EVALUATION OF THE TRAFFIC PRODUCING TURBULENCE WITHIN A MODELLED STREET CANYON USING COMPUTATIONAL FLUID DYNAMICS CALCULATIONS

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ABSTRACT
The motion of vehicular traffic has been identified as a significant source of mechanically-generated turbulent kinetic energy within urban street canyons. As the bulk of free stream wind flow is too weak to penetrate within the street canyon under calm wind conditions, the Traffic Producing Turbulence (TPT) becomes the dominant factor in mixing and diluting traffic-related pollutants. Full scale experiments can not give satisfactory insights into the TPT dynamics, because of the difficulty to study the TPT in isolation from other sources of turbulent kinetic energy within the canyon. For that reason, Computational Fluid Dynamics (CFD) calculations were adopted in order to improve our understanding of the process. Suitability of the CFD calculations in predicting real flow fields was evaluated using wind tunnel data.

1. INTRODUCTION
The coupled processes of wind flow and TPT have been extensively studied in the literature by means of analytical formulations, numerical models, and wind tunnel experiments. However, most of the formulations proposed were intended for single lane and flat roadways, where the complexity of bounding walls interaction and vortical flow, typical of street canyon-type geometries, were absent (Stern and Yamartino, 2001). Moreover, studies addressing the combining effects of wind flow and TPT in urban street canyons most often adopted a “linear” method, consisting in resolving the flow field generated by the wind flow only, with TPT included as an extra Turbulent Kinetic Energy (TKE) term superimposed to the mean flow. However, it is possible to identify two main weaknesses in such approach:

a) the postulated linearity, which leads to neglect the interaction between the wind flow field and the TPT. Such interaction results in the advection of flow and turbulence generated by moving vehicles toward the leeward side of the canyon, and it has been documented by several filed measurements (e.g. Vachon et al., 2002);

b) the neglecting of a possible organised motion produced by the moving vehicles. Wind tunnel investigations by Kastner-Klein et al. (2001) found that the advection-type flow induced by moving vehicles outweighed the turbulent fluctuations, especially in the case of one-way traffic.

The aim of this work is to model both the flow and the turbulence induced by moving vehicles, when an external wind flow is also present, using CFD calculations and adopting a cost-effective methodology to address the aforementioned points a) and b).

2. METHODOLOGY
At any given point within a street canyon, mean velocity and turbulence are generated by the combined effects of wind flow and vehicular traffic (neglecting turbulence generated by thermal processes). In particular, velocity fluctuations are due to the following processes: I. turbulence in the atmosphere; II. a vehicle passing the point will generate a wake, producing deformation of the flow, and thus turbulence; III. turbulence in the wake. The organised flow is due to: IV. external wind flow; V. vehicle motion.

In this work the modelling of processes I to V was achieved by considering the moving vehicles as being local sources of momentum, "immersed" into an external wind filed. Turbulence and flow generated by the external wind (I and IV) were directly solved with this methodology. Turbulence due to passing vehicle (II) was also accounted for by modelling vehicles as steady blocks,(?) interacting with the wind field and the other vehicles flow. Finally, the wake and flow of the vehicle (III and V) were directly implemented at the position occupied by the vehicles. This is a simplification of the real flow field, but it does allow for a faster solution of the problem, saving computational resources.

In this study, the general purpose CFD code FLUENT was used with the standard k-ε turbulence model. The boundary conditions provided for velocity, turbulence and dissipation were those suggested by Richard and Hoxey (1993) for the standard k-ε model, modified to account for the depth of the boundary layer δ:

