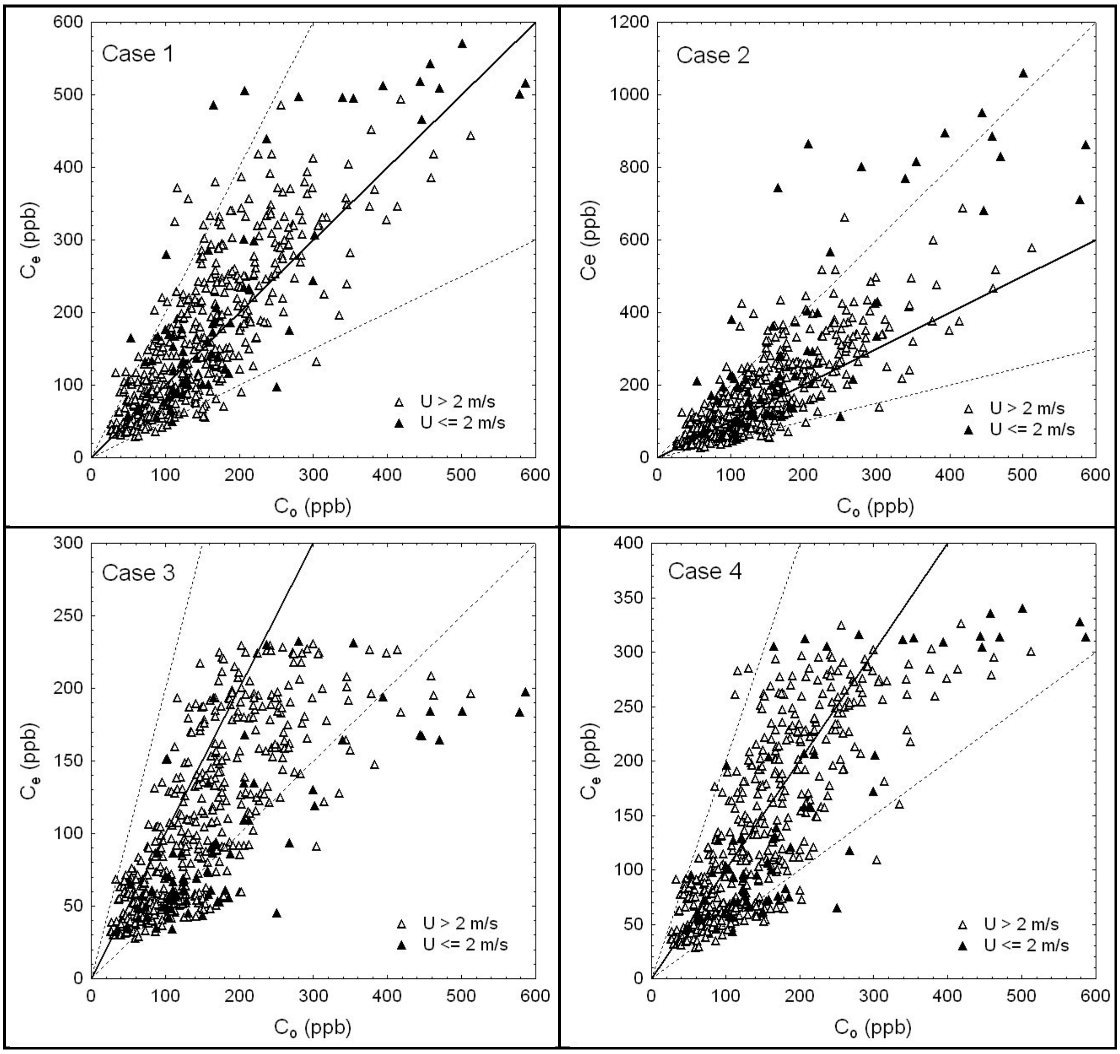

Figure 4. Scatter plots of estimated (C_e) and observed (C_o) concentrations for Cases 1, 2, 3 and 4.

Table 1. Statistical measures calculated for hourly NO_x concentrations.

	Mean (ppb)	Sigma (ppb)	Bias (ppb)	NMSE	Corr	FA2	FB	FBfn	FBfp
All data (N = 516)									
Obs.	154.78	90.34	---	---	---	---	---	---	---
Case 1	173.87	114.10	-19.08	0.17	0.820	0.921	-0.116	0.094	0.211
Case 2	198.85	158.31	-44.07	0.39	0.808	0.860	-0.249	0.069	0.318
Case 3	106.43	58.46	48.36	0.38	0.728	0.793	0.370	0.399	0.029
Case 4	140.01	83.80	14.77	0.16	0.789	0.905	0.100	0.201	0.101
Block $U \leq 2m\ s^{-1}$ (N = 65)									
Obs.	193.22	129.76	---	---	---	---	---	---	---
Case 1	223.85	159.26	-30.64	0.19	0.843	0.908	-0.147	0.077	0.224
Case 2	318.52	280.18	-125.30	0.81	0.844	0.723	-0.490	0.033	0.522
Case 3	97.34	56.30	95.88	0.96	0.766	0.523	0.660	0.669	0.009
Case 4	147.27	97.28	45.95	0.26	0.831	0.862	0.270	0.325	0.055
Block $U > 2m\ s^{-1}$ (N =451)									
Obs.	149.24	81.65	---	---	---	---	---	---	---
Case 1	166.66	104.05	-17.42	0.16	0.806	0.922	-0.110	0.098	0.208
Case 2	181.60	122.47	-32.36	0.25	0.804	0.880	-0.196	0.077	0.273
Case 3	107.74	58.65	41.51	0.28	0.762	0.831	0.323	0.355	0.032
Case 4	138.96	81.62	10.28	0.14	0.791	0.911	0.071	0.180	0.108

