



# The Modelling of Turbulence from Traffic in Urban Dispersion Models – Part I: Theoretical Considerations

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Received 8 April 2002; accepted in revised form 19 September 2002

**Abstract.** The modelling of pollutant dispersion at the street scale in an urban environment requires the knowledge of turbulence generated by the traffic motion in streets. In this paper, a theoretical framework to estimate mechanical turbulence induced by traffic in street canyons at low wind speed conditions is established. The standard deviation of the velocity fluctuations is adopted as a measure of traffic-produced turbulence (TPT). Based on the balance between turbulent kinetic energy production and dissipation, three different parameterisations for TPT suitable for different traffic flow conditions are derived and discussed. These formulae rely on the calculations of constants that need to be estimated on the basis of experimental data. One such estimate has been made with the help of a wind tunnel data set corresponding to intermediate traffic densities, which is the most common regime, with interacting vehicle wakes.

**Key words:** dispersion modelling, low wind conditions, pollutant dispersion, street canyon, traffic-produced turbulence, urban areas

## 1. Introduction

Low wind speed conditions are typically associated with the worst air pollution episodes in cities. Urban dispersion models poorly reproduce these episodes, with the pollutant concentration generally overestimated. In these cases the turbulence, mechanically generated by traffic motion, becomes responsible for much of the dilution of pollutants in streets. Especially for low wind speed conditions, any improvement in the estimation of the traffic-produced turbulence (TPT) will impact significantly on model predictions of concentration values.

Field measurements of TPT are not readily available. It is difficult, in a field experiment, to separate TPT from other forms of turbulence such as wind-generated,

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or thermally generated turbulence. Rotach [1] and Louka [2] provide field measurements for flow and turbulence in street canyons but do not explicitly address TPT. However, the recent Nantes99 experiment [3,4] had among its aim the determination of turbulent kinetic energy ( $TK E_1$ ) production due to vehicle's motion. Although the data analysis is still under process, important insights have been delivered on TPT components in an urban street canyon. They will be further discussed in connection with wind tunnel data and the theoretical framework developed in the present study.

In wind tunnel studies, the investigation of flow and dispersion characteristics in street canyons has been of great importance during the last years (see, e.g., Brown *et al.* [5], Schatzmann *et al.* [6], Kastner-Klein [7]). Regarding the flow field parameters, mainly vertical profiles of mean and turbulent velocity components have been measured and analysed.

Some major questions arising from these studies are: (i) How strong is the influence of the particular experimental arrangement on the observed flow characteristics in a street canyon and (ii) in what way can these characteristics be parameterised. These questions were first addressed by Kastner-Klein *et al.* [8] through an inter-comparison of three wind tunnel studies [5, 7, 9]. Furthermore, wind tunnel results have been compared with data from related field experiments [10]. In both studies the analysis focused on vertical profiles of mean velocity and turbulent kinetic energy inside the street canyon and above roof level. It was shown that qualitative similarity exists between the flow characteristics in the wind tunnel model and its atmospheric counterpart. A good agreement was ascertained between the flow characteristics obtained in different wind tunnel studies inside and above idealised street canyons of similar geometries. A vortex-type motion and associated reverse flow in the lower part of the canyon was observed in isolated as well as in urban-type idealised canyons. As an example, velocity vectors and streamlines determined in the central plane of an idealised street canyon are plotted in Figure 1 [7]. The in-canyon re-circulation is clearly indicated by the inversely directed flow at street level and nearly zero velocity values in its centre. Amplification of turbulent kinetic energy typically occurred in the flow region just above the roof levels, in particular for situations with changes of surface roughness.

The effect of traffic on mean flow, turbulence and concentration patterns in street canyons has also been subject of wind tunnel studies by Kastner-Klein *et al.* [10–13]. Different traffic configurations were simulated by small metal plates moving on two belts along the street in the wind tunnel model (see Kastner-Klein [7] for technical details). The wind flow was directed perpendicular to the street. In order to ensure Reynolds number independence, the wind velocity was varied in the range from 5 m/s up to 12 m/s. Thus, the results resemble the interaction of traffic- and wind-induced flow components in the street canyon. While the longitudinal (cross-canyon) mean flow component was only slightly affected by whether the traffic was one-way or two-way, the lateral (along-the-canyon) mean flow component was strongly affected (see [10]). For both traffic arrangements the turbulence

