EXPERIMENTAL AND NUMERICAL VERIFICATION OF SIMILARITY CONCEPT FOR DISPERSION OF CAR EXHAUST GASES IN URBAN STREET CANYONS

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Abstract. In urban conditions, car exhaust gases are often emitted inside poorly ventilated street canyons. One may suppose however that moving cars can themselves produce a certain ventilation effect in addition to natural air motions. Such ventilation mechanism is not sufficiently studied so far. A similarity criterion relating the vehicle- and wind-induced components of turbulent motion in an urban street canyon was proposed in 1982 by E. J. Plate for wind tunnel modelling purposes. The present study aims at further evaluation of the criterion and its applicability for a variety of wind and traffic conditions. This is accomplished by joint analyses of data from numerical simulations and wind tunnel measurements.

Key words: traffic emissions, street canyon, wind tunnel, numerical, modelling, similarity

1. Introduction

Car exhaust gases considerably contribute to the atmospheric pollution in urban areas. In many cases, these gases are emitted under conditions of poor ventilation in narrow street canyons of big cities. One may assume still that moving vehicles can themselves produce a certain ventilation effect in a street canyon.

The generation of secondary air motions by traffic was investigated in a number of *in situ* experiments (Eskridge and Hunt 1979, Eskridge and Rao 1983, Delaunay and Houseaux 1997), and also in numerical (Hertel and Berkowicz 1989, Stern and Yamartino 1998) and wind tunnel (Eskridge *et al*. 1979, Eskridge and Thompson 1982, Brilon *et al*. 1987, and Kastner-Klein *et al*. 1998) model studies. In the literature, the air motions produced by traffic are usually associated with the so-called vehicle-induced turbulence. However, in many instances the organised transport of pollutant by vehicle-induced mean air motion should be also taken into account (Eskridge and Hunt 1979, Delaunay and Houseaux 1997).

Diffusion and dispersion of gaseous pollutants in street canyons take place under the joint influence of natural and vehicle-induced air motions. The relations and interactions between these transport mechanisms are not sufficiently studied so far. In particular, there are very few field measurements that allow a separate quantification of natural and vehicle-induced components of pollutant transport. In this situation, wind tunnel and numerical modelling may be useful approaches towards understanding basic features of the combined transport phenomena.

A similarity criterion relating the wind- and vehicle-induced components of turbulent motion in an urban street canyon was proposed by Plate (1982). This criterion was originally formulated as criterion for the wind tunnel modelling of turbulent diffusion in a street canyon with traffic and will be hereafter referred to as PMC.

In the present paper, we try to interpret the PMC in a more general sense and verify it as similarity parameter for gas dispersion in a street canyon under the joint effect of natural ventilation and vehicle-induced turbulent air motions.

2. Similarity Concept

Plate (1982) suggested that the *traffic-to-wind turbulence kinetic energy (TKE) production ratio is a similarity criterion for the wind tunnel modelling of diffusion of car-exhaust gases in a street canyon with traffic*.

Based on the above idea, Kastner-Klein *et al*. (1998) expressed the wind-related TKE production per unit canyon volume as $G_w \propto u^3 / H$, where H is the canyon depth scale and u is the reference velocity of the external wind flow. The TKE production due to vehicle motions was estimated as $G_v \propto C_{dv} \cdot A_v \cdot v^3 \cdot n_v /(B \cdot H)$, where C_{dv} is the aerodynamic drag coefficient and A_v is the frontal area of an individual vehicle, v is the traffic velocity, n_v is the amount of vehicles per unit length of the canyon (traffic density), and B is the canyon width scale. Thus, the traffic-to-wind TKE production ratio is expressed as $P_t = G_v / G_w = n_p (v^3 / u^3)$, where $n_p = C_{dv} \cdot A_v \cdot n_v / B$ is the dimensionless traffic density.

