A STREET CANYON MODEL FOR THE SCREENING OF POLLUTANT ACCUMULATION AT PEDESTRIAN LEVEL, APPLICATION TO SEVERAL EUROPEAN CITIES

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Abstract: a simple box model has been developed in order to determine pollutant concentrations in excess in street canyon. It is based on the balance between emission and exchange at roof level. The turbulences produced by the traffic and the wind speed at roof level are taken into account. Several data sets have been used to determine some model parameters and to evaluate the model performances. Comparison with pedestrian measured values is shown and discussed

Key words: *Street canyon, model, NOx*

1. INTRODUCTION

Pollutant concentrations observed at kerbside into under-ventilated streets may be several time higher that the value observed at roof level, which represents the urban background pollution concentration. To calculate the pollutant in excess, several microscale dispersion models have been developed with different levels of complexity: empirical or statistical, box, Gaussian, CFD (see Vardoulakis S. et al 2003). At low wind speeds, the ventilation of the street decreases and the pollutant accumulation is stronger. The street ventilation tends to be controlled by the vertical turbulent diffusion and by the mixing at roof level. Under such circumstances and for regulatory purposes, the utilisation of a box model is a good compromise between more sophisticated street canyon models (as OSPM, ADMS, MIMO…) and empirical or statistical approaches. More, the box model is based on the idea of a well mixed volume, so it is easy to take into account other pollutant transformation processes as chemistry or particle agglomeration. So the aim of this work is to develop a simple box model in order to calculate the pollutant in excess inside street canyons. With this model, the mixing at roof level is supposed to be driven by a characteristic time τ which is a function of the traffic Nv and the wind speed Uwind at roof level.

Two research projects have been realized on street pollution modelisation, TRAPOS dealing with turbulence and pollution induced by traffic (TRAPOS, 2001) and Street Emission Ceiling (SEC) which has analysed the pollutant in excess in several European cities (Moussiopoulos, 2004, 2005). They provided time series of observations that are useful for model validation. In the present work, some TRAPOS NOx data have used to determine the function $\tau = f(N_{trafic}, U_{wind})$. Afterward the box model has been applied to calculate the NOx concentrations inside three other streets of European cities, the same which have been already analysed during the SEC project. Comparison with pedestrian measured values is shown and discussed.

2. MODEL DESCRIPTION

At moderate and high wind speed, the pollutant exchange between the street and the urban canopy is mainly controlled by a vortex developed inside the street canyon (Berkowitcz, 1997; Rafailidis, 1997). However, at low wind speed ($<1ms^{-1}$), the flow pattern with a vortex is difficult to accept since the wind speed energy may be too weak to drive a vortex (Coppalle, 1999). The street ventilation tends to be controlled by the vertical turbulent diffusion and the mixing at roof level.

In a box model, it is assumed pollutants are well mixed inside the street. Without gas or particle transformations, the main flux which is taken into account is located at roof level and it controls the air quality inside the street. Pollutant concentration is given by the balance between the emissions $E(\mu g s^{-1} m^{-3})$ and the previous flux,

$$\frac{dC(t)}{dt} = -\frac{(C(t) - C,bcg)}{\tau} + Ec(t) \quad with \quad Ec(t) = eC(g/km)10^{-3} N_{trafic}(veh/s)/(H\ W) \tag{1}$$

where τ is the characteristic time scale of the exchanges at roof level. Under the steady state approximation (Palmgren, 1996), the above relation becomes

$$(C(t) - C,bcg) = \tau E_C(t) \tag{2}$$

H being the height of the street and W the width.

The steady state assumption is valid because the characteristic time scale of exchange is about one minute and it is lesser than the characteristic time of emission within the street, about 15 minutes at rush hours. So transfer at roof level is much faster than the traffic emission variations.

