Evaluation of scaling concepts for traffic-produced turbulence based on laboratory and full-scale concentration measurements in street canyons

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1. Introduction

The role of traffic-produced flow disturbances in the dispersion of near-road pollutants has been subject of several field, laboratory, and numerical studies carried out during the last years. The traffic-produced turbulence (TPT) plays especially an important role with low wind speeds that are quite typical for urban street canyons. Nevertheless only few of existing urban dispersion models account for TPT effects. An example is the Operational Street Pollution Model (OSPM) described in Berkowicz (2000). Our experiments with OSPM have shown that the incorporated TPT parameterisations are crucial for practical applications. Without TPT parameterisations, the modelled peak concentrations have been significantly overestimated. A similar result has been obtained with a 3-D CFD model if traffic influences on flow dynamics and dispersion were not taken into account (Berkowicz et al., 2001). These findings emphasise the necessity of including TPT parameterisations in urban dispersion models. However, the TPT parameterisation used in OSPM cannot be easily transferred to other models and needs further evaluation. A more general approach to describe the influence of TPT on dispersion in street canyons will be discussed in the present paper.

2. Scaling concepts

In numerical modelling of street canyon pollution, an inverse proportionality between the street level concentration c and a wind speed u measured above roof is commonly assumed. It is argued that in many instances hydrostatic stability effects and traffic-induced turbulence are of minor importance and street canyon ventilation is dominated by mechanical, wind-induced turbulence. For high Reynolds numbers, which are typical for field conditions even with relatively low wind velocities, the parameters relevant to the latter ventilation mechanism can be scaled by a reference wind velocity and accordingly also the street canyon concentrations. Taking into account the specific emission per length, E, and a reference length scale L, the dimensionless concentration c^* is calculated by

$$c^*_{st} = c \cdot u \cdot L / E \, . \tag{1}$$

Validity of Eq. (1) is vitally important for practical applications of microscale numerical and physical modelling. Since the simulations can be limited to one wind velocity, time and costs for air pollution studies can be significantly reduced. Wind-tunnel studies of street canyon dispersion provide evidence for conformity with Eq. (1), but such experiments are usually performed with relatively high wind velocities to ensure Reynolds-number similarity and additional ventilation mechanisms, like the ones due to thermal effects or traffic motions, are not simulated (see e.g. Kastner-Klein., 1999). Field data analyses have often demonstrated that street canyon concentrations are not inversely proportional to wind speed (Schädler et al., 1996 and Ketzel at al., 1999), since particularly with lower wind velocities TPT effects start to play an important role. For regulatory purposes, an empirical method (VDI, 1998) has been proposed to account for the TPT effect. To avoid operationally significant over-predictions it is recommended in *op. cit.* to use $u^{0.35}$ as velocity scale in Eq. (1) for situations with wind velocities smaller than 3 m/s. Ketzel et al. (1999) have shown that this method needs to be improved.

If we assume that turbulent motions related to wind and traffic are mixed inside the canyon, a summation of velocity variances induced by wind and traffic motions seems to provide a more appropriate velocity scale u_s. Based on the assumption that the velocity variances can be taken proportional to the wind velocity u and traffic velocity v respectively, the velocity scale u_s can be constructed as

$$u_s = (a \cdot u^2 + b \cdot v^2)^{1/2} \, . \quad (2)$$

The resulting formula for the normalized concentration is then presented by

$$c^*_{\mathrm{mod}} = c \cdot u_s \cdot L/E = c \cdot L \cdot \sqrt{a \cdot u^2 + b \cdot v^2} \big/ E \, . \quad (3)$$

According to this definition, c^*_{mod} has the assessed value of one. The constant *a* depends on the street geometry and is related to the c^*_{st} - value (Eq. 1) calculated for a particular street, as illustrated by the following analysis: Neglecting of the TPT effect in Eq. (3) yields

$$c \cdot u \cdot L/E = 1\big/\sqrt{a} \, . \quad (4)$$

The left-hand side of Eq. (4) coincides with the definition of c^*_{st} and thus: $c^*_{st} = 1\big/\sqrt{a}$. Typical values of *a* observed in wind tunnel experiments are of the order of $a = 2E-4$ (see Tab. 3.1) which corresponds to the value $c^*_{st} \approx 70$ found for the studied street canyon configuration without moving traffic.

