Aerosol and Air Quality Research, 17: 865–874, 2017

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2016.05.0204

Large Eddy Simulation of Vehicle Induced Turbulence in an Urban Street Canyon with a New Dynamically Vehicle-Tracking Scheme

Yunwei Zhang, Zhaolin Gu[*], Chuck Wah Yu

School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an 710049, China

ABSTRACT

Moving vehicles could have a considerable influence on air flow and turbulence within urban street canyons, especially the vehicle induced turbulence (VIT), which is an important consideration for pollutants' dispersion and local air quality management. To simulate air flow in urban street canyons with moving vehicles, an Euler-Lagrangian method was further developed by this study. The method involved dynamically tracking each moving vehicle and determining the vehicle induced drag force on surrounding air. Simulations under different background wind velocities and vehicle speeds show that, moving vehicles could pose a strong effect on wind turbulence, but have a lesser effect on average wind field within a street canyon. The presence of VIT was mainly in the lower areas of a street canyon. The average standard deviation of velocity (σ_{w0}) in the lower areas is about 0.5 m s^{-1}. In comparison with theoretical and experimental VIT models, VIT values produced by our simulations were higher than those obtained by experimental model, and were slightly lower than those produced by theoretical model. Instantaneous air flow fields within a street canyon were also investigated. Our results have indicated that the existence of local eddies could be a contribution factor to VIT.

***Keywords*:** Vehicle induced turbulence; Street canyon; Wind field; Air quality management; Moving vehicles.

INTRODUCTION

Exhaust fumes from motor vehicles are major sources of air pollution in urban environments (Perry and Gee, 1994; Cheng *et al.*, 2012). The dispersion of fine particulates in a deep street canyon has been discussed previously (Zhang *et al.*, 2011). Air recirculation inside a street canyon could hinder the outward transport of airborne pollutants, which could lead to poor air quality within an urban street canyon (Oke, 1988; Sharma and Khare, 2001; Xie *et al.*, 2005). Moving vehicles could induce air flow and turbulence to pose a significant influence on dispersion of pollutants in an urban street canyon, especially in lower areas of a street canyon (Qin *et al.*, 1993) and/or under weak background wind conditions (Mazzeo and Venegas, 2005; Solazzo *et al.*, 2007). Therefore, studying air flow and turbulence induced by moving vehicles is crucial for understanding pollutants' dispersion characteristics in an urban street canyon (Zhang *et al.*, 2012a).

In-situ measurements, wind tunnel and numerical simulations have been conducted to determine air flow and pollutants' dispersion characteristics in an urban street canyon (Zhang *et al.*, 2013a). Depaul *et al.*'s (1986) in-situ measurements showed that turbulences induced by moving vehicles could reach up to a height of 7 m in an urban street canyon. Qin *et al.* (1993) found that air flows induced by moving vehicles could reach a height of 12 m by their in-situ observations in a street canyon. Ahmad *et al.*'s (2002) wind tunnel simulation demonstrated that moving vehicles could cause considerable reduction of pollutant concentration in a street canyon when the background wind was weak. Mazzeo and Venegas (2005) analyzed the effect of vehicle induced turbulence (VIT) on CO concentration within a street canyon, and their findings had indicated the existence of VIT, which was a contributory factor to a 29% reduction of CO concentration.

Numerical simulations have illustrated considerable influences of moving vehicles on turbulences and pollutant dispersions in urban street canyons. Kastner-Klein *et al.* (2000a) characterized the VIT with different parameters which were verified by their wind tunnel data, as well as by their numerical model. Kastner-Klein *et al.* (2003) found the numerical results were poor under weak wind conditions, when the WinOSPM model without VIT was used to simulate the distribution of pollutants in an urban street canyon. Some researchers attributed the poor results of Kastner-Klein *et al.*'s (2003) simulation to the absence of VIT which was not considered in the WinOSPM model (Kastner-Klein *et al.*, 2003; Di Sabatino *et al.*, 2003; Mazzeo and Venegas 2005). Therefore, Solazzo *et al.* (2007) adopted a parameterized model proposed by Di Sabatino *et al.*

[*] Corresponding author.
E-mail address: guzhaoln@xjtu.edu.cn

(2003) to introduce the VIT to the WinOSPM model, and this had improved their simulation results considerably. They also found numerical simulations were obviously sensitive to the VIT parameterized model. The effect of moving vehicles on air flow and turbulence could be difficult to simulate with one parameterized model. This would be due to the effect of moving vehicles on air flow and turbulence relating many factors, such as one/two-way traffic, traffic lane, background wind velocity and vehicle moving speed. Therefore, some scholars had tried to simulate the effect of moving vehicles by tracking moving vehicles using Computational Fluid Dynamic (CFD) modelling (Jicha *et al.*, 2000, 2002; Katolicky and Jicha, 2005; Solazzo *et al.*, 2008).