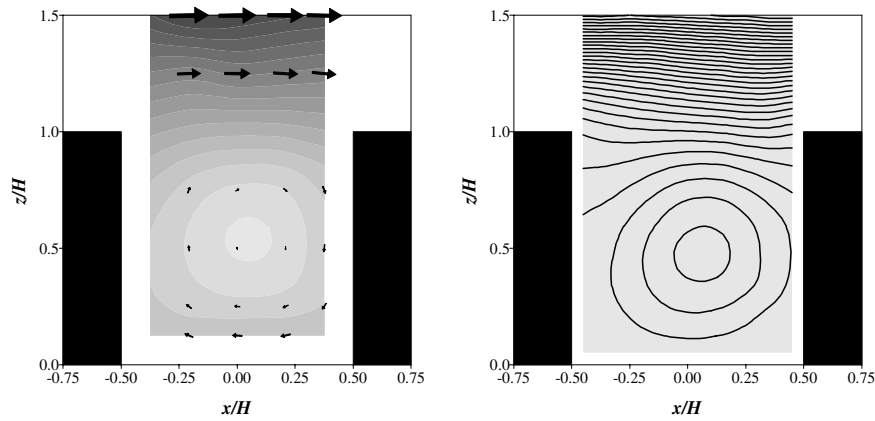


Figure 1. Velocity vectors from wind tunnel experiments (left diagram, velocity values are represented by the underlying shading and the length of the vectors) and streamlines (right diagram) measured in the wind tunnel inside and above an idealised street canyon without traffic [7]).

intensity inside the canyon, in particular in the lower part and close to the leeward canyon wall, was much larger than in the case without traffic, but the increase is more pronounced in the two-way traffic case than in the one-way traffic case. The presence of traffic and its arrangement were also shown to affect the concentration distribution along the leeward canyon wall [10]. For the cases without traffic and two-way traffic the concentration pattern was approximately symmetric with respect to the central transverse plane of the canyon. The increased turbulence intensity in the case of two-way traffic agrees with lower concentration values compared to the no-traffic results. In the case of one-way traffic, the concentration distribution was strongly skewed emphasising the significant mean flow component along the canyon.

Results presented by Kastner-Klein *et al.* [10] clearly showed that for two-way traffic situations mean flow components are not affected by traffic motions while all components of turbulent kinetic energy are increased in the region of the traffic layer. For instance, the lateral component values were more than double these for the case without traffic. In this region, the interaction of the air motion caused by vehicles moving in opposite directions leads to an enhancement of turbulence intensities without noticeably contributing to the mean transport along the canyon. The lateral shift of the maximum turbulence intensities towards the leeward canyon wall results from the low-level advection associated with the canyon vortex induced by the above-canyon wind flow. Consequently the dispersion of street-level emissions is enhanced compared to the no-traffic case and maximum concentration values at the leeward canyon wall are consistently reduced by the increased turbulent transport.

Vachon *et al.* [4] describe generally the same effects of traffic motions on the turbulence field in an urban street canyon. The measurements were made in a street in the city of Nantes (France) during the full-scale experiment Nantes99. In the lower part of the street canyon, increased levels of turbulent kinetic energy were found, which could be attributed to turbulence created by vehicle motions. Close to the traffic region, turbulence enhancement was observed on the leeward and windward side of the street canyon. However, on the leeward side the influence was more pronounced and the vertical extent of the region with increased turbulence levels was much larger than on the windward side. This indicates again the advection of turbulence created in the traffic layer towards the leeward wall due to the wind-induced street-canyon vortex.

Although these recently obtained wind tunnel and field results have significantly contributed to a better understanding of TPT effects on flow and dispersion in street canyons and their interaction with wind-induced flow phenomena, the incorporation of traffic effects in dispersion models is still rudimentary. In the literature, only a few applications of relatively simple parameterisations for TPT have been reported. For instance, in the widely used Operational Street Pollution Model (OSPM, [14]), traffic in a street canyon is treated as the superposition of individual vehicles. The TPT parameterisation is based on the assumption that the motion of vehicles produces an overall variance of the velocity fluctuations proportional to the square of the vehicle velocity [15]). The coefficient of proportionality is linked to the drag coefficient of the vehicles and its value is empirically determined by fitting velocity variances and concentration data obtained in field experiments. Parameterisations of TPT for dispersion models, based on numerical modelling, have been proposed by Sini *et al.* [16] and Stern *et al.* [17]. A comparison of model calculations with wind tunnel data has been presented by Kastner-Klein *et al.* [12].