The constant *b* associated with the traffic-related velocity variances $\sigma_t = \sqrt{b} \cdot v$ must account for the σ_t-dependence on traffic density, vehicle drag coefficients, and rate of heavy traffic. An analysis based on the turbulence production-dissipation balance has shown that diverse parameterizations can be proposed for σ_t in relation to different flow regimes associated with variable traffic densities. This analysis has been elaborated in a TPT working group of the TMR network TRAPOS (Berkowicz, 2001) and is presently prepared for publication. The two main parameterization approaches are the OSPM one (Berkowicz, 2000) that provides:

$$\sigma_t = c_1 \cdot \left(\sum\nolimits_i C_{D,i} \cdot n_i \cdot A_i / S \right)^{1/2} \cdot v \, , \quad (5)$$

and the scaling concept PMC which has been derived from a wind tunnel similarity criterion (Kastner-Klein, 2000):

$$\sigma_t = c_2 \cdot \left(\sum\nolimits_i C_{D,i} \cdot n_i \cdot A_i / S \right)^{1/3} \cdot v \, . \quad (6)$$

The index *i* describes the vehicle type classification, *i.e.*, passenger cars, vans, trucks, etc., C_D is the vehicle drag coefficient, *n* is the number of vehicles per unit street length, *A* is the average vehicle frontal area and *S* is the street width. The constants c_1 or c_2 ideally should be universal (independent of traffic parameters and street geometry). The OSPM method complies with situations of relatively sparse traffic when a formation of separate wakes behind each vehicle is anticipated, meanwhile the PMC concept corresponds to situations with higher traffic densities and interacting wakes.

Below, the revised method of concentration scaling will be verified against experimental data. First, a analysis of wind-tunnel results will be considered (see section 3). An implementation of the developed parameterizations to an analysis of concentration data measured in two streets in the German cities Hannover and Berlin will be presented in section 4.

Tab. 3.1: Results of a wind tunnel data analysis

plate thickness d in mm	**traffic density n in 1/m**	**linear regression coefficients**		
		b	**a**	**R^2**
3	5	3.57E-05	2.01E-04	0.974
3	10	5.77E-05	2.24E-04	0.994
3	20	7.97E-05	1.99E-04	0.987

3. Wind-tunnel results

In a wind tunnel study of street canyon dispersion the influence of traffic motions has been simulated by small metal plates, which were moving on two belts along the street. More details concerning the experimental set-up are given in Kastner - Klein (1999) and Kastner-Klein et al. (2000). Variations of wind velocity, vehicle speed and traffic density have been performed. For a wind direction perpendicular to the street the TPT influence on street level concentrations is analysed following the concept described above. Linearization of Eq. (3) and reformulation in terms of c_{st}^{*} yields

$$\left(c_{st}^{*}\right)^{-2} = a + b \cdot (v/u)^{2} . \qquad (7)$$

The wind-tunnel data are well described by this relation (left plot in Fig. 3.1). The parameters *a* and *b* evaluated for three traffic densities are given in Tab. 3.1. As expected, the parameter *a* is approximately constant since the building configuration was fixed during the experiments. The variation of the parameter *b* with traffic density can be approximated as $b = 1.44E - 5 \cdot n^{2/3}$ which matches the relation $b \propto n^{2/3}$ that follows from the PMC concept (Eq. 6). The right plot of Fig. 3.1 represents the almost perfect correlation of concentration data with the velocity scale u_s calculated according to Eq. (2) with $b = 1.44E - 5 \cdot n^{2/3}$ and $\overline{a} = 2.08E - 4$ (average value).

4. Comparison with full-scale data

The wind-velocity dependence of concentration values (black symbols) measured in two street canyons in Hannover and Berlin (normalized by the emission rate and the street width *S*) is shown in Fig. 4.1. Only leeward side concentrations are taken into consideration. Obviously, the data start to deviate from the high wind speed approximation defined by Eq. (1), dashed black line, at wind velocities of approximately 5 m/s. The trend of the measured data is well described by the OSPM version accounting for the TPT effects (gray symbols). The gray lines represent a straightforward transformation of the wind-tunnel results to the full-scale situations. The parameter *a* in this case has been determined from the best fit to the full-scale data for wind speeds higher than 5m/s. The values of the parameter *b* correspond to the wind tunnel experiments with $n = 5/\mathrm{m}$ (gray solid line) and $n = 20/\mathrm{m}$ (gray dashed line). For the vehicle speed, constant values of $v = 50$ km/h in the case of the lower traffic density, and $v = 40$ km/h in the case of the higher one, have been taken. This simple transformation of the wind tunnel results agrees well with the full-scale data. It can be concluded that the modified scaling method leads to a significant improvement of the concentration prediction for lower wind speeds compared to the standard normalization. However, the large scatter of the full-scale data does not allow a differentiation between the performance of the OSPM or PMC method.