Solazzo *et al.* (2008) used empirical formula to modify the k and ε equations in the traffic wake region in their CFD simulations, to model the effect of moving vehicles on air flow and turbulence. Jicha *et al.* (2000, 2002) proposed an Euler-Lagrange method to model the effect of moving vehicles on air flow and turbulence in an urban street canyon. In Jicha *et al.*'s (2000, 2002) Euler-Lagrangian method, the effect of moving vehicles on ambient air was modelled by calculating the drag force between a single moving vehicle and its ambient air. However, drag forces between moving vehicles and ambient air were averaged in Jicha *et al.*'s (2000, 2002) CFD simulations; and empirical formula was still used to modify the k and ε equations. In fact, vehicles were not tracked in Jicha *et al.*'s (2000, 2002) simulations.

In our current work, the Euler-Lagrangian method was further developed to calculate the drag force between moving vehicles and ambient air, involving tracking of each moving vehicle. The effects of moving vehicles on air flow and turbulence in an idealized four-lane urban street canyon under different background wind velocities and vehicle speeds were studied with large eddy simulations (LES) (Zhang *et al.*, 2013b, 2015).

METHODS

Drag Force Model for Moving Vehicles

In our current work, each moving vehicle was regarded as a moving obstacle in a street canyon, and was treated as a solid moving "particle" in air flows in a street canyon. Therefore, a moving vehicle would dynamically occupy a number of control volumes. The directly affected region was included in the simulation, as shown in Fig. 1. For each control volume in the directly affected region, the drag force was calculated by Eq. (1):

$$F_{D,i} = C_D A\,|V_{h,i} - u_i|\,(V_{h,i} - u_i) \quad (1)$$

where, C_D is the drag coefficient, $F_{D,i}$ is the drag force on air in i direction, A is the maximum cross-sectional area of the vehicle in the current control volume in i direction, $V_{h,i}$ is the vehicle velocity in i direction, u_i is the wind velocity in i direction. According to Kastner-Klein *et al.*'s (2003) experiments, the drag coefficient was selected as 0.33 in the following simulations.

In the present drag force model, location and directly affected region for each vehicle was tracked. For a special moving vehicle, the influence on air flow would be changing spatially. The current drag force model would track moving vehicles using the Lagrangian approach and reproduce air flow using the Eulerian framework, which is an Euler-Lagrange model in a general sense. It therefore has the potential to simulate the instantaneous effect of single moving vehicle on local air flow and turbulence in a street canyon.

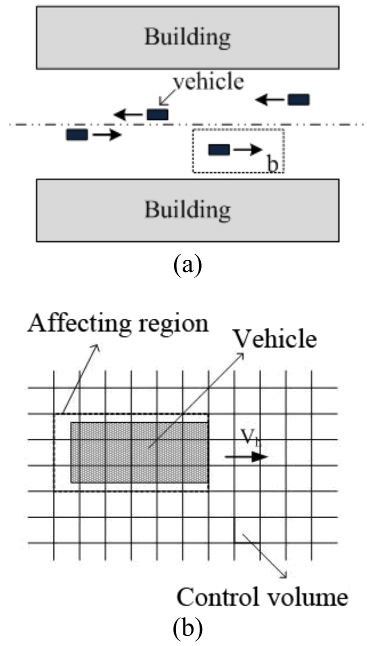


Fig. 1. Diagram of vehicle moving conditions in the two-way-four-lane street canyon (a), and a vehicle's location, control volume distribution and the direct affected region in a two-dimensional plane (b).