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z+z_0}{z_0}\right) \qquad (1a)$$

$$k = \frac{u_*^2}{\sqrt{C_\mu}}\left(1-\frac{z}{\delta}\right) \qquad (1b)$$

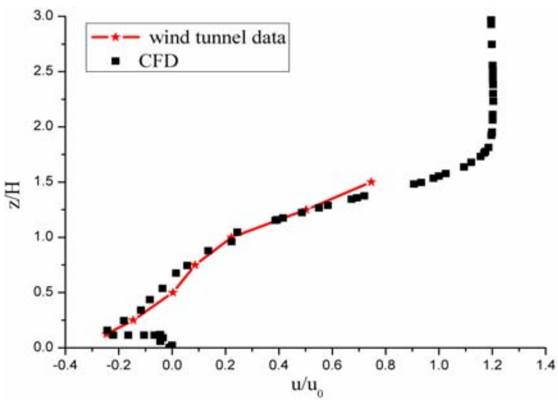
$$\varepsilon = \frac{u_*^3}{\kappa(z+z_0)}\left(1-\frac{z}{\delta}\right) \qquad (1c)$$

In Eqs. (1) u_* is the friction velocity and z_0 the roughness length. κ and C_μ are empirical parameters. The values used in the simulations are reported in Table1.

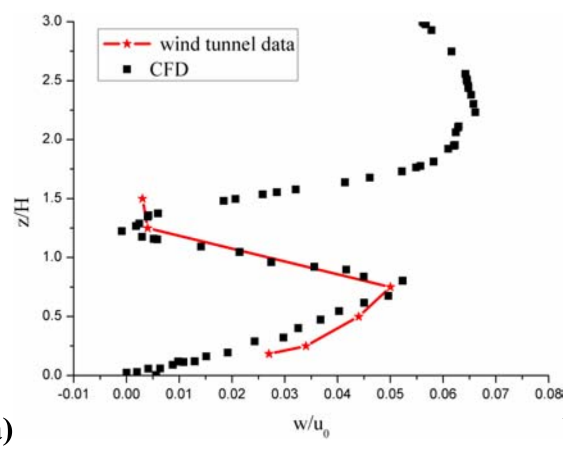
Table 1. Numerical values of the parameters in Eqs. (1)

κ	C_μ	δ (m)	u_0 (m s^{-1})	u_* (m s^{-1})	z_0 (m)
0.40	0.09	0.480	7.0	0.43	0.0007

The reliability of the model was tested using published wind tunnel data by Kastner-Klein et al. (2001). The case of n_v = 10 m^{-1} and V/u_0 = 0.7, with two lines of vehicles moving in the same direction (1-way), was selected for evaluation, where n_v is the density of vehicles per lane, V their velocity and u_0 the reference wind velocity at the top of the boundary layer. Modelled mean horizontal and vertical velocity components (Figs. 1a and 1b), and TKE profiles (Fig. 1c), were compared against wind tunnel measurements at a vertical section in the middle of the canyon. Normalised concentration profiles on the leeward side (Fig. 1d) are also shown. Passive tracer were released from two line sources at street level, to mimic the configuration of the wind tunnel experiment.



a)