In his work, Soulhac (1998) proposed that τ can be given by

$$\frac{1}{\tau} = \frac{\sigma_w}{\sqrt{2\Pi} H} \tag{3}$$

where σ_w is the variance of the fluctuations of the vertical wind speed at roof level. We have assumed it is given by the some of two terms $\sigma_w^2 = \sigma_{w,t}^2 + \sigma_{w,U}^2$ with $\sigma_{w,t}^2 = a1*N_{trafic}$ representing the turbulence produced by the traffic and $\sigma_{w,U}^2 = a2\ U_{wind}^2$ representing the initial turbulence existing at roof level added to the one produced by the flow itself inside the street. *a1* and *a2* are empirical constants that have to be determined. The proposed parameterisation is justified by several arguments. As explain in the TRAPOS report (Berkowicz, 2004), the proportionality between $\sigma_{w,t}^2$ and N_{trafic} is possible at low traffic density, for which there is no interaction between wakes of each vehicle. Otherwise $\sigma_{w,t}^2$ should be proportional to N_{trafic}^{α}, where α is less than one. This issue is important and the relationship between traffic and the induced turbulence is not well established as shown by Solazzoa (Solazzoa, 2007). In the present work and for simplicity, it has been assumed α=1. The relation $\sigma_{w,U}^2 = a2\ U_{wind}^2$ is well known and often used in the surface layer of atmospheric boundary layer. However the coefficient a2 takes a different value at roof level over urban areas.

3. OPTIMISATION OF THE MODEL PARAMETERS

The parameters *a1* and *a2* are determined by a least square fitting minimisation of the error function $\Im(a1, a2) = \sum (C^{mod} - C^{obs})^2$. The procedure has been applied on NO_x long time series observed in Jagtev, Berlin (hourly concentrations observed in 1995, TRAPOS, 2001) and in Rouen (Coppalle, 1999; 15 mn averaged concentrations observed during one month in winter).

The street dimensions and the daily traffic within the streets are given in Table 1. The sizes and the traffic of Berlin and Jagtev streets are comparable, the streets are large with high traffic loads. The street in Rouen is not so large, the traffic is on a single lane but it is so intense that it gives often strong pollutant accumulations at kerb-sides.

The optimised values of *a1* and *a2* coefficients are also presented in Table 1. They have been obtained taking a traffic average emission rate e_{NOx} equal to 1.4 (gKm^{-1}) for the three cases. In Jagtev and Berlin streets, the heavy duty vehicle traffic is important, and the previous e_{NOx} value can be representative of the emission averaged over light and heavy vehicles. This may be not the case for the Rouen street, since heavy duty vehicle traffic is very low. However, without knowledge of the exact traffic composition in the Rouen street, we have decided to keep the same value as for Jagtev and Berlin.

Table 1. Main characteristics of the streets chosen for the model development, also shown the coefficients a1 and a2, optimised from the NOx data of each site.

	Berlin (Shildhornstrasse) 95 Working days	Jagtev 95 Working days	Rouen. Jan.-Feb in 1997
Street width (m) Height(m)	20 26	25 18	10 15
Traffic load(Vh/j)	45000	22000	8080
a1 =	0.112	0.190	0.246
a2 =	0.0374	0.0388	0.464

The comparison between calculated and observed values is presented on figure 1, which shows the error distribution. The scatter plots for Rouen and Jagtev are similar and present the same pattern. It is clear that the simple model results are better for low wind speed (U_{wind}<$2ms^{-1}$). One can see the shape of error distribution diagrams is symmetrical in relation to the x axis, suggesting there are no particular trend towards overestimation or underestimation. However, the tails of the distribution do not go to zero value, there is a small number of strong errors in the predicted values. This will be a restriction for the model utilisation to predict extreme events, as percentiles 95 or 98.

Another way to assess the model reliability is to use statistical indices, as suggested in the so-called 'Model Evaluation Kit' (Olesen, 1994). Some of them have been calculated:

The Fractional bias
$$FB = \frac{(\overline{NOx}^{mod} - \overline{NOx}^{obs})}{(\overline{NOx}^{mod} + \overline{NOx}^{obs})/2}$$

The normalised mean square error
$$NMSE = \frac{\overline{(NOx^{mod} - NOx^{obs})^2}}{\overline{NOx}^{mod}\,\overline{NOx}^{obs})}$$

The correlation
$$COR = \frac{\overline{(NOx^{mod} - \overline{NOx}^{mod})(NOx^{obs} - \overline{NOx}^{obs})}}{\overline{\sigma}^{mod}\,\overline{\sigma}^{obs})}$$

The Table 2 gives the calculated statistical index values for the three streets.

Table 2. Statistical indices calculated with data set for each site.

Berlin Working days	Jagtev 95 Working days	Rouen. Jan.-Feb in 1997
FB= -1.48 E-02 NMSE= 0.245 COR= 0.740	FB= -4.68 E-03 NMSE= 0.239 COR= 0.829	FB= -1.47E-02 NMSE= 0.117 COR= 0.898

The statistical index values reported in table 2 show model performances which are very similar to those obtained in other works, as for example in the SEC project (Moussiopoulos, 2004, 2005). This is encouraging for the used of the box model approach, mainly under low wind speed conditions. The present results show: -1 the relationship $\sigma_w^2 = a1*N_{trafic} + a2\ U_{wind}^2$ gives a good agreement between predicted and calculated NOx values, -2 the turbulence produced by the traffic (TPT) must be taken into account in street canyons. For example, the PTP contribution in σ_w^2 value is about 50% for the present results.