Numerical Methods and Modelling Conditions

To study the effect of moving vehicles on air flow and dispersion of pollutants in an urban street canyon, LES were conducted. The drag force induced by moving vehicles was added to the additional source term of the governing equation (Zhang *et al.*, 2011), as shown in Eq. (2).

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial\left(\overline{u_i u_j}\right)}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \frac{1}{\mathrm{Re}}\frac{\partial^2 \overline{u_i}}{\partial x_j x_j} + S_i \quad (2)$$

where, $\overline{u}_i$ and $\overline{u}_j$ are the resolved-scale velocities in i and j directions, $\overline{p}$ the resolved-scale virtual pressure, τ_{ij} the sub-grid stress and S_i the additional source term, which is the drag force $F_{D,i}$ in the current simulations. In view of energy conservation, the drag force (as a source) would increase the mean kinetic energy of air flow, and is converted to turbulence kinetic energy (as a sink) consequentially. The energy conservation and conversion processes would provide the theoretical basis to explain the generation and evolution of VIT in a street canyon.

An idealized uniform street canyon with aspect ratio, AR = 1 was selected, with the street canyon width (W) and building height (H) being 30 m. The traffic condition was supposed to be in two-way four-lane traffic, which is common in Xi'an, China. The four lanes are symmetrically located in the central region of a street, with two lanes on each side. Vehicles were assumed to enter into the computational domain in a constant frequency on four traffic lanes, as shown in Fig. 1(a). Length, width and height ratio of the vehicle model was 4:2.5:2. The ratio of the vehicle width (W_v,) and the street canyon width (W) was 1:15. The computational domain was triple building height (H) in z direction, double building height in y direction (spanwise) and x direction (streamwise), respectively. The background wind direction was perpendicular to the street. A uniform grid system was used in discretization of the computational domain, setting the grid sizes $\Delta x \times \Delta y \times \Delta z$ as $0.0333H \times 0.0667H \times 0.0333H$. The time step in simulations was 0.03s. A self-produced CFD cord was used in our current simulations, which was validated by our previous works (Gu *et al.*, 2010; Zhang *et al.*, 2011). The finite volume method was used to discretize the governing equations and the SIMPLE method was used to solve the discretized equations.

Wind velocities on top of the computational domain were selected as reference wind velocities (U_{ref}). These were weak background wind velocity (3 m s^{-1}) and high background wind velocity (10 m s^{-1}). The corresponding Reynolds numbers ($Re = U_{ref} \cdot H/\nu$) were 9×10^6 and 3×10^7, respectively. The total traffic volume was 1800 veh h^{-1}. Three vehicle moving speeds (V_s), 9 km h^{-1} (2.5 m s^{-1}), 36 km h^{-1} (10 m s^{-1}) and 54 km h^{-1} (15 m s^{-1}), were simulated in this study. Based on observations in Xi'an (Zhang *et al.*, 2012a), vehicles moving at a speed of around 9 km h^{-1} would represent the case of heavy traffic condition, and the other two vehicle speeds would indicate light (free-flowing) traffic conditions. The correspondence traffic densities (n_v) were 0.2, 0.05 and 0.0333 vehicles per metre, respectively. The position of each vehicle was tracked from it entering the computational domain to it going out of the computational domain.

Case Arrangement

Six cases were simulated in the current work. The computational conditions are shown in Table 1, in which, Case NVS was without considering the moving vehicles within a street canyon, and Cases VS1-VS5 were with moving vehicles at different speeds within a street canyon.

To reduce the computational load and account for the consequence of air flows in a long street, periodic boundary condition was adopted for a specified street canyon length ($L = 2H$) in the spanwise direction. Periodic boundary condition was also adopted in the streamwise (x) direction to demonstrate consequences of air flow in a series of different street canyons. The upper boundary was specified as a slip condition with zero vertical variation. The periodic boundary condition took effects of a series of moving vehicles into considerations. Effects of moving vehicles would be different in strength and domain. Details on periodic boundary conditions would not be discussed in the current work, as this paper is a feasibility study on the method to simulate moving vehicles and the effect on air flow in an urban street canyon. In order to ensure the full development of flow fields, data were analyzed after each simulation had been running for over 10 minutes.

Table 1. The simulation cases and the parameter values.