The concept underlying the PMC reads that dimensionless values of pollutant concentration $c_* = c \cdot U \cdot L / E$ in the street canyon and in its wind tunnel analogue should be identical when P_t is the same in the model and in the prototype. In the expression for c_*, c is the actual concentration in ppm, U and L are characteristic velocity and length scales of the flow, respectively, and E $[L^2 \cdot T^{-1}]$ is the source strength per unit length. The car emissions are considered as line sources.

The PMC indirectly presumes that the turbulent component of the vehicle-induced pollutant transport ultimately dominates its organised component by car-induced mean air motion. Wind tunnel concentration measurements presented in Figure 1 support earlier findings of Kastner-Klein *et al*. (1998) that turbulent transport is indeed the main mechanism of pollutant dispersion in a street canyon with two-way traffic moving in opposite directions.

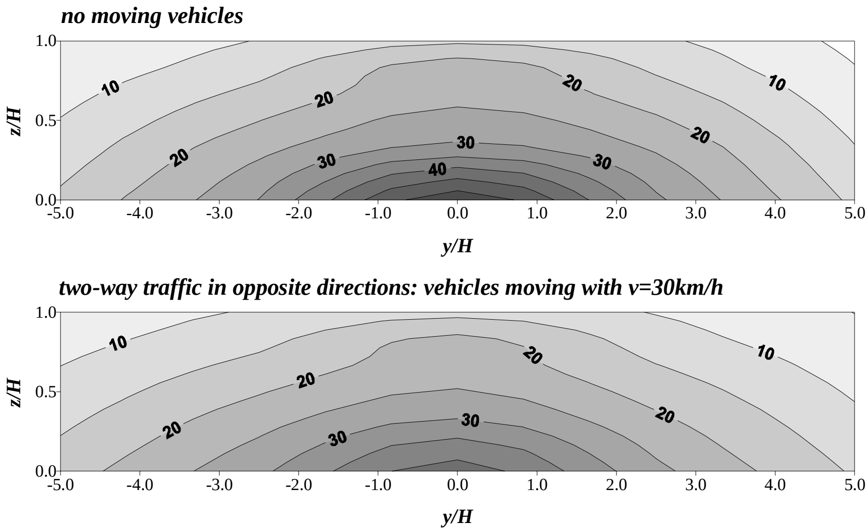

Figure 1. Values of c_* at the lee wall of the upwind building in the wind tunnel model of a street canyon without traffic (upper plot) and with two-way traffic in opposite directions (lower plot). For simulation details see section 3 and Kastner-Klein *et al*. (1998).

The PMC concept also implies interaction between the wind-induced and traffic-induced turbulent air motions inside the canyon. Thus, locally generated small-scale vehicle-induced turbulence is assumed to be transported within the canyon volume by larger-scale wind-induced turbulent motions. The PMC is not valid when external wind vanishes.

The production ratio P_t allows another interpretation in terms of turbulence scale analysis. Following the traditional line of such analysis (Tennekes and Lumley 1972) one may take the TKE production by wind, G_w, proportional to $u_w^{\,3}/l_w$, where u_w and l_w are, respectively, the velocity and length scales of wind-induced turbulent motion in the canyon. For the contribution to the TKE production by moving vehicles, G_v, the scaling considerations provide $G_v \propto (v^3/l_v)(V_v/V_c) \propto (v^3/l_v)(nl_v^{\,3}/l_c^{\,2}l) \propto n_v v^3 (l_v/l_c)^2$, where V_v is the total volume of air disturbed by vehicles, V_c is the in-canyon air volume, n is the amount of vehicles in the canyon, l is the canyon length, (therefore $n_v = n/l$), and l_v, l_c are, respectively, the length scales of the vehicle-induced turbulent motion and of the canyon cross-section. We thus refer the TKE production by all vehicles in the street canyon to the volume of the canyon.