The emission rate e(gkm^{-1}) is not well know in the present calculations. Without an accurate knowledge of the apportionment between trucks and light vehicles, or between diesel and gazoline cars, it is not possible to calculate the exact value of the emission rate e. So we decided to use a single value e=1.5 gkm^{-1} for all site. This is a working assumption, and since the concentration within the street is proportional to the emission rate value, this uncertainty has direct effects on the $a1$ and $a2$ optimised values.

The previous comparisons between calculated and observed values must not be viewed as a complete validation of the box model since the statistical indices are calculated on the same data as those used to determine the model parameters $a1$ and $a2$. More complete estimation of the model performances will be carried out below with its application to other cases.

4. APPLICATION TO SEVERAL CASES IN EUROPE

The model has been applied to calculate the NOx concentrations inside three streets, Marylebone in London, Horsngatan in Stockholm and Franfurter in Berlin. Thanks to the SEC project (Moussiopoulos 2005), one year data for NOx concentration (pedestrian level and background values) and meteorological conditions (at roof level) are available. Also provided are daily mean traffic and emission. As seen in Table 1, the A2 value does not change strongly between Berlin, Jagtev and Rouen cities. The averaged value is <A2>=0,0408. This is not the case for A1 coefficient which roughly decreases with increasing street sizes. The turbulence induced by the traffic is mainly produced in the wake of each vehicle, but this turbulence must be averaged over the street section S=W*H for using with the present box model approach. So as a first approximation, A1 coefficient is assumed to be inversely proportional S and is given by A1=A1°/S. Applying this relation to the three coefficients A1 given in Table 1, we can calculate averaged value <A1°> and we found value <A1°>=60,25. The above <A1°> and <A2> values have been used in the case of Marylebone, Horsngatan and Franfurter streets. The average daily variation of NOx concentrations have been calculated and they are compared with observations in Figures 2-4.

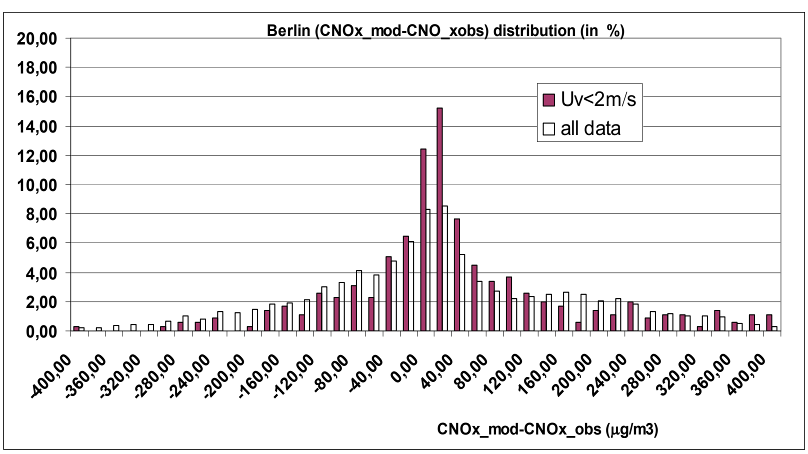

Figure 1. Error distribution, plain symbols for data at low wind speed (<2ms^{-1}), empty symbols for all data (Berlin Shildhornstrasse).

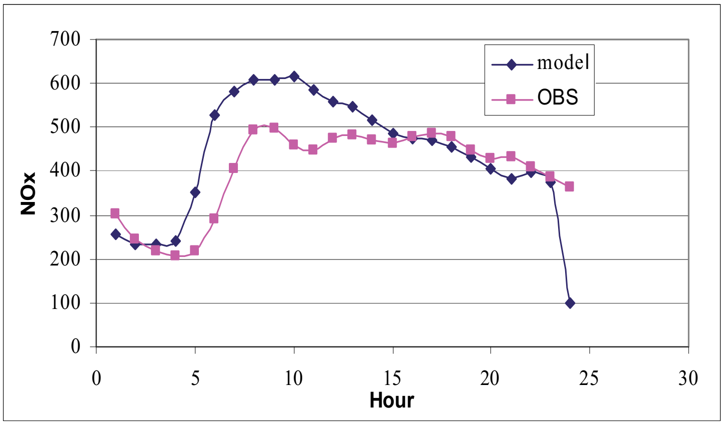

Figure 2. Average daily variation of NO_2 concentrations at street level in Marylebon (London) compared with observations.