Cases	Background wind velocity (U_{ref}) /m s^{-1}	Vehicle speed (V_s) /km h^{-1} (m s^{-1})
NVS	3	0
VS1	3	9 (2.5)
VS2	3	36 (10)
VS3	10	9 (2.5)
VS4	10	36 (10)
VS5	10	54 (15)

RESULTS AND DISCUSSION

Instantaneous and averaged wind velocities and turbulences in a street canyon were studied. LES simulated results of Case VS4 were compared with data obtained from wind tunnel experiments for model validation, as shown in Fig. 2. The air flow and turbulence characteristics within an urban street canyon under different vehicle moving speeds and background wind velocities were analysed. Results are shown in Figs. 3 and 4. Finally, LES simulated results were compared with the theoretical and experimental VIT models. Comparisons of results are shown in Table 2.

Model Validation against Wind Tunnel Experimental Data

Kastner-Klein *et al.* (2000b, 2001, 2003) simulated moving vehicles in a street canyon using solid boxes on driving crawler in their wind tunnel experiment, to study effects of moving vehicles on air flow, turbulence and pollutant's dispersion within a street canyon. In Kastner-Klein *et al.*'s (2003) wind tunnel experiments, vehicle speed was set at 30 km h^{-1}, wind velocity at a height of $4H$ was used as the reference wind velocity (U_{ref}), which varied from 5 m s^{-1} to 12 m s^{-1}. The experimental conditions were similar to that of Case VS4 in our current work, as shown in Table 1. Therefore, results of case VS4 were compared with results of Kastner-Klein *et al.*'s (2001) wind tunnel experiment for model validation.

The reference wind velocity was the average wind velocity at $4H$ level in Kastner-Klein *et al.*'s (2001) wind tunnel experiments, while it was the average wind velocity at $3H$ in Case VS4 in our current work. However, water tunnel experiments carried out by Li *et al.* (2008) showed that wind velocities above $2H$ would change little with rising height elevation. There are also some differences in vehicle moving conditions set in Case VS4 in our current work in comparison to conditions set in Kastner-Klein *et al.*'s (2001) wind tunnel experiments. In Kastner-Klein *et al.*'s (2001) wind tunnel experiments, vehicles were set in two-way two-lane traffic. The two lanes were set close to buildings. In Case VS4 of our current work, vehicles were set in two-way four-lane traffic. Vehicle lanes were set in the central region of the road, and there were pavements on both sides of the road. Vehicle moving conditions in Case VS4 were set according to actual traffic conditions in Xi'an (Zhang *et al.*, 2012a).