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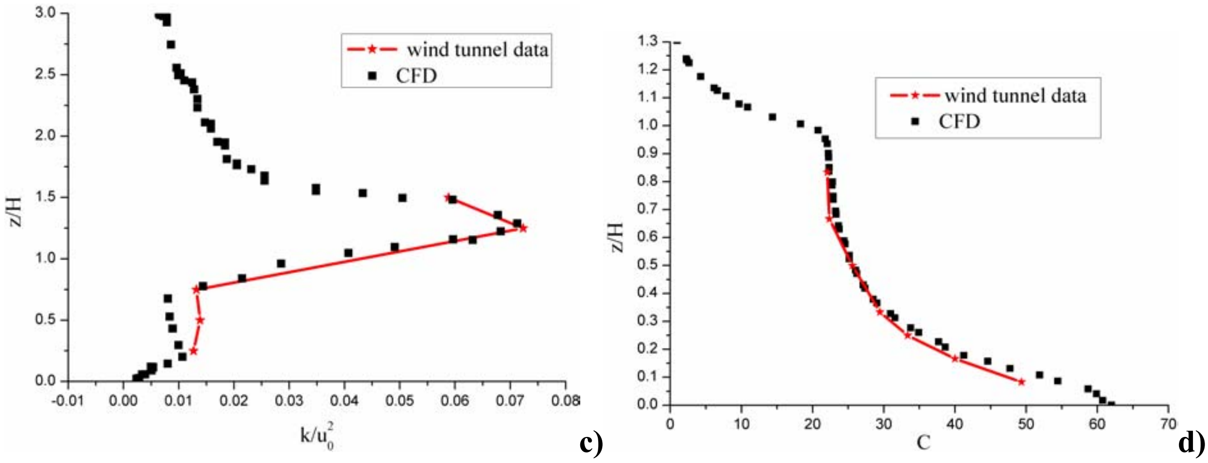
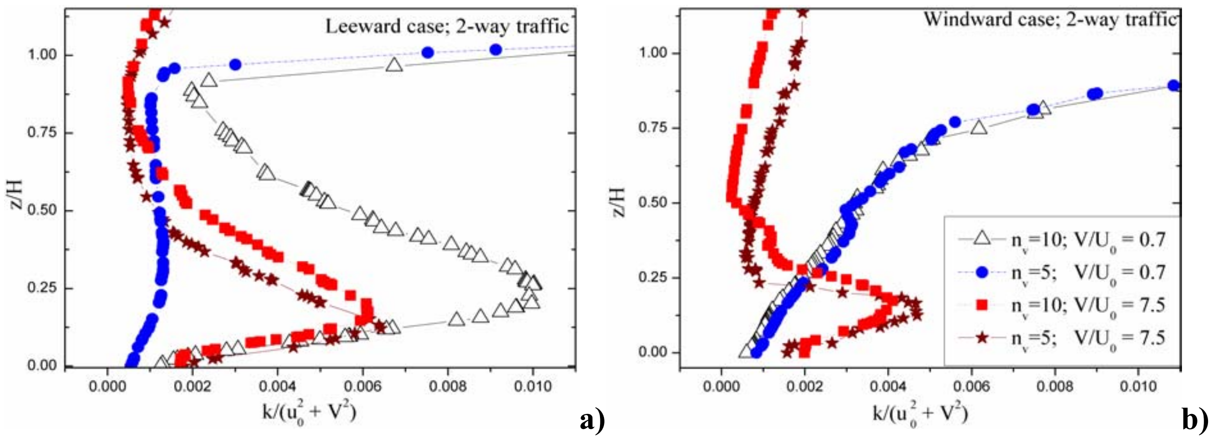


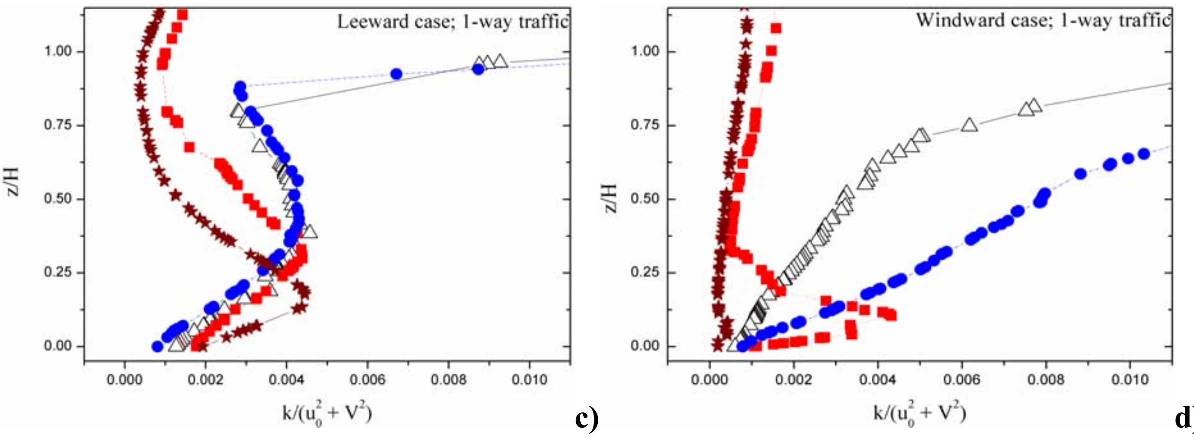
Figure 1. Comparison between wind tunnel data and CFD calculations for mean horizontal (a) and vertical (b) velocity components, TKE (c) and normalised concentration (d).