CONCLUSIONS

This paper presents an evaluation of air pollutant concentrations (C) inside a street canyon estimated using four different schemes to introduce traffic-produced turbulence (TPT)(= bV^2) in the expression C= [E $(aU^2 + bV^2)^{-1/2}$ W^{-1} + C_b]. Seven months of hourly NO_x concentrations have been estimated in an asymmetric street canyon in Buenos Aires city using meteorological data registered at the domestic airport (located 3.5 km from the site). Urban background (C_b) concentrations have been estimated using DAUMOD urban model.

The four parameterisations of TPT considered in calculations include: the theoretical formulation of (bV^2) introduced by Di Sabatino, S. et al. (2003) applied following the schemes given in Kastner-Klein, P. et al. (2003) (Case 1) and in Solazzo, E. et al. (2008) (Case 2); the semi-empirical approach incorporated in the Danish Operational Street Model (Berkowicz, R. et al., 1997) (Case 3); and a proposed empirical function of *b* with traffic density, derived from four full-scale street canyon data sets (Case 4).

The statistical evaluation of the four schemes is done comparing hourly NO_x concentrations estimated for leeward conditions with observations in a street canyon of Córdoba Ave. in Buenos Aires city. Statistical measures reveal that the performance of the four parameterisations is satisfactory. Results of the four parameterisations show greater errors for light wind speeds ($U \leq 2$ m s^{-1}). The theoretical formulation introduced by Di Sabatino, S. et al. (2003) applied according to Kastner-Klein, P. et al. (2003) (Case 1) and the empirical proposed expression of *b* [equation (7)] (Case 4) show lower errors and higher fraction of modelled values between a factor 2 of observations.

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REFERENCES

Berkowicz, R., O. Hertel, S.E. Larsen, N.N. Sorensen and M. Nielsen., 1997: Modelling traffic pollution in streets. Ministry of Environment and Energy, NERI, 55pp.

Berkowicz, R., M. Ketzel, G. Vachon, P. Louka, J. M. Rosant, P.J. Mestayer and J.M. Sini, 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*, **2**, 311-324.

Chang, J.C. and S.R. Hanna, 2004: Air quality model performance evaluation, *Meteorology and Atmospheric Physics*, **87**, 167-196.

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

GCBA, 2006: *Informes sobre Índice de Tránsito*. Gobierno de la Ciudad de Buenos Aires. Buenos Aires. (in Spanish).

GCBA-ACOM, 2006: *Mapa Estratégico de Ruido-Ciudad Autónoma de Buenos Aires* (Strategic Noise Map-City of Buenos Aires), Gobierno de la Ciudad Autónoma de Buenos Aires y Asociación Civil Oir Mejor (in Spanish).

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

Kastner-Klein P., R. Berkowicz and E. Fedorovich, 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 Conf. on Urban Air Quality, Loutraki, Greece, Inst. of Physics, London, CD-Rom, Paper RAQ.3.3.

Kastner-Klein, P., E. Fedorovich, M. Ketzel, R. Berkowicz and R. Britter, 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*, **3**, 145-172.

Kondo H. and T. Tomizuka, 2009: A numerical experiment of roadside diffusion under traffic-produced flow and turbulence. *Atmospheric Environment*, **43**, 4137-4147.

Mazzeo, N.A. and L.E. Venegas, 2003: Carbon monoxide and nitrogen oxides emission inventory for Buenos Aires City (Argentina), In: Sokhi R.S. and Brechler, J. (eds), Proceedings 4th International Conference on Urban Air Quality, Measurement, Modelling and Management, University of Hertfordshire, UK. 159-162

Mazzeo, N.A. and L.E. Venegas, 2010: Development and application of a methodology for designing a multi-objective and multi-pollutant air quality monitoring network for urban areas. In: A. Kumar (ed.) Air Quality. Sciyo, Rijeka, Croatia, 23-47.

Mazzeo, N.A.and L.E.Venegas, 2011: Study of natural and traffic-producing turbulences analysing full-scale data from four street canyons. *International Journal of Environment and Pollution*, in press.

Solazzo, E., S. Vardoulakis, X. Cai. 2007: Evaluation of traffic-producing turbulence schemes within Operational Street Pollution Models using roadside measurements, *Atmospheric Environment*, **41,** 5357-5370.

Solazzo, E., X. Cai and S. Vardoulakis, 2008: Modelling wind flow and vehicle-induced turbulence in urban streets. *Atmospheric Environment*, **42**, 4918-4931.

Vachon, G., P. Louka, J.M. Rosant, P.G. Mestayer and J.F. Sini, 2002: Measurements of traffic-induced turbulence within a street canyon during the Nantes´99 experiment, *Journal of Water Air& Soil Pollution: Focus*, **2**,127-140.

Venegas, L.E., N.A. Mazzeo and A.L. Pineda Rojas, 2011: Evaluation of an emission inventory and air pollution in the Metropolitan Area of Buenos Aires. In: D. Popovic (ed.) Air Quality Modelling and Applications, InTech, 261-288.

Venegas, L.E. and N.A. Mazzeo, 2011: Traffic pollution modelling in a complex urban street. *International Journal of Environment and Pollution*, in press.