Adaptation of results from CFD-models and wind-tunnels for practical traffic pollution modelling

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1 Introduction

For air quality assessment and regulatory purposes the estimation of statistical values on an annual basis is normally required. Limit values are formulated in terms of annual mean, 98-percentiles or even 99.8 percentiles (EC, 1999). In the case of street traffic pollution this implies that air quality modelling must be performed taking all the possible combinations of meteorological and traffic conditions into account. For reasons of cost and time efficiency advanced detailed modelling methods like Computational Fluid Dynamics (CFD) calculations and wind tunnel measurements are able to investigate a limited set of meteorological conditions, e.g. 36 different wind directions of incoming flow and one selected wind speed and traffic emission pattern. The modelled concentrations are expressed in terms of a dimensionless parameter c* and the actual concentrations are subsequently calculated assuming simple scaling with wind speed (e.g. 1/u scaling) and emissions.

Although this method works well for higher wind speeds, it is less suited in the case of lower wind speeds typical for urban street-canyons. It is known from several field studies (Schädler et al. 1996, Ketzel et al. 2000) that in urban street canyons the dependence of concentrations on wind speed is much weaker than 1/u. Furthermore, the flow pattern in a street-canyon changes at lower wind speeds. Vortex circulation, usually observed at higher wind speeds, disappears or becomes very intermittent at lower wind speeds. Considering e.g. hourly averages, this results in smaller concentration gradients across the street.

The paper presents an assessment of different scaling approaches for several street-canyon data using the model MISKAM (Eichhorn, 1995) as well as wind tunnel measurements.

2 Scaling approaches

A detailed description of scaling concepts and evaluation of these against laboratory and field data is given in Kastener-Klein et al. (2001). In the following we give the definitions for the different scaling approaches we use in this paper.

For a given urban structure the dimensionless concentration c* can be defined as

$$c^* = \frac{c \cdot u \ \cdot L}{E} = f(\Phi) \qquad (1)$$

where c is the modelled or measured concentration including dimensions, u is the wind speed at a reference point usually the position of meteorological measurements, L is a scaling length usually the width or the height of the street canyon, E is the emission flux per unit length and f(Φ) describes the variation with wind direction.

To overcome some of the above described difficulties arising in connection with using CFD modelling or wind-tunnel results for low wind speed conditions, the former draft of the German Guideline (VDI 1998) recommended, that for roof level wind speeds less than 3 m/s, the 1/u scaling (Eq. 2a) should be replaced by $1/u^{0.35}$ scaling (Eq. 2b),.

$$c = \frac{c^* \cdot E}{L \cdot u} \qquad \text{; for: } u \geq u_1 \text{ ; } u_1 = 3\, m/s \tag{2a}$$

$$c = \frac{c^* \cdot E}{L \cdot u^m} \cdot \frac{u_1^{\ m}}{u_1} \qquad \text{; for: } u < u_1 \text{ ; } m = 0.35 \tag{2b}$$

This ‘VDI-method’ was considered as a first very rough parameterisation of different phenomena that are observed for low wind speeds. However, more recent studies strongly indicate that turbulence created by the traffic flow in the street becomes the dominating dispersion mechanism in the case of low wind speeds and accordingly the main reason for the deviation from the 1/u dependence (Kastner-Klein et al., 2000). Consequently Kastner-Klein et al. (2001) suggested to modify the velocity scaling of concentration by defining a velocity scale u_s that includes the traffic produced turbulence (TPT) σ_{w0}:

$$c = \frac{c^* \cdot E}{L \cdot u_s} \tag{3}$$

$$u_s = \sqrt{u^2 + (a_1 \cdot \sigma_{w0})^2} \qquad \text{; with } a_1 = 15 + 5 \cdot \sin \varphi \tag{4}$$