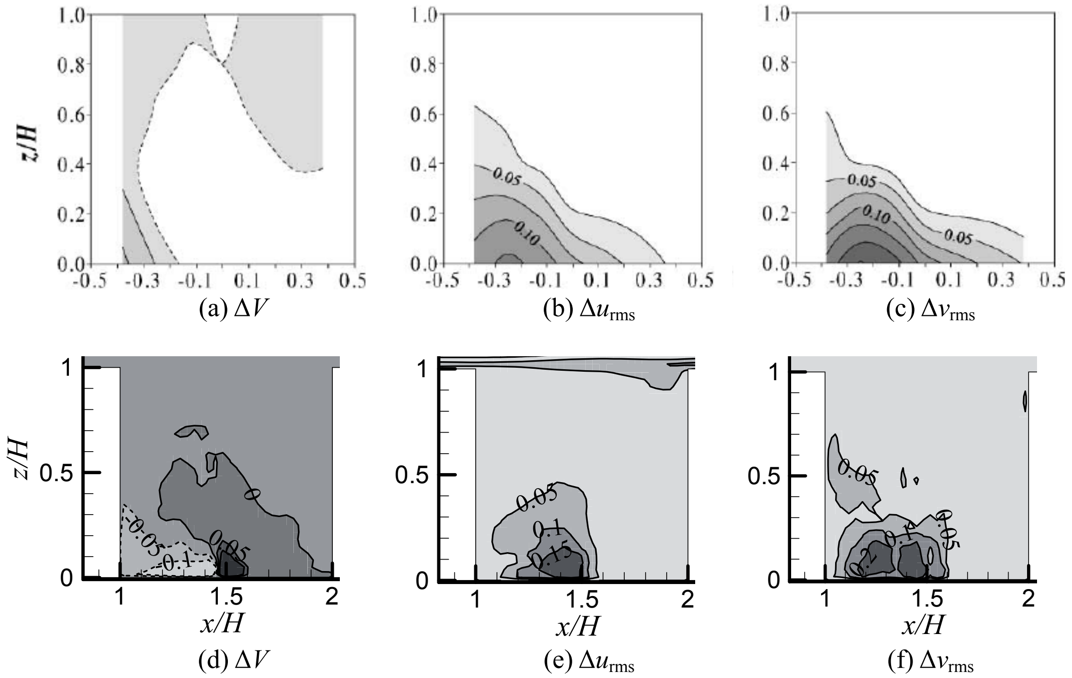


Fig. 2. Moving vehicles induced air flow and turbulence variations in street canyons in Kastner-Klein *et al.*'s (2001) wind tunnel experiments (upper) and in Case VS4 (lower).

Moving vehicles can significantly change the air flow and turbulence characteristics in an urban street canyon, especially in the lower portion of a street canyon. Variations in moving vehicles would induce air flow and turbulence in an urban street canyon and these were determined by subtracting the air flow and turbulence under the conditions when without vehicle movement. Fig. 2 shows the air flow and turbulence variations induced by moving vehicles in a street canyon from Kastner-Klein *et al.* (2001) wind tunnel experiments and in Case VS4 of our current work. Variations of average wind velocity in *y* direction (ΔV) and turbulence in *x* and *y* directions (Δu_{rms} and Δv_{rms}) are non-dimensioned by the reference wind velocity (U_{ref}).

Generally speaking, fairly good agreements could be found between the simulated results and the wind tunnel experiment data (Kastner-Klein *et al.*, 2001) by qualitative comparisons in terms of magnitude and distribution. When affected by the main air recirculation vortex, the induced wind velocity and turbulence variation caused by a moving vehicle would tilt to the leeward wall at the lower portion of a street canyon. In the wind tunnel experiment reported by Kastner-Klein *et al.* (2001), vehicle induced wind velocity and turbulence variation would be closer to the corner, as traffic lanes were close to buildings. While in our current simulation, the vehicle induced wind velocity and turbulence variation were shown to be closer to the midline, as the traffics were located in the central region of the road. The coordinate origin of *x* axis was at the left endpoint of the computational domain in our current simulations, while the coordinate origin of *x* axis was in the middle of Kastner-Klein *et al.*'s (2001) modelled street canyon. Fig. 2 also shows the variations in induced wind velocities of moving vehicles. There were differences in symbols, as vehicles were introduced to run on the left side lane in the wind tunnel experiments (Kastner-Klein *et al.*, 2001), whereas in our current simulations, vehicles were introduced to run on the right side lanes. As a group, the proposed vehicle drag force model has the potential to model the effects of moving vehicles on air flow and turbulence in an urban street canyon.

Turbulent Flow Characteristics in a Street Canyon with Moving Vehicles

The average wind velocities and turbulence inside a street canyon under different background wind and traffic conditions were investigated by our experiments. VIT were analyzed with root mean square (rms) values of *u*, *v* and *w* velocity components. In Figs. 3 and 4, the vertical profiles of average wind velocities and turbulence were shown on two lines: l1, $x = 1.25\ H$ and l2, $x = 1.75\ H$ on a spanwise middle cross section ($y = H$) of a road. The line l1 is located between the traffic lanes and the leeward wall, and the line l2 is located between the traffic lanes and the windward wall. The statistical average was conducted for 10 minutes. There were about 75 vehicles passed each traffic lane during the averaging time.

In Case NVS, which considered conditions without moving vehicles inside a street canyon, the averaged wind velocities and rms values were very weak, as shown in Figs. 3 and 4. In a street canyon with moving vehicles, either the average wind velocities or rms values of velocity components would change in comparison to the Case NVS, without moving vehicles. The variation magnitude of rms values of velocity components was obviously larger than variation in average wind velocities. Thus, the main effect of moving vehicles would be on air flow turbulence. This is the reason why some authors used the "vehicle induced