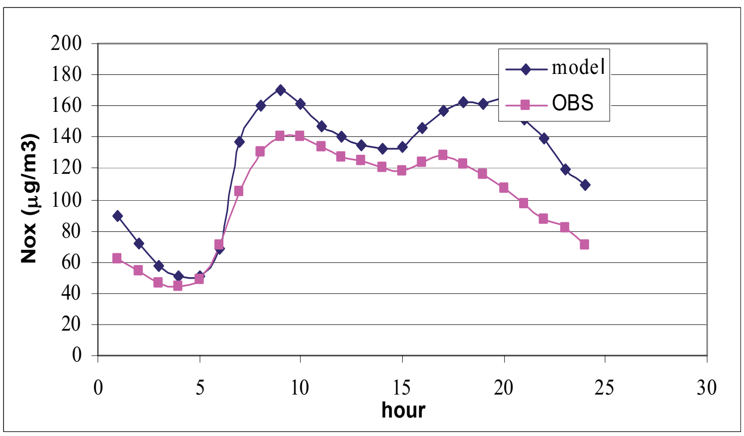

Figure 3. Average daily variation of NO_2 concentrations at street level in Franfurter (Berlin) compared with observations.

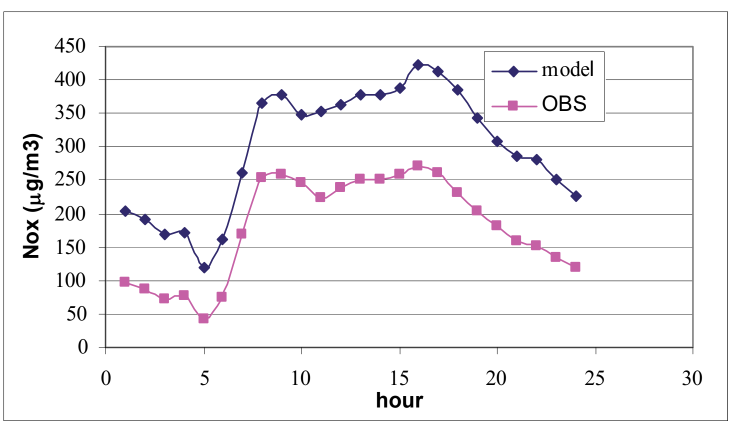

Figure 4. Average daily variation of NO_2 concentrations at street level in Horsngatan (Stockholm) compared with observations.

The agreement for London and Berlin is correct, and lesser for Stockholm. For all cases, there is a model over-prediction. For these cities, evaluations of other street models have been performed in the SEC project, and they are available in the project report (Moussiopoulos, 2005). Comparable agreements and model performances are presented, but the model values are generally under-estimated. The present box model results are encouraging but they can be improved. First, the model coefficient A1 and A2 have been determined using an emission factor equal to

1.4 gkm^{-1} for the three previous cities (Jadkev, Berlin and Rouen). Other estimations of these coefficients are necessary and they have to be performed knowing more accurate emission factors. The turbulence produced by the traffic is taken into account in the present approach, but the relation between this turbulence, represented by $_W$, and the traffic has to be improved. Vehicle speed should be taken into account. Finally, other cases must be analysed in order to determine more accurate values of the model coefficients A1 and A2.

5. CONCLUSION

In this work, a simple box model has been developed in order to determine pollutant concentrations in excess in street canyon. It is based on the balance between emission and exchange at roof level. The last one is given by a characteristic time which is a function of the variance of the vertical wind speed σ_w A simple relation has been used between σ_w and the traffic flow and the wind speed at roof level. This allows taking into account the effect the induced turbulence produced by the traffic and the wind speed. However, two model coefficients must be determined by comparisons with observations. This has been done with three street data sets and then the model has been applied to other cases. The agreement and the model performances are similar to the ones obtained in other work, as for example in the SEC project. However further works are necessary to improve the relationship between σ_w, which represent a value averaged over the street volume, and the production of traffic turbulence.

The present box model is well suited for low wind speed conditions and it must be considered as a screening method for regulatory purposes. One must remember the emission rate of the traffic within the street must be well known. The box model approach makes it possible to calculate chemistry transformation. The next step will be to take into account of the NO/NO_2 conversion inside the street.

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