When wind is oriented approximately perpendicular to the canyon, one may assume that $u_w \propto u$ and $l_w \propto l_c \propto H$. This provides $P_t = G_v / G_w = n_g (v^3 / u^3)$, where $n_g = n_v l_v^2 / H$ is another estimate of the dimensionless traffic density. The above expression for P_t yields the same dependence on traffic and wind parameters as the one obtained by Kastner-Klein et al. (1998) following the idea of Plate (1982).

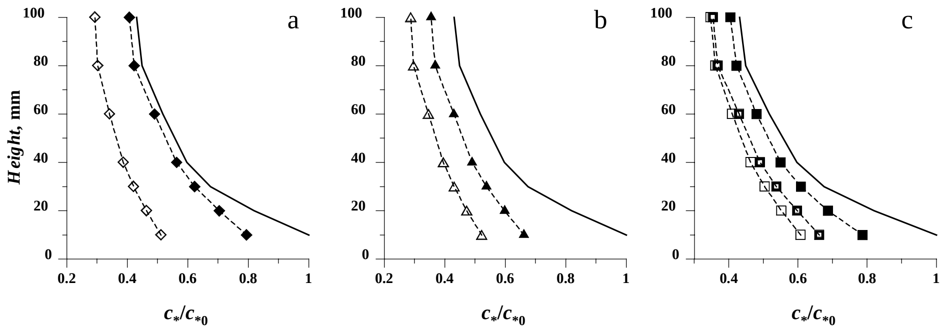

Figure 2. Wind tunnel data on the attenuation of concentration with (a) different wind velocities: u=4.9m/s (open symbols) and u=10m/s (filled symbols) with fixed v=12m/s (43km/h), and n_v=7vehicles/100m; (b) different traffic velocities: v=17m/s (61km/h, open symbols) and v=12m/s (43km/h, filled symbols) with fixed u=7m/s and n_v=7vehicles/100m; (c) different traffic densities n_v=13vehicles/100m (open symbols), n_v=7vehicles/100m (half-filled symbols), and n_v=4vehicles/100m (filled symbols) with fixed v/u=1.7. Solid lines show the reference concentration profile without traffic, c_{*0} is the normalised concentration at the lowest position of corresponding reference profile.

Based on the above considerations we may interpret the PMC in a more general sense and regard it as a similarity parameter for turbulent diffusion regime in a street-canyon airflow with two interacting turbulence production mechanisms separated in scale range.

3. Wind Tunnel Data

In a wind tunnel, an urban street canyon was simulated by two rectangular blocks oriented perpendicular to the flow. The block length was 120cm, width 12cm, and the canyon height H and width B were both 12cm. The model scale was

1:150. A method, first proposed by Brilon *et al*. (1987), of simulating traffic by metal plates mounted on the belts moving above line sources was used. The overview of the simulation methodology and experimental set-up are presented in Kastner-Klein *et al*. (1998). The concentration measurements were performed at the lee wall of the upwind block/building. The measured concentrations were normalised using as scaling quantities the building height (the canyon depth) and the wind velocity in the approaching flow, at the height z=6.7cm (0.56 of the building height) that corresponds to 10-m elevation in the nature.