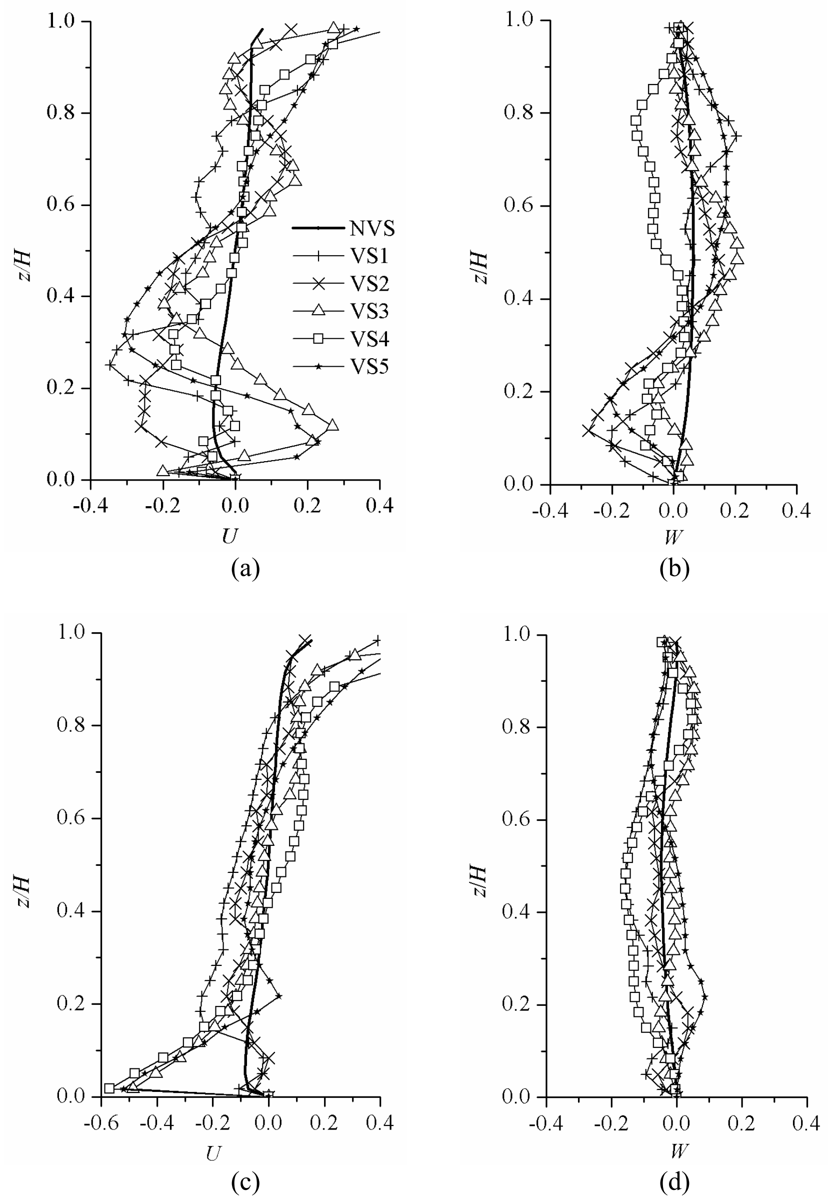


Fig. 3. The vertical distribution of normalized average wind velocities on the spanwise middle cross section. (a, U on line l1; b, W on line l1; c, U on line l2; d, W on line l2).

turbulence" to represent the moving vehicles' effects on wind characteristics in an urban street canyon (Kastner-Klein *et al.*, 2001; Di Sabatino *et al.*, 2003; Katolicky and Jicha, 2005; Mazzeo and Venegas, 2005; Kanda *et al.*, 2006; Kondo and Tomizuka, 2009).

In our current simulations, thermal effects were not considered, thus the mechanical turbulence generated by synoptic wind and moving vehicles would be the main factors affecting the dispersion of pollutants within a street canyon (Solazzo, 2007). In operational dispersion models, e.g., the Canyon Plume Box Model (CPBM) and WinOSPM, the VIT is generally included in the turbulent vertical dispersion parameter, σ_w, which can be calculated by Eq. (3):

$$\sigma_w^2 = aU_{ref}^2 + \sigma_{w0}^2 \qquad (3)$$

where the constant a is empirically set to equal 0.01 (Solazzo, 2007), σ_{w0}, is the vehicle induced vertical turbulence, denoted by w_{rms} in the current work.

