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Scaling considerations regarding the influence of vehicle induced turbulence on dispersion in street canyons

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We express the turbulence energy production by vehicles in an urban street canyon (see Kastner-Klein et al. 1999 for details of derivation) as:

$$G_v = \frac{v^3}{l_v} n \frac{l_v{}^3}{LH^2} = n_v v^3 \frac{l_v{}^2}{H^2} = \frac{w_v{}^3}{l_v},$$

where n is total amount of vehicles in the canyon, L is the canyon length, v is the traffic velocity, n_v is the vehicle density per unit canyon length, l_v is the length scale of turbulence induced by car motions, H is the characteristic length scale of the canyon cross-section (*e.g.* the canyon depth), and w_v is effective velocity scale of car-induced turbulence in the canyon, let say, a rms value of velocity fluctuations related to car motions. The above expressions yield:

$$w_v = \frac{l_v}{H^{2/3}} n_v{}^{1/3} v .$$

Strictly speaking, in the derived relationships the equality signs have to be replaced by signs of approximate equality, and also proportionality coefficients should be introduced.

Then one can summate velocity variances caused by wind (taking w_w proportional to u) and due to the traffic:

$$w^2 = w_w{}^2 + w_v{}^2 ,$$

where w is the rms velocity value resulting from both mechanisms acting together. This value may be used for scaling of the concentration field in a street canyon with moving vehicles.

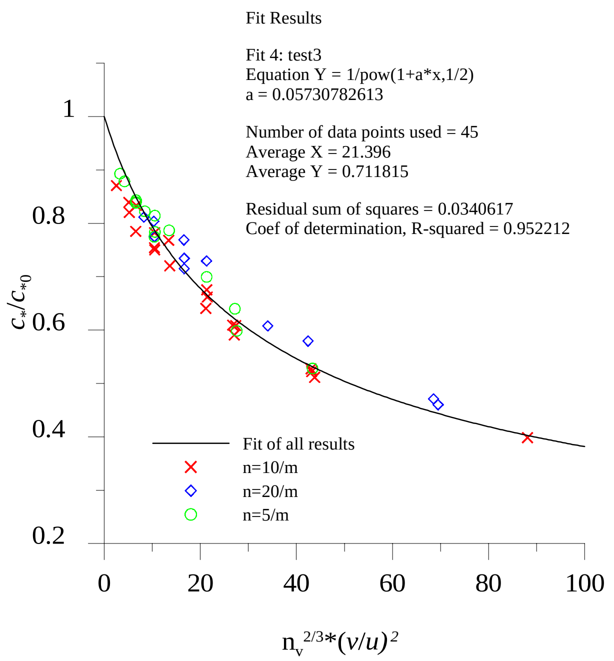
This can be a kind of theoretical framework for the combined case, when car-induced velocity variance is derived from turbulence production considerations, but then directly summated with wind-related velocity variance.

The concentration values normalised with u and w are related as $c_{*u} = c_{*w}(u/w)$. Thus, we can put down:

$$c_{*u} \propto \frac{u}{w} \propto \left(1 + \frac{l_v^{\ 2}}{H^{4/3}} n_v^{\ 2/3} \frac{v^2}{u^2}\right)^{-1/2} = \frac{1}{(1 + a \cdot x)^{1/2}},$$

where $a = \dfrac{l_v^{\ 2}}{H^{4/3}}$ is the geometrical scaling parameter, and $x = n_v^{\ 2/3} \dfrac{v^2}{u^2} \propto P_t^{\ 2/3}$, where P_t is the modelling criterion of Plate (1982), see also Kastner-Klein et al. (1998).

Below results are shown of the scaling application to the concentration field in a wind-tunnel model of an urban street canyon with moving vehicles.



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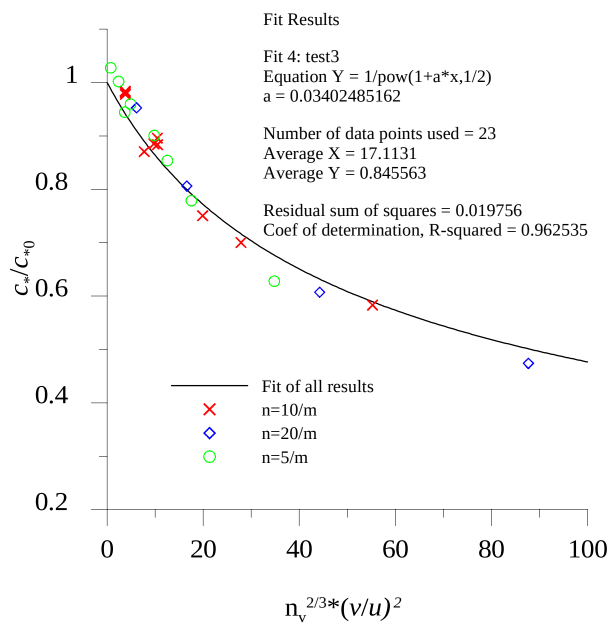