This paper aims at clarification of the link between traffic motions and concentration distributions in street canyons at low wind conditions. Although our understanding of TPT is still incomplete, there is evidence [18] that model predictions of parameterised dispersion models can be significantly improved, in particular at low wind speeds, if turbulence levels associated with traffic movement are related to the number of vehicles in the street and the vehicle speed. However, the range of applicability of presently applied TPT formulations must be specified, which also requires discussion of their physical bases and further evaluation [12]).

A simple model for TPT will be presented that is based on principal physical mechanisms of vehicle motions in a street canyon. This work is distinct from the work of Eskeridge and Hunt [19] that addresses the traffic turbulence in vehicle wakes but not specifically for street canyons. The aim of the TPT model presented here is to determine the required modification of the turbulence field on the street scale to predict dispersion of street-level emissions when wind-generated turbulence is not the dominant effect. To achieve this aim the study addresses the following topics: (i) Clarification of the term ‘traffic-produced turbulence’, (ii) evaluation of averaging volumes with respect to dispersion modelling; (iii) specification of

the various length scales involved in the modelling of traffic-produced turbulence; (iv) investigation of the differences amongst presently used parameterisations for TPT; (v) verification of these parameterisations against field data; (vi) analysis of the TPT effect on concentration predictions for different traffic flow regimes.

## 2. Theoretical Background

In this section, a conceptual framework is developed to parameterise traffic-produced turbulence under various traffic densities. This type of parameterisation is required for the incorporation of traffic effects in urban dispersion models. We focus on integral, operational models, in which a summation of TPT and background turbulence components is often implemented. Aspects of the TPT parameterisation that will be discussed in this paper are likely to be also applicable in numerical dispersion models.

As stated in the introduction, the main goal of our study is to improve concentration predictions under conditions when wind-generated and thermally generated turbulence play only a minor role and TPT components are the dominant dispersion mechanisms. In this respect the parameterisation of traffic-produced turbulence is only an intermediary result, and its implementation in urban dispersion models must be also addressed.

As a measure of TPT, the standard deviation of the velocity fluctuations  $\sigma_t$  can be introduced. In order to account for the three components of the traffic-produced velocity fluctuations ( $\sigma_{ut}, \sigma_{vt}, \sigma_{wt}$ )  $\sigma_t$  has been defined by:

$$TKE_t = 0.5 \cdot (\sigma_{ut}^2 + \sigma_{vt}^2 + \sigma_{wt}^2) \equiv 0.5 \cdot \sigma_t^2. \quad (1)$$

Since the traffic related velocity fluctuations strongly vary in space, a representative TPT magnitude must be based on a spatially averaged value

$$\sigma_{mt} = \frac{1}{V_t} \iiint \sigma_t \, dx \, dy \, dz \quad (2)$$

of the standard deviation. Accordingly, for an implementation in operational dispersion models the averaging volume  $V_t$  must be appropriately specified. The TPT parameterisation presented in this paper focuses on the derivation of a physically grounded formulation for  $\sigma_{mt}$  and a determination of adequate averaging volumes.

The TPT analysis is based on the production-dissipation balance for turbulent kinetic energy generated by a single vehicle or a row of vehicles in a street canyon. The general form for the production of turbulent kinetic energy  $P$  for one or several vehicles can be written as:

$$P = N \cdot v \cdot C_D \cdot \left( \frac{1}{2} \rho \cdot v^2 \right) \cdot h^2, \quad (3)$$

where  $N$  is the number of vehicles producing turbulence (dimensionless),  $C_D$  is the average drag coefficient of the vehicles,  $v$  is the vehicle speed,  $h$  is the geometrical

length scale of the vehicles (e.g.,  $\sqrt{A}$  with  $A$  = frontal area of the vehicle;  $h^2$  must be the area used in defining the drag coefficients) and  $\rho$  is the fluid density.