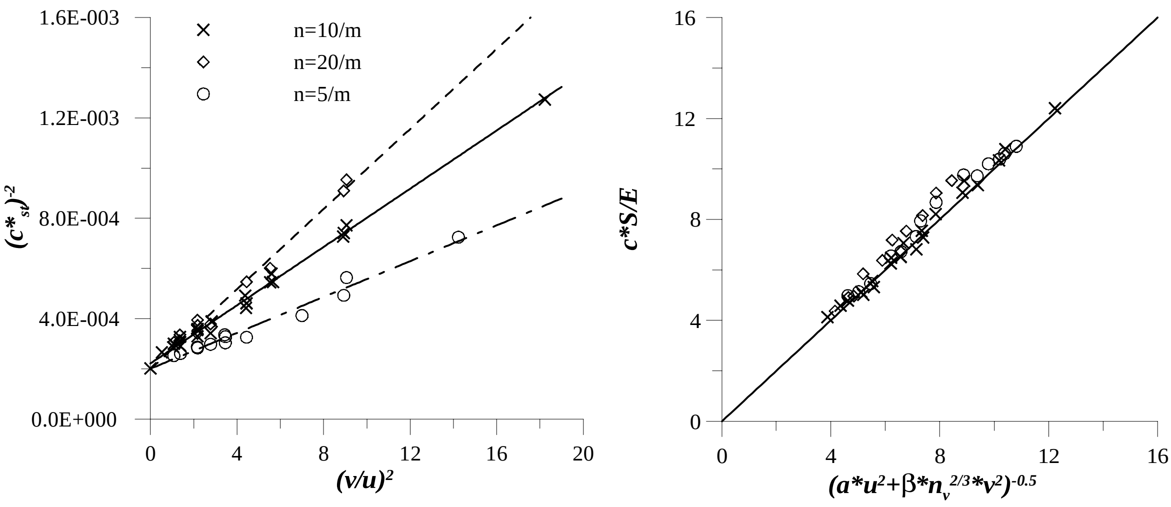

Fig. 3.1: Testing of scaling concept against wind tunnel concentration measurements in idealized street canyons (Kastner-Klein, 1999).

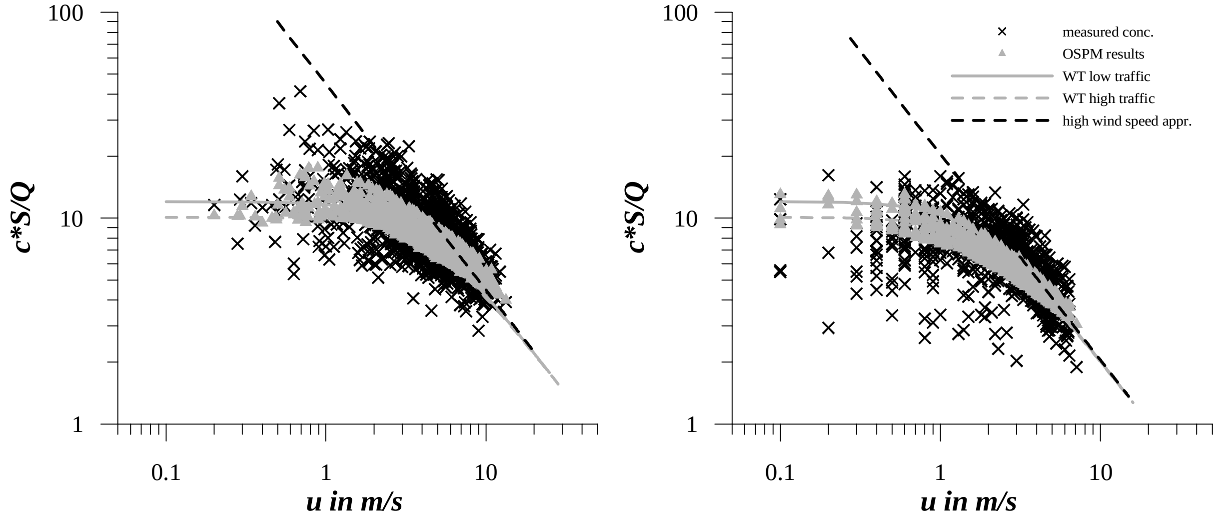

Fig. 4.1: Comparison of concentrations measured in Göttingerstrasse, Hannover (left plot) and Schildhornstrasse, Berlin (right plot) with OSPM results, the high wind speed approximation and two curves corresponding to results from wind tunnel studies with different traffic density.

5. Summary

Based on the turbulence production-dissipation balance for TPT, a scaling concept for concentration data has been developed and evaluated against field and wind tunnel data. The proposed scaling is in good agreement with wind tunnel results. It describes concentration distributions measured in real urban conditions more realistically than the presently employed standard method, which assumes the concentration to be inversely proportional to a reference wind velocity.

6. References

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