$$\sigma_{w0} = \sqrt{\sum_i (b_i \cdot N_i \cdot v_i / W)} \tag{5}$$

The parameter a_1 introduced here is an empirical weighting factor for the relative importance of the TPT on the dispersion in the street canyon, which depends on the angle φ between the street and the approaching wind. For a leeward receptor position (φ = 90°) a_1 equals 20 whereas for a windward position (φ = -90°) the value of a_1 is 10. The index *i* describes the type of vehicle, i.e. trucks, cars etc., b is a constant related to the size and shape of the vehicle class, *N* is the number of vehicles per time unit, *v* is the vehicle speed and *W* the width of the street. The estimation of σ_{w0} (Eq. 5) is based on the method implemented in the Operational Street Pollution Model, OSPM (Berkowicz, 2000). Other formulations are presented and discussed in Kastner-Klein et al.(2001). We refer to this method (Eqn. 3-5) in the following as ‘TPT scaling’.

In addition to the previously described scaling method we introduce an averaging of the modelled dimensionless concentrations over a range of wind directions depending on the wind speed.

$$\Delta\Phi = \pm \frac{\sigma_{vc}}{u} \qquad \text{; for } u < 1\, m/s \text{ ; } \quad \sigma_{vc} = 0.5\, m/s \text{ ; } \quad \Delta\Phi \text{ in radiant} \tag{6a}$$

$$\Delta\Phi = \pm 0.5 \qquad \text{; for } u \geq 1\, m/s \tag{6b}$$

This approach simulates the wind meandering and is used in the same way in OSPM. It is applied only in connection with the TPT scaling and we refer to this method as ‘TPT + WDA’.

3 Models and data

The above scaling methods were applied to calculate annual time series of NOx concentrations for the street canyon monitoring stations in Jagtvej, Copenhagen and Göttinger Strasse, Hannover. A detailed description of the datasets is e.g. included in Ketzel et al. (2000). Dimensionless concentrations determined from calculations by the CFD model MISKAM, version 4.2, and wind tunnel measurements at the University of Hamburg were used as input data. In addition the meteorological and concentration measurements at the field locations have been employed in the data analysis.

4 Results and discussion

The average NOx concentration and the slope and linear regression coefficient of the scatter-plots modelled-measured concentration have been estimated for the calculated time series obtained with the different scaling methods and models. Only working days were used and the intercept for the regression was forced to zero. The results are summarised in the tables 1 and 2 for Jagtvej and Göttinger Strasse respective. For comparison the tables contain also the OSPM results for the two cases. The OSPM calculation for Göttinger Strasse contains an empirical correction e.g. lowering of the wind speed for leeward position of the receptor point, which is estimated from the field observations. It is obvious both from the estimated averages and the slopes that the 1/u scaling strongly overestimates the concentrations. Changing the scaling method to ‘VDI’, ‘TPT’ and ‘TPT+WDA’, gradually lowers the overestimation, which is reflected in lower averages and slopes. In almost all cases the correlation increases with changing the scaling method in the described order.

Table 1 Results for Jagtvej, NOx in ppb.

	scaling method				
MISKAM	**1/u**	**VDI**	**TPT**	**TPT+WDA**	**measured**
average NOx	166.4	148.3	117.9	117.4	100.5
slope	1.74	1.46	1.11	1.10	
R^2	0.73	0.83	0.82	0.83	
Wind tunnel	**1/u**	**VDI**	**TPT**	**TPT+WDA**	**measured**
average NOx	118.9	106.7	85.4	85.3	100.5
slope	1.24	1.06	0.81	0.80	
R^2	0.67	0.73	0.76	0.81	
OSPM				**TPT+WDA**	**measured**
average NOx				103.8	100.5
slope				1.01	
R^2				0.86	

Table 2 Results for Göttinger Strasse, NOx in µg/m^3.

	scaling method				
MISKAM	**1/u**	**VDI**	**TPT**	**TPT+WDA**	**measured**
average NOx	634	516	326	324	362
slope	1.81	1.39	0.80	0.80	
R^2	0.42	0.54	0.38	0.49	
Wind tunnel	**1/u**	**VDI**	**TPT**	**TPT+WDA**	**measured**
average NOx	655	534	328	321	362
slope	1.96	1.51	0.85	0.83	
R^2	0.46	0.61	0.61	0.72	
OSPM				**TPT+WDA**	**measured**
average NOx				342	362
slope				0.91	
R^2				0.82	