The production of turbulent kinetic energy per unit mass  $P_t$  is

$$P_t = \frac{N \cdot v \cdot C_D \cdot \left(\frac{1}{2} \rho \cdot v^2\right) \cdot h^2}{\rho \cdot V_t} = \frac{\frac{1}{2} N \cdot C_D \cdot v^3 \cdot h^2}{V_t}. \quad (4)$$

The averaging volume  $V_t$  could be identified with the volume of a relatively thin layer at the bottom of the canyon that is restricted to the traffic region, with the volume of the canyon as a whole, or with some volume in the region in between. Selection criteria will be further discussed in the next section.

The general form for the dissipation of turbulent kinetic energy per unit mass  $\varepsilon$  is given by

$$\varepsilon = c_1 \cdot \frac{\sigma_{mt}^3}{l_\varepsilon}, \quad (5)$$

where  $l_\varepsilon$  is the length scale used to model the dissipation of turbulent kinetic energy, i.e., the dissipation length scale, and  $c_1$  is the dimensionless constant.

By equating (4) and (5) we obtain the general expression for  $\sigma_{mt}^3$ :

$$\sigma_{mt}^3 = c_2 \cdot N \cdot \frac{C_D \cdot h^2 \cdot l_\varepsilon \cdot v^3}{V_t}, \quad (6)$$

where  $c_2 = (2c_1)^{-1}$ .

So far no particular choice of the averaging volumes or the length scales has been made. To proceed further it is necessary to distinguish between the different traffic configurations. We begin our analysis with the situation of light traffic density, then consider moderate traffic density and finally large traffic density.

### 3. Analysis of the Effect of Three Different Traffic Configurations

#### 3.1. LIGHT TRAFFIC DENSITY – NO FLOW INTERACTION AMONG THE VEHICLES

In the case of light traffic density without interaction between the vehicle wakes we have to consider the turbulence in the wake of a single vehicle. The size of the wake will be related to the geometrical length scale of the vehicle, which will also determine the dissipation length scale. Thus, the unknown parameters in Equation (6) can be described by:

$$N = 1, \quad (7)$$

$$V_t \propto h^3, \quad (8)$$

$$l_\varepsilon \propto h. \quad (9)$$

Using Equations (7)–(9) the following expression for the measure of average turbulent kinetic energy  $\sigma_{wt}^2$  in a single wake can be derived:

$$\sigma_{wt}^2 = c_3 \cdot C_D^{2/3}, \quad (10)$$

where  $c_3$  is another dimensionless constant.

For the implementation in dispersion models, we are not interested in the turbulence  $\sigma_{wt}^2$  in one particular wake, but in an average value ( $\sigma_{ct}^2$ ) over a part of the street canyon of length  $L$ , width  $W$  and height  $H$ . For the case of non-interacting wakes the  $\sigma_{ct}^2$  value can be defined by volume averaging:

$$N \cdot \sigma_{wt}^2 \cdot V_w = \sigma_{ct}^2 \cdot V_c, \quad (11)$$

where  $V_w \propto h^3$  corresponds again to the volume of the wake and  $V_c$  describes the volume inside the canyon over which we average. This volume  $V_c$  is not necessarily equal to  $L \cdot W \cdot H$ , but we can define it as

$$V_c = L \cdot S_c, \quad (12)$$

where  $S_c \leq W \cdot H$  is the cross-section area in the canyon in which TPT is active. In particular,

$S_c = W \cdot h$  describes turbulence averaged over the traffic layer

and

$S_c = W \cdot H$  describes turbulence averaged over the whole canyon.

The number of vehicles can be expressed as

$$N = L/L_v = L \cdot n_v \quad (13)$$

with

$L_v$  distance between vehicles,

$n_v$  number of vehicles per unit length.

Using Equations (12)–(13) and (10) in Equation (11) we get finally the expression:

$$\sigma_{ct}^2 = c_4 \cdot n_v \cdot C_D^{2/3} \cdot v^2 \cdot \frac{h^3}{S_c} \quad (14)$$

This expression (with a new dimensionless constant  $c_4$ ) shows the expected behaviour  $\sigma_{ct}^2 \propto n_v \cdot v^2$  and is conceptually in agreement with the TPT parameterisation used in the OSPM model [14]. More specifically, Equation (14) coincides with the OSPM parameterisation if  $S_c = Wh$  and  $c_4 = b^2 \cdot \frac{A}{A_P} \cdot C_D^{-2/3}$  where  $b^2$  is a factor related to the drag coefficient and  $A$  and  $A_P$  are the average frontal area and plan area of the vehicle, respectively. This analysis shows that the TPT parameterisation

used in the OSPM model is correctly derived for light traffic density, for which the vehicle wakes are not interacting.