Normalized vertical turbulence, w_{rms}/U_{ref}, could reveal the relative effect of VIT and the synoptic wind near road surface on pollutants' dispersion within a street canyon. Therefore, if the normalized vertical turbulence is larger than 0.1, the VIT would act as a major factor on pollutants' dispersion within a street canyon. However, if the normalized vertical turbulence is smaller than 0.1, the synoptic wind near road surface would be the main factor influencing the pollutants' dispersion in a street canyon.

In our simulations as shown in Fig. 4 and Table 1, for weak background wind conditions (Cases VS1 and VS2), the normalized vertical turbulence was obviously larger than 0.1, especially in the lower portion of the street canyon.

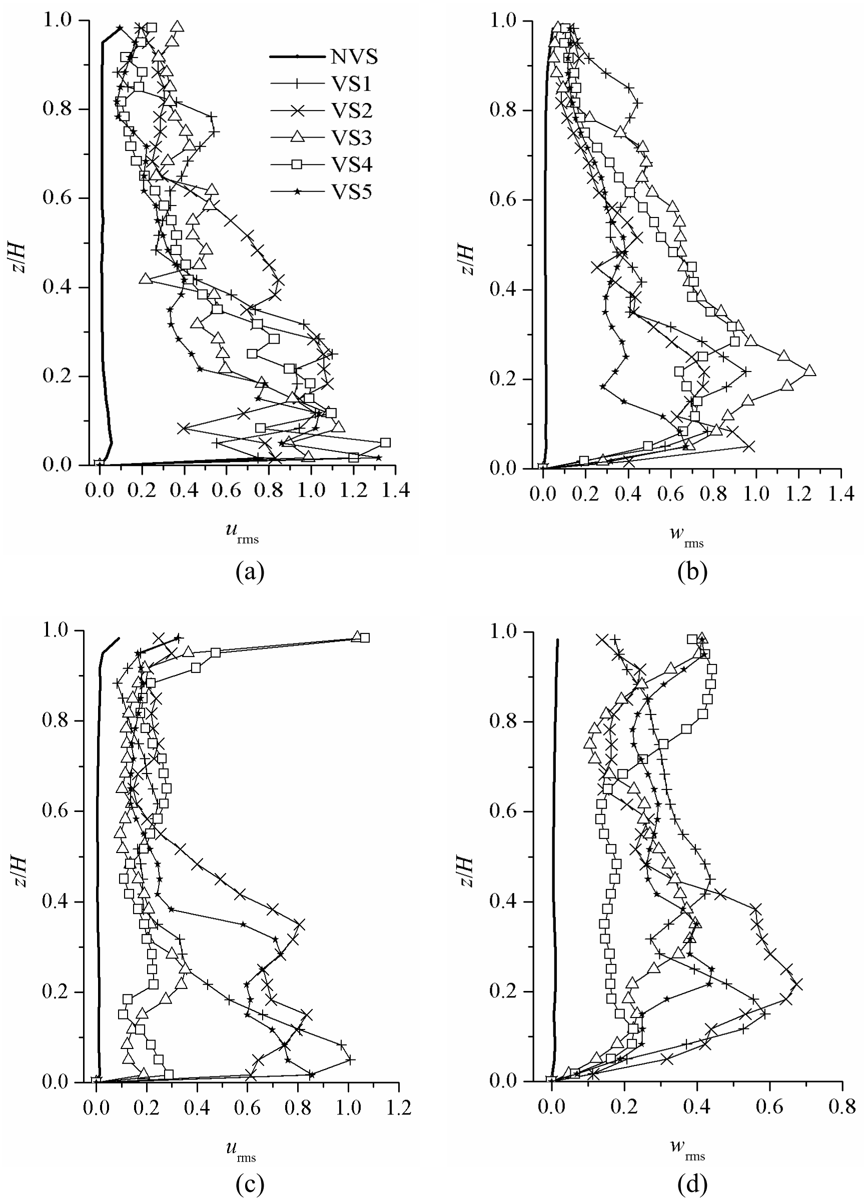


Fig. 4. The vertical distributions of normalized wind turbulence on the spanwise middle cross section (a, u_{rms} on line l1; b, w_{rms} on line l1; c, u_{rms} on line l2; d, w_{rms} on line l2).