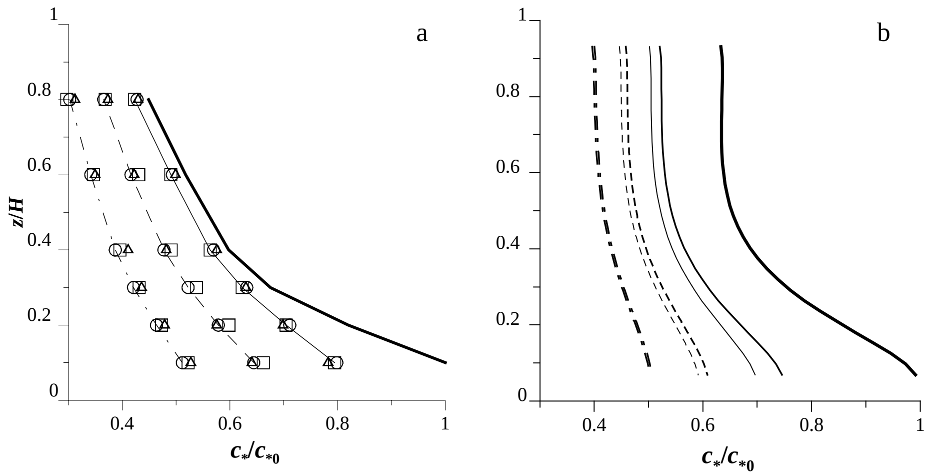

Figure 3. Concentration attenuation with different traffic-to-wind TKE production ratios as function of height normalized by the canyon depth *H*. In (a), are the wind tunnel data for P_t=1.7 (solid line), P_t=6.9 (dashed line), and P_t=13.8 (dashed and dotted line) with u from 4.9 to 14.2m/s, v from 6 to 24m/s, and n_v from 4 to 15 vehicles/100m. In (b) are numerical data for P_t=2.2 and 4.1 (solid lines), P_t=13.8 and 15.6 (dashed lines), and P_t=54.8 (dashed and dotted lines) with u=4m/s, v from 4 to 19m/s, and n_v from 4 to 19 vehicles/100m. Heavy solid lines show reference concentration profiles; c_{*0} is defined as in Figure 2.

Scaled concentration profiles in Figure 2 refer to the measurement location at the mid-length of the canyon. The individual effect of each scaling parameter represented in P_t is demonstrated. Comparison of Figures 2a and 2b shows that variations of v and u alter c_* in the mutually opposite way: the increase of v reduces concentration value whilst the increase of u makes the c_* value larger. The response magnitudes are approximately the same in both cases. Proceeding to Figure 2c one may deduce that with the increasing traffic density the ventilation effect becomes stronger. Comparison of 2c with 2a and 2b shows however that the absolute influence of traffic density on the c_* reduction is smaller than that of either *u* or *v*.

The above observations provide evidence in support of the PMC concept.

4. Comparisons with Numerical Predictions

The basic numerical model employed in our study was the model of Sini *et al*. (1996). It explicitly computes flow field in a street canyon and accounts for the vehicle-induced turbulence through additional production terms in balance equations for the TKE (k) and its dissipation rate ε. The k production by vehicles is taken proportional to the traffic density (expressed in the model as amount of vehicles per unit time) and second power of traffic velocity relative to the mean flow. An analogous parameterisation is employed for generation term in the ε balance equation. The value of proportionality coefficient was obtained from the best match with the wind tunnel data for one model situation. This value was kept constant throughout the entire set of model runs with different traffic velocities and densities.