### 3.2. INTERMEDIATE TRAFFIC DENSITY – INTERACTION BETWEEN THE VEHICLE WAKES

In the case of intermediate traffic densities, leading to the interaction between the wakes of the vehicles, we consider immediately the average turbulence produced by a row of vehicles. Taking into account that in this case:

$$N = L \cdot n_v, \quad (13)$$

$$V_t = V_c = L \cdot S_c, \quad (15)$$

and again

$$l_\varepsilon \propto h \quad (16)$$

the average turbulent kinetic energy of interest can be finally expressed as

$$\sigma_{ct}^2 = c_5 \cdot (n_v \cdot C_D)^{2/3} \cdot v^2 \cdot \frac{h^2}{S_c^{2/3}}, \quad (17)$$

where another dimensionless proportionality constant,  $c_5$ , is introduced.

In this case of intermediate traffic density, the drag coefficient  $C_D$  remains almost constant or changes modestly as the vehicles are not densely packed. Thus, for a given street canyon geometry, the  $\frac{\sigma_{ct}^2}{v^2}$  ratio changes with traffic density according to  $n_v^{2/3}$ , i.e., slower than in the previous case, which showed a linear dependence of  $\frac{\sigma_{ct}^2}{v^2}$  on  $n_v$ . It will be shown in the second part of the paper that Equation (17) corresponds to a similarity criterion for the interaction of wind and traffic motions in street canyons that has been proposed by Plate [20] and verified by Kastner-Klein *et al.* [9] and [12].

### 3.3. LARGE TRAFFIC DENSITY – STRONG FLOW INTERACTION AMONG THE VEHICLES

In the case of congested traffic (large traffic density), the approach is the same as in the case of interacting wakes, but we assume that the vehicles are densely packed so that the effective length scale for dissipation is the distance between vehicles and no longer the length scale of the wake:

$$l_\varepsilon \propto L_v = 1/n_v. \quad (18)$$

This leads to the following formulation for the average turbulence in the canyon region, which is affected by TPT



$$\sigma_{ct}^2 = c_6 \cdot C_D^{2/3} \cdot v^2 \cdot \frac{h^{4/3}}{S_c^{2/3}}. \quad (19)$$

This expression (with a new dimensionless constant  $c_6$ ) shows that the TPT effect is expected to become independent of the number of vehicles if traffic densities are very high. It must be also noted that as the spacing between the vehicles decreases,  $C_D$  will reduce due to vehicle sheltering and  $\sigma_{ct}^2/v^2$  will consequently decrease.

### 3.4. AVERAGING VOLUMES

With the analysis described above, different parameterisations for TPT can be obtained by specifying an appropriate averaging volume for  $\sigma_{mi}$  and an appropriate length scale to express the dissipation of turbulent kinetic energy. We argue that for the first two cases analysed (light and moderate traffic densities), a geometrical length scale of the vehicle  $h$  is the most suitable length scale for the dissipation of turbulent kinetic energy generated in the traffic layer. The selection of the averaging volume will depend on the type of dispersion model in which the parameterisation will be implemented. The street-canyon volume is an appropriate choice for incorporation in operational dispersion models, where the street canyon is often described as a kind of box. If we are looking at dispersion at street level, the use of the volume  $hWH$ , that is the traffic layer volume, is more appropriate. As the final aim is the determination of the concentration field in the street canyon, the choice of the volume is a key parameter for the answer. In some cases, the choice of an average volume between the canyon volume and the traffic layer volume could be suitable for the calculation of the concentration field.

## 4. Comparison with Experimental Data

Implementation of the proposed TPT parameterisations in dispersion models requires their experimental verification and the provision of recommendations regarding the values of the introduced constants. However, it is rather difficult to extract information about purely traffic-produced mean flow and turbulence components from full-scale measurements and the wind tunnel studies discussed in Section 2. In both cases, the flow and dispersion measurements were conducted under conditions with external flow and in order to verify TPT parameterisations against these data sets an extended analysis accounting for interactions between wind-driven and traffic-produced motions is necessary. Such type of analysis will be presented in the second part of this paper [21]).