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Additionally we tested combined velocity scales derived from the summation of turbulence production terms by wind and traffic and also from the summation of turbulent kinetic energies.

a) summation of turbulence production terms:

The wind-related TKE production per unit canyon volume is $G_w \propto u^3 / H$, where H is the canyon depth scale and u is the reference velocity of the external wind flow.

For G_v, the scaling considerations provide $G_v \propto (v^3 / l_v)(V_v / V_c) \propto n_v v^3 (l_v / l_c)^2$, where V_v is the total volume of air disturbed by vehicles, V_c is the in-canyon air volume, l_v and l_c are, respectively, the length scales of the vehicle-induce turbulent motion and of the canyon cross-section. 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 $n_g = n_v l_v^{\,2} / H$.

Now let us formally put down $G_w + G_v = u_e^{\,3} / l_e$, where subscripts *e* denote effective scales for the canyon. Expressing G_w and G_v through velocity scales *u* and *v*, length scales l_v and *H*, and density n_v as shown above, we obtain:

$$\frac{u_e^{\,3}}{l_e} = \frac{u^3}{H} + n_v v^3 \frac{l_v^{\,2}}{H^2} = \frac{Hu^3 + n_v l_v^{\,2} v^3}{H^2} = \frac{u^3 + n_v \frac{l_v^{\,2}}{H} v^3}{H}.$$

Thus, we may take *H* for l_e and $\left(u^3 + n_v \frac{l_v^{\,2}}{H} v^3 \right)^{1/3}$ for u_e and normalise everything with these scales.

This means:

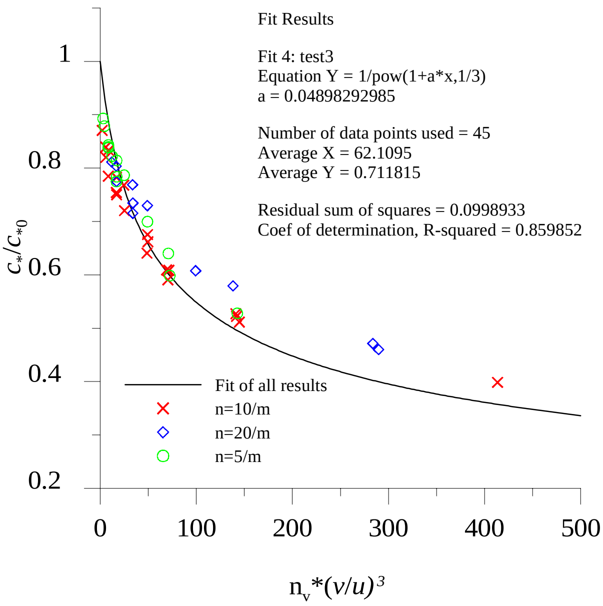
$$\frac{u_e}{u} = \left(1 + \frac{l_v^{\,2}}{H} \cdot n_v \frac{v^{\,3}}{u^3} \right)^{1/3} \equiv (1 + a \cdot x)^{1/3}$$

with:

$$a \propto \frac{l_v^{\,2}}{H}; \qquad x = n_v \frac{v^{\,3}}{u^3}$$

and for the standard normalised concentration ($c \cdot u$) we should receive:

$$c \cdot u \propto \frac{u}{u_e} = 1 \Bigg/ \left(1 + \frac{l_v^{\,2}}{H} \cdot n_v \frac{v^{\,3}}{u^3} \right)^{1/3} \equiv 1/(1 + a \cdot x)^{1/3}.$$