Although the values in Tables 1 and 2 clearly indicate an improvement of model performance due to the modified scaling methods such information is not sufficient for an assessment of the different scaling methods. To verify the applicability of the scaling methods a more detailed analysis including the dependence on wind direction, wind speed, amount of traffic etc. must be performed. An example of such type of analysis is presented in Figures 1 and 2. The different scaling methods have been applied to MISKAM results for selected wind speeds and the dependence on wind direction has been plotted. The 1/u scaling method is not included in the Figures, since the values in Table 1 and 2 display its bad performance. The VDI scaling method results in an overestimation of concentrations for both selected wind speed ranges. In particular for low wind speeds (Fig. 2) the VDI method also fails in reproducing the less pronounced leeward – windward concentration gradient. The results using the ‘TPT+WDA’ scaling show the best agreement with measured data. Introducing the TPT method brings most of the improvement while the wind direction averaging (WDA) gives fewer changes in the results.

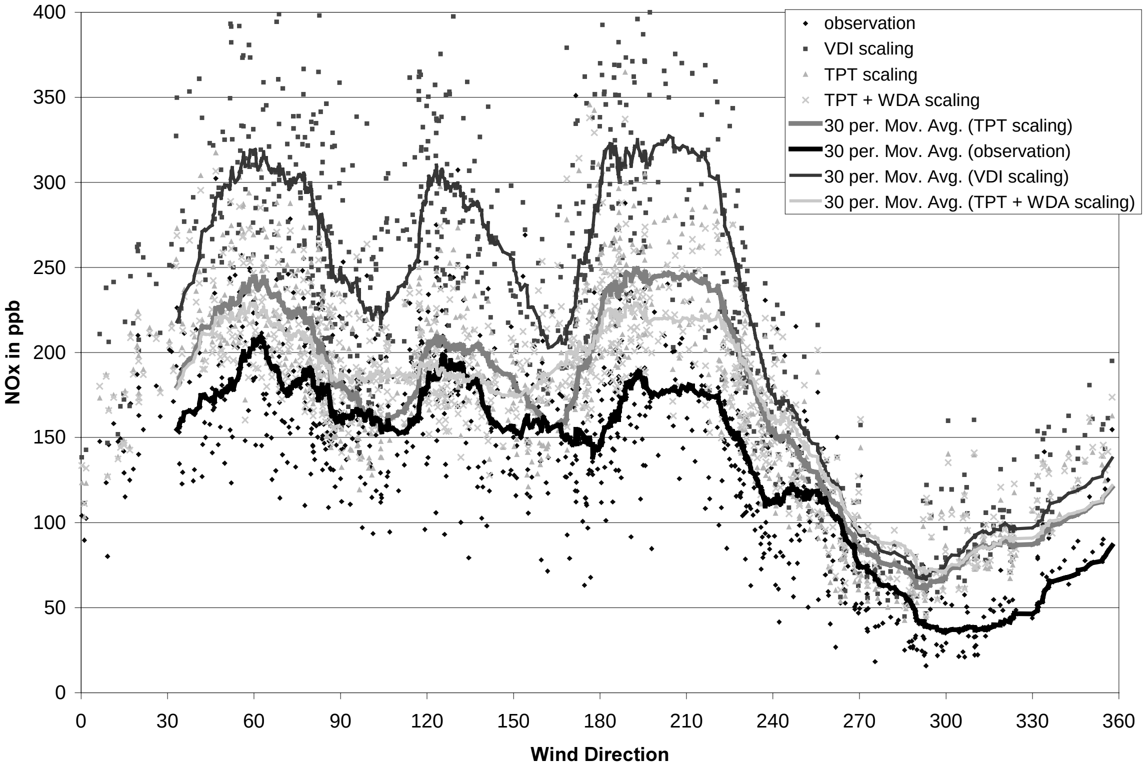

Figure 1 Scaled MISKAM results for Jagtvej. Only day time hours (8h-18h) and wind speeds between 3 m/s and 5 m/s. The lines indicate moving averages (over 30 data points) for the different scaling methods.