Some insights on the purely traffic-produced flow-field components are available from one laboratory data set corresponding to conditions without external wind flow. The experimental arrangement is shown in Figure 2. Laser Doppler measurements of mean and turbulent velocities of the along-the-canyon and transverse component were taken in the central plane of an idealised street canyon.

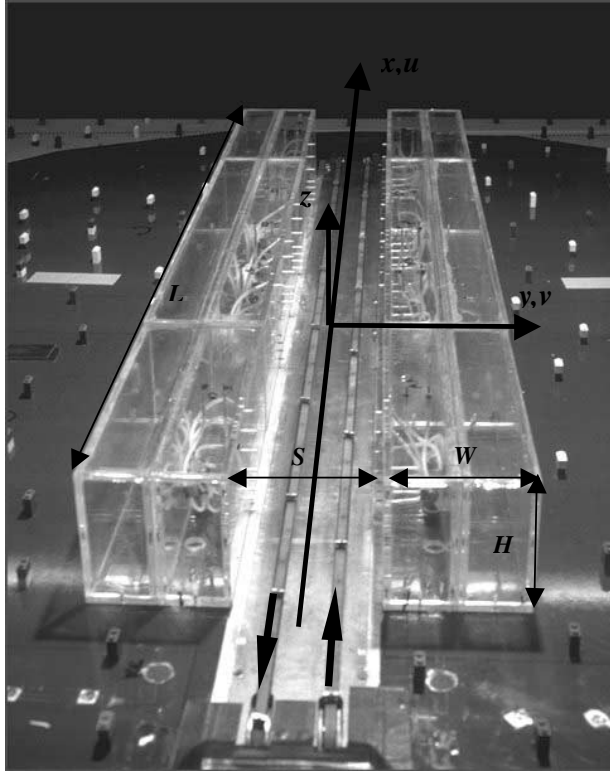


Figure 2. Sketch of the experimental set up during a laboratory study of traffic-produced mean and turbulent velocity components in the central plane of an idealised street canyon ( $S = H = W = 12$  cm,  $L = 120$  cm) without external wind-driven flow. The arrows in the front indicate the direction of motion of the two belts equipped with metal plates that were moving along the street with the velocity  $v_t \approx 12$  m/s.

As in the experiments by Kastner-Klein *et al.* [9] and [12], traffic motions were simulated by small metal plates mounted on two belts moving along-the-canyon in opposite direction. Only one set of measurements was made, with actual plate velocity in the wind tunnel  $v_t \approx 12$  m/s and plate density  $n_v = 20$  m<sup>-1</sup>. The Reynolds number during the experiments was around 8000 which ensured that the flow was fully turbulent and therefore Reynolds number independent. If scaled to full-scale the measurements correspond to conditions with traffic speed in the range of 20 to 60 km/h. Results for the mean velocity components normalised by  $v_t$  are presented in Figure 3. Inside the traffic layer, the mean flow component along the canyon reaches up to 25% of the plate velocity. However, the average value inside the traffic region is zero, due to the opposite sign of the vehicle motions in the two lanes.

Increased turbulence levels are observed in the lower quarter of the canyon. Figure 4 illustrates that slightly lower root mean square values are found for the trans-

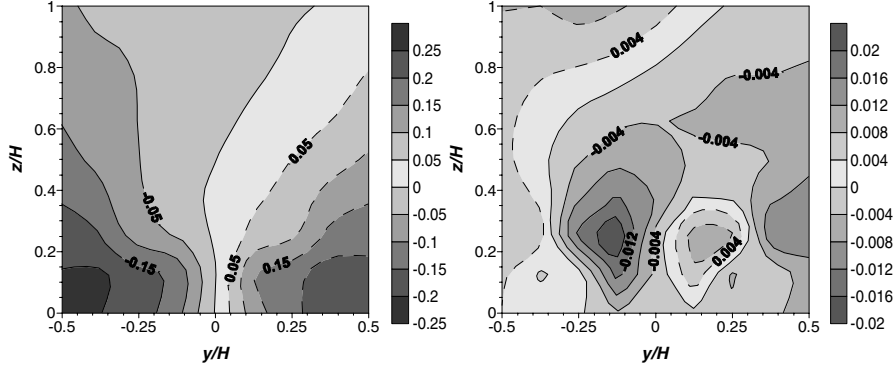


Figure 3. Traffic-produced mean velocity components in the central plane of an idealised street canyon without external wind-driven flow. The left plot shows the along-the-canyon component normalised by the plate velocity; the right plot shows the transverse component normalised by the plate velocity.