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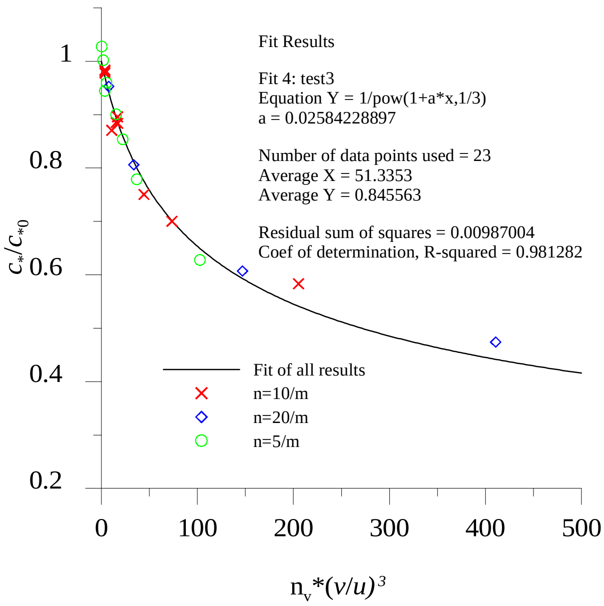

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b) summation of turbulent kinetic energies:

If we now employ a similar procedure for summation of turbulence energies related to wind and vehicle motions, we will get:

$$u_e{}^2 = u^2 + v^2 \frac{V_v}{V_c} = u^2 + v^2 n \frac{l_v{}^3}{H^2 L} = u^2 + v^2 n_v \frac{l_v{}^3}{H^2},$$

where traffic density n_v has the same meaning as in the above expression with cubes, and L is the scale of the canyon length. Thus, in this case the velocity scale is:

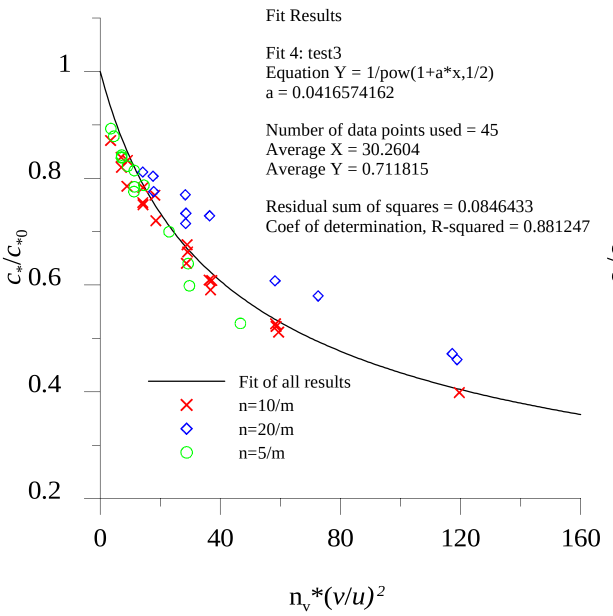
$$u_e = \left(u^2 + v^2 n_v \frac{l_v{}^3}{H^2} \right)^{1/2}$$

and

$$\frac{u_e}{u} = \left(1 + \frac{l_v{}^3}{H^2} \cdot n_v \frac{v^2}{u^2} \right)^{1/2} \equiv (1 + a \cdot x)^{1/2}, \qquad \text{with:} \quad a \propto \frac{l_v{}^3}{H^2}; \qquad x = n_v \frac{v^2}{u^2}.$$

For the standard normalised concentration ($c \cdot u$) we should receive in this case:

$$c \cdot u \propto \frac{u}{u_e} = 1 \Big/ \left(1 + \frac{l_v{}^3}{H^2} \cdot n_v \frac{v^2}{u^2} \right)^{1/2} \equiv 1/(1 + a \cdot x)^{1/2}.$$



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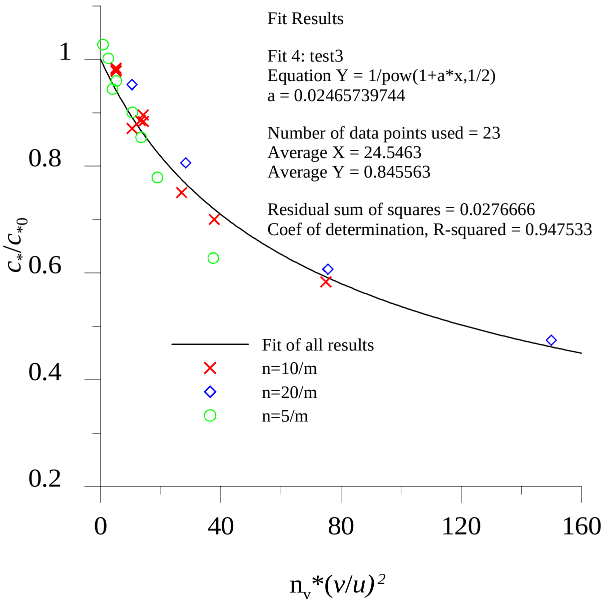

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