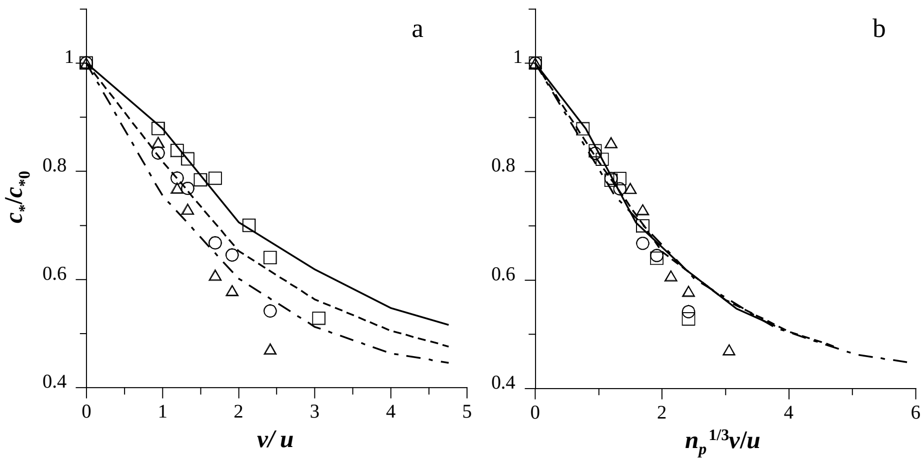

Figure 4. Local similarity of the concentration field in an urban street canyon. Symbols are the wind tunnel data and lines are numerical results. In (a), the roadside concentration field is shown as function of *v/u* for three different n_v: 4vehicles/100m (squares and solid lines), 7vehicles/100m (circles and dashed lines), and 13vehicles/100m (triangles, and dashed and dotted lines). In (b), the wind tunnel and numerical data from (a) are presented as function of the similarity parameter P_t in 1/3 power.

Calculated concentration profiles are compared in Figure 3 with the wind tunnel data. The presented data correspond to a broad variety of situations different with respect to the traffic and wind-flow characteristics. Both wind tunnel and numerical results display apparent and similar clustering tendency according to the P_t values. This provides one more proof to the idea that parameter P_t is a similarity number for the diffusion pattern in a street canyon with traffic.

The wind tunnel and numerical data on the pollutant concentration in an individual location within the street canyon (at the roadside level near the leeward building wall) are presented in Figure 4. It is easy to see that data for different model situations practically collapse to one curve when plotted against P_t. The data convergence, and agreement between the wind tunnel and numerical data are nearly perfect with P_t <8 (or $P_t^{1/3}$<2). The increase of discrepancies with the higher P_t values may be explained by residual flow entrainment due to moving vehicles. Such entrainment, which becomes stronger with larger traffic velocities and densities, is neither taken into account in the numerical model nor by the PMC. However, it apparently affects the concentration pattern in the considered wind tunnel measurement location when P_t gets large.

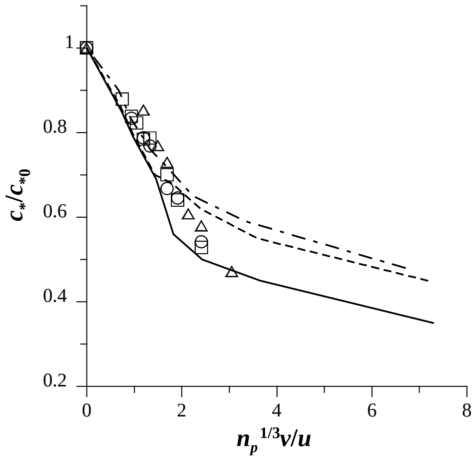

Figure 5. The wind tunnel data from Figure 4, points, compared with the numerical data of Stern and Yamartino (1998), lines. The numerical results refer to the situations with low traffic (solid line), medium traffic (dashed line), and high traffic (dashed and dotted line) according to classification by Stern and Yamartino (1998).

Additionally, we employ for comparison the data from a numerical model study by Stern and Yamartino (1998), who incorporated vehicle-induced turbulence effect in the CALGRID, a photochemical model for regulatory applications. In this model, the TKE production rate by traffic is estimated from the energy dissipated by a vehicle as it pushes its way through the ambient air.

In Figure 5, the wind tunnel data are plotted against P_t together with results of Stern and Yamartino (1998). In this case, the numerical data show less universal behaviour with respect to the similarity parameter than model data from the present study in Figure 4b. However, the independent numerical data in Figure 5 agree well with the wind tunnel measurements approximately in the same interval of the P_t number values as our numerical results, namely in the range P_t <8.

5. Conclusions

Presented results from the combined wind tunnel and numerical model study generally confirm validity of the traffic-to-wind turbulence production ratio P_t as similarity number for the regime of turbulent diffusion in an urban street canyon with moving vehicles. In particular, clearly exposed local similarity have been observed in the concentration field at P_t <8, which in the conducted experiments corresponded to moderate vehicle-to-wind velocity ratios (v/u<3) and traffic densities less than 15 vehicles per 100 m.

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