Despite some minor discrepancies in TKE level within the canyon, where the model underestimated the TKE magnitude by almost 20%, CFD results compared very satisfactorily with the wind tunnel data. Horizontal and vertical mean velocity profiles were in excellent agreement with the observations. In addition, the modelled concentration profile closely matched the wind tunnel measurements, proving that the model can reliably mimic mean and turbulent quantities.

3. RESULTS AND DISCUSSION

In modelling the flow and turbulence induced by moving vehicle, several traffic conditions and configurations were considered by varying the density and velocity of vehicles, the traffic arrangement (1- or 2-way traffic), and the velocity of the external wind flow. Vehicular emissions were simulated by modelling each vehicles as a source of CO, rather than by line sources. Vehicles were modelled as having a frontal area of 2 m^2. TKE and CO concentration profiles were compared at the leeward and windward side of the street canyon. TKE was normalised with the combined velocity $(u_0^2 + V^2)$, whereas concentrations were normalised with the number of sources, i.e. the number of vehicles and their emission strengths. Results are given for the case of a street canyon with height to width ratio of one.

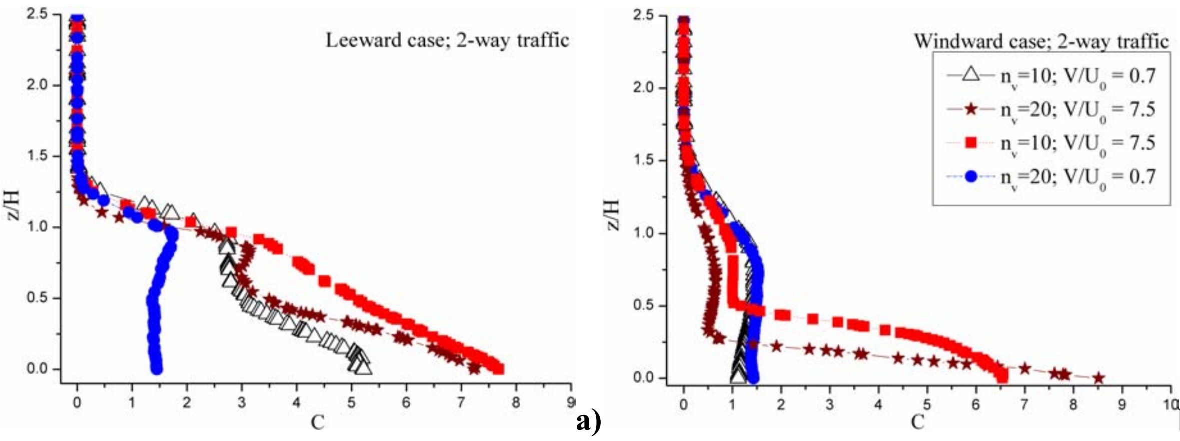




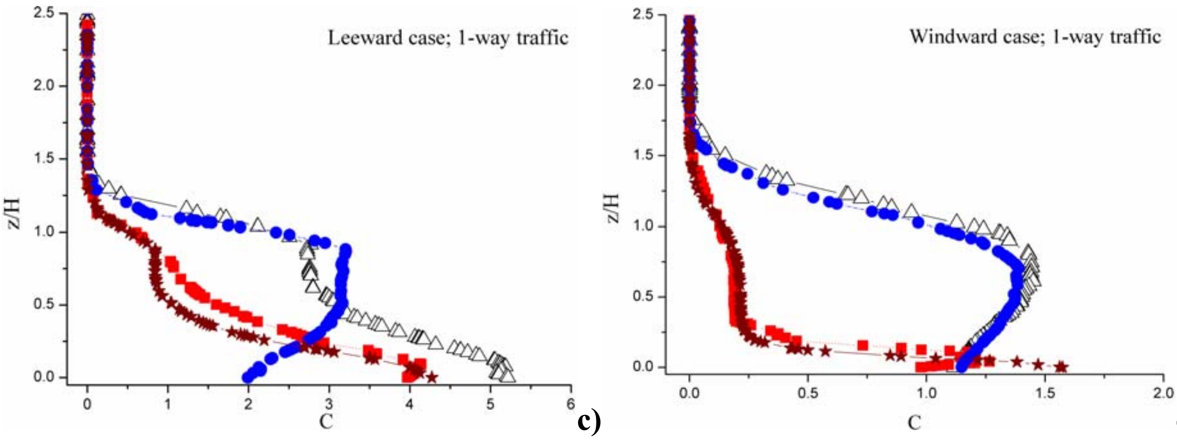
c) d)