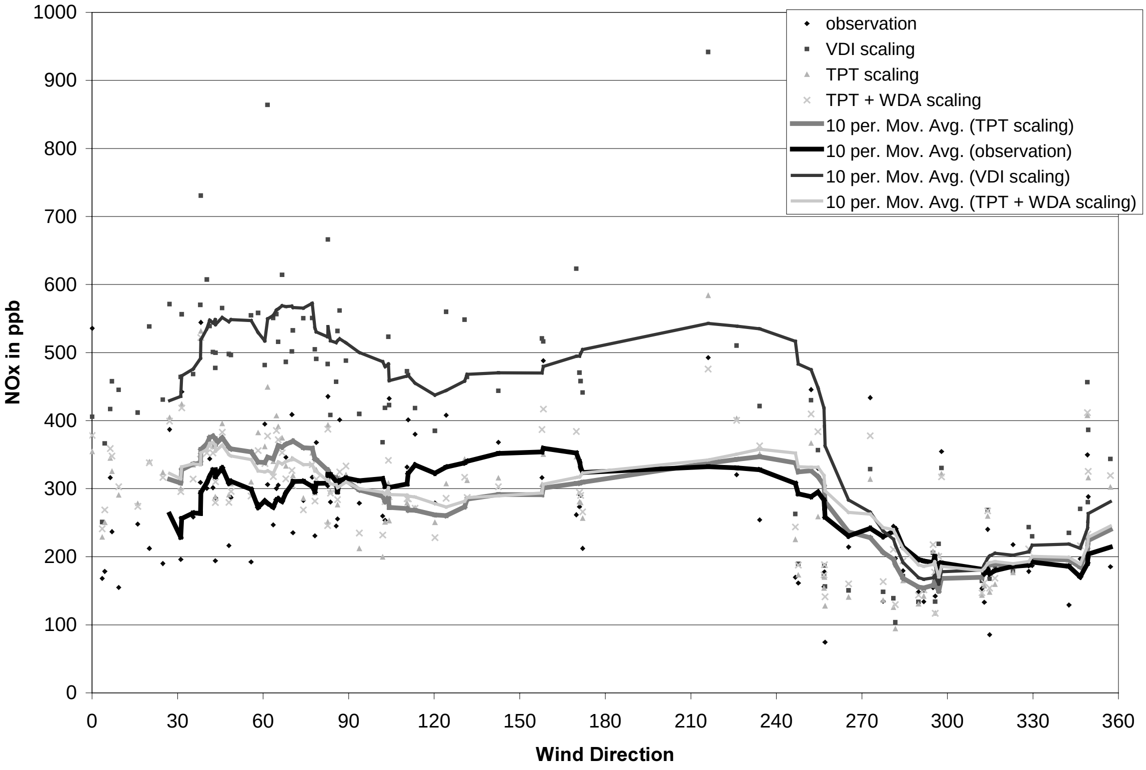

Figure 2 Scaled MISKAM results for Jagtvej. Only day time hours (8h-18h) and wind speeds below 1.5 m/s. The lines indicate moving averages (over 10 data points) for the different scaling methods.

5 Conclusions

Compared to the simple $1/u^{0.35}$ scaling method for concentrations described in VDI (1998), the agreement between modelled and measured concentrations in urban street canyons could be significantly improved by the proposed scaling concept. This concept has been based on a velocity scale that accounts for pollutants dispersion by traffic produced turbulence. A further but less evident refinement of the results could be achieved by introducing a wind direction averaging procedure.

The presented method contains a number of empirical but physically grounded parameters. A first set of parameters has been estimated, but further evaluation with more data sets is necessary before introducing the method into operational scaling

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