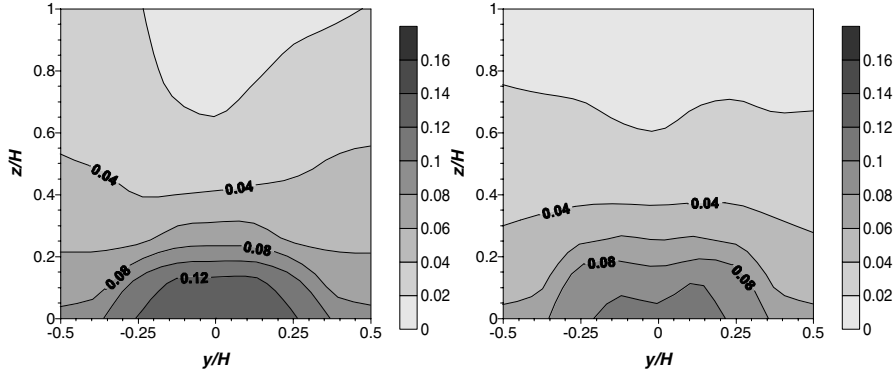


Figure 4. Traffic-produced turbulent velocity components in the central plane of an idealised street canyon without external wind-driven flow. The left plot shows the root mean square value of the along-the-canyon component normalised by the plate velocity  $\sigma_u/v_t$ ; the right plot shows the root mean square value of the transverse component normalised by the plate velocity  $\sigma_v/v_t$ .

verse component than for the along-the-canyon component. In order to compare the data with the theoretical analysis presented in the previous section, an estimate of the normalised average  $TKE_{ct}$  scale  $(\sigma_{ct}/v_t)^2$  must be determined. Due to the lack of data on the vertical velocity component, the  $TKE_t$  scale (Equation (1)) was estimated assuming  $\sigma_w^2 = 0.5 \cdot (\sigma_u^2 + \sigma_v^2)$ , which yields

$$(\sigma_t/v_t)^2 = 3/2 \cdot ((\sigma_u/v_t)^2 + (\sigma_v/v_t)^2). \quad (20)$$

The field of the normalised  $TKE_t$  scale is presented in Figure 5 and as an average value for the lower quarter of the canyon, the value

$$(\sigma_{ct}/v_t)^2 \approx 0.019 \quad (21)$$

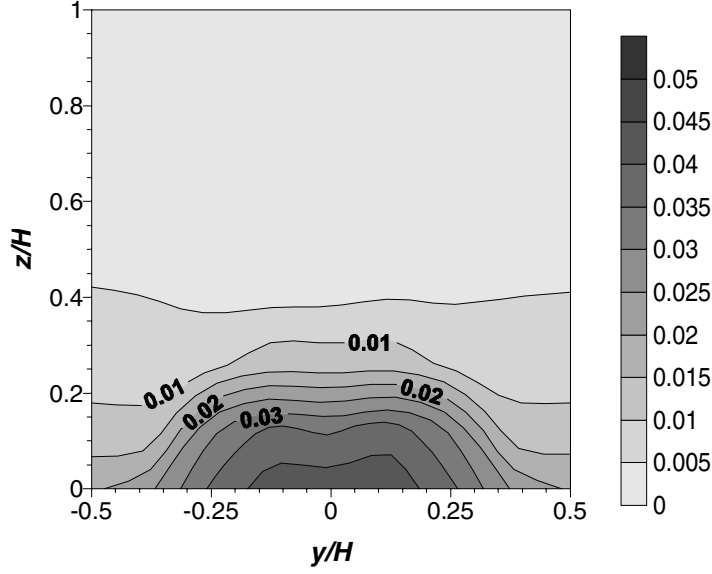


Figure 5. Estimated normalised  $TKE_t$  scale  $(\sigma_t/v_t)^2 = 3/2 \cdot ((\sigma_u/v_t)^2 + (\sigma_v/v_t)^2)$  in the central plane of an idealised street canyon without external wind-driven flow.