Figure 2. Normalised TKE for 2-way traffic configuration: leeward (a) and windward (b) side, and 1-way traffic configuration: leeward (c) and windward (d) side. Symbols as in (b).

Vertical profiles of turbulence on the leeward and windward side within the street canyon are shown in Fig. 2. Similar TKE patterns on the leeward and windward side were found, depending on the ratio V/u_0. When the external wind velocity outweighed the velocity of vehicles (V/u_0 = 0.7), a strong TKE peak was detected near the roof level. TKE peaks at street level, where turbulence intensity was driven by traffic velocity, with a weaker influence of the vehicle density, were detected. Such behaviour was similar for both traffic arrangements analysed, 1- and 2-way. The analysis of TKE showed that its magnitude at street level was very similar for V/u_0 = 7.5 for the leeward cases, independently of the traffic density. In the case of Fig. 2a, for V/u_0 = 0.7 and n_v = 10, a very strong contribution to the overall TKE level due to the traffic density was detected, compared to the corresponding case of n_v = 5. Analysis of the windward results confirms that the main TKE peak is due to the external wind flow, whereas at street level the contribution of the vehicular motion to the total TKE is negligible for the case V/u_0 = 0.7, but very significant for the case for V/u_0 = 7.5. Results for cases with V/u_0 = 0.7 (Fig. 2c) showed that turbulence generated by traffic produced a non-negligible effect on the TKE profile at street level. By contrast, windward results for the same case (Fig. 2d) were clearly not influenced by vehicle movement. This important result shows the non-linearity of the interaction between vehicle's wakes and external wind flow. In fact, the turbulence produced by the wake of moving vehicles is advected towards the leeward side of the canyon by the external wind flow, leaving the windward side unaffected. Such process is less pronounced for the cases when V outweighs the wind velocity u_0.



a) b)



c) **d)**

Figure 3. Normalised concentration for 2-way traffic configuration: leeward (a) and windward (b) side, and 1-way traffic configuration: leeward (c) and windward (d) side. Symbols as in (b).

Concentration patterns (Figs. 3) also showed interesting results. Firstly, profiles were rather different than that in Fig. 1d, where the emissions were simulated by line sources. Secondly, the 2-way traffic in most cases produced higher concentrations at street level on both sides of the canyon. Moreover, comparing Figs. 3b and 3d, it emerged that the traffic arrangement significantly influenced the concentration distribution. The higher concentration magnitudes in Fig. 3b were detected for the low wind velocity scenario, even though the vehicle velocity was higher in that case. This is a confirmation that the removal of pollutants is manly driven by the advection operated by the wind flow. Interestingly, in Fig. 3d, the cases associated with low wind condition showed the concentration increasing with height, as a consequence of the dilution of pollutants due to the TPT at street level.

CONCLUSIONS

In this study, a realistic simulation of the combining effect of wind flow and traffic movement was achieved. CFD calculations were carried out in order to analyse the effects of several traffic (i.e. density and direction of traffic flow) and wind conditions on the flow field and dispersion patterns within an urban street canyon. The model was validated using recent wind tunnel data. The obtained results of TKE and concentration distribution were very encouraging. It should be noted that the quantification of the turbulent processes due to the traffic motion can help develop parameterisations for implementation within operational dispersion models. Further research will aimed at better characterising the TPT contribution to the exchange mechanisms at the canyon top and the influence of traffic arrangement on the overall velocity and turbulent patterns.

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