was determined. Since the investigated traffic density resembles an intermediate value, this result should be comparable with calculations according to Equation (17). Based on the values for the traffic density  $n_v = 20 \text{ m}^{-1}$ , drag coefficient  $C_D \approx 1.2$  (standard reference value for rectangular shaped, relatively thin metal plates, see, e.g., [22]), geometrical length scale of the vehicle  $h^2 = A_{plate} \approx 5 \cdot 10^{-5} \text{ m}^2$  and affected canyon area  $S_c \approx 0.25 \cdot H \cdot W = 3.6 \cdot 10^{-3} \text{ m}^2$  Equation (17) gives the following result:

$$\left( \frac{\sigma_{ct}}{v_t} \right)^2 = c_5 \cdot (n_v \cdot C_D)^{2/3} \cdot \frac{h^2}{S_c^{2/3}} \approx 0.018 \cdot c_5. \quad (22)$$

The experimentally observed value (21) and theoretically estimated value (22) conform if the constant  $c_5$ , introduced in Equation (17), has a value of approximately one. However, it must be taken into account that only one data set was available for the comparison and for any recommendation of a particular value concerning the constants or length scales in the proposed parameterisations an elaborated verification against data sets for a variety of vehicle velocities and densities is still required. Thus, the comparison carried out can be only considered as an indication that the order of magnitude of TPT estimates with Equation (17) is correct, but not as a proof for a particular parameterisation.

## 5. Conclusions

Traffic-produced turbulence (TPT) is important for estimation of pollution concentration levels in streets. It is expected that the modelling of TPT in operational urban dispersion models will grow in importance, as air quality regulations in urban areas are made more restrictive.

In the present paper, a theoretical framework for parameterisation of turbulent transport by traffic induced air motions in street canyons is established. It has been demonstrated how parameterisations for TPT can be obtained based on the consideration of  $TKE_t$  generation and dissipation in a street canyon.

The analysis distinguishes between three traffic flow conditions: (i) Light traffic conditions (isolated vehicles, non-interacting vehicle wakes); (ii) moderate traffic conditions corresponding to non-isolated (interacting) vehicle wakes; and (iii) heavy (congested) traffic conditions characterised by strongly interacting wakes. By introducing the averaged standard deviation of the velocity fluctuations  $\sigma_{mt}$  as a measure of the kinetic energy of turbulent fluctuations generated by traffic, it has been shown that the numerical value of  $\sigma_{mt}$  depends upon the choice of the volume where the balance between  $TKE_t$  production and dissipation takes place and the choice of the dissipation length scale.

We argue that for light and moderate traffic conditions, a geometrical length scale of the vehicle  $h$  is the most appropriate length scale for the dissipation of  $TKE_t$  generated in the traffic layer. For congested traffic, the effective length scale for dissipation is the distance between vehicles. The appropriate averaging volume to use in an analysis will depend on the intended application.

The parameterisations for TPT derived for the three different traffic regimes require the knowledge of proportionality constants that have to be experimentally determined. The value of the constant for the most common traffic condition, i.e. the moderate traffic regime, has been estimated by analysing laboratory data from velocity measurements inside an idealised street canyon with two-way traffic without external wind flow. According to this analysis the suitable formula to parameterise TPT in an urban dispersion model is  $\sigma_{ct}^2 = (n_v \cdot C_D)^{2/3} \cdot v^2 \cdot \frac{h^2}{S_c^{2/3}}$ . However, further verifications with additional data sets from both wind tunnel and full-scale experiments under variable traffic densities are still required.

## Acknowledgements

The authors gratefully acknowledge the support from the TRAPOS project in the framework of the TMR Programme of the European Commission. This paper is part of the results achieved by the working group on Traffic-Produced Turbulence established during the TRAPOS project. Discussions with many TRAPOS colleagues during project workshops are deeply acknowledged. This work would have

not been possible without the enthusiasm and the intense collaboration had between the authors while working together on this project.

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