For strong background wind conditions (Cases VS3, VS4 and VS5), the normalized vertical turbulence, overall, was smaller than 0.1. Generally, VIT was much larger in the lower portion of a street canyon than those in the upper portion, and VIT near the leeward wall (l1) was larger than those near the windward wall (l2).

In our current simulations under the same background wind condition (Cases VS3-VS5), the VIT did not show any variation with increasing speeds of moving vehicles. The result of the same traffic flow, 1800 veh h^{-1}, was set for all Cases in our current simulations.

Comparison with Theoretical and Experimental VIT Models

VIT in urban street canyons are usually parameterized in different schemes. Di Sabatino *et al.* (2003) proposed a theoretical model to estimate VIT in a street canyon. Traffic condition was divided into three regimes by the parameter of traffic density n_v: light (no interacting vehicle wakes), intermediate (interacting vehicle wakes) and large (strongly interaction vehicle wakes). The VIT in Di Sabatino *et al.* (2003)'s model was parameterized as the spatially averaged standard deviation of velocity fluctuations, σ_{w0}, as Eqs. (4a), (4b) and (4c), respectively.

$$\sigma_{w0}^2 = b_1 v_1^2 = c_1 n_v C_D^{2/3} h^3 S_c^{-1} v_1^2 \quad (4a)$$

$$\sigma_{w0}^2 = b_2 v_2^2 = c_2 (n_v C_D)^{2/3} h^2 S_c^{-2/3} v_2^2 \quad (4b)$$

$$\sigma_{w0}^2 = b_3 v_3^2 = c_3 C_D^{2/3} h^{4/3} S_c^{-2/3} v_3^2 \quad (4c)$$

where v_1, v_2 and v_3 are the average vehicle velocities for light, intermediate and large traffic densities and b_1, b_2 and b_3 are the related coefficients, respectively; h is the geometrical length scale of vehicles (e.g., square root of the frontal area of vehicle), S_c is the cross-section area in a street canyon in which VIT is active, which is also the averaging volume. Selection of an averaged volume is related to the area and parameterization is implemented in dispersion models.

Within the WinOSPM, the VIT was calculated by Eq. (5)

$$\sigma_{w0}^2 = bv^2 = (C_D^2 n_v h^2 W^{-1})v^2 \tag{5}$$

where W is the width of a street canyon, v is the average vehicle velocity (Solazzo *et al.*, 2007).

Di Sabatino *et al.*, (2003) compared the calculation result by Eq. (4b) with Kastner-Klein *et al.*'s (2001) wind tunnel experimental data, and the specified constant c_2 has a value of approximately one. However, only one data set was available for the comparison. For any recommendation of a particular value concerning the constants or length scales in the proposed parameterizations, an elaborated verification against data sets for a variety of vehicle velocities and densities would be needed (Di Sabatino *et al.*, 2003). The current work compared the simulated results of Cases VS2, VS4 and VS5 with the theoretical model (Di Sabatino *et al.*, 2003) according to Eq. (4b), and compared the Cases VS1 and VS3 with the theoretical model according to Eq. (4c). The calculated constant values of c_2 and c_3 are shown in Table 2.

The traffic and background wind conditions of Case VS4 is similar to that of Kastner-Klein *et al.*'s (2001) wind tunnel experiment. According to the averaged σ_{w0} in the lower half of a street canyon in Case VS4, c_2 was specified and has a value of 0.909, which is lower than the value calculated according to the wind tunnel experimental data. For Cases VS2 and VS5, the calculated values of c_2 are 0.798 and 0.641, respectively. Therefore, the values of c_1, c_2 and c_3 in Eqs. (3a), (3b) and (3c) could vary with different speeds and traffic densities of moving vehicles.

The parameterized σ_{w0} in the WinOSPM was implemented in the total canyon area. Thus our simulated results averaged in the total area of a street canyon were compared with the results obtained by the empirical model simulated in WinOSPM (Solazzo *et al.*, 2007). The comparison is shown in Table 2. Generally, the simulated results in our current work are higher than the calculated results from the empirical model obtained using WinOSPM. Although VIT could be calculated directly in our current work, in the wind tunnel experiments (Kastner-Klein *et al.*, 2001) and in the theoretical model (Di Sabatino *et al.*, 2003), parameters and constant values in operational models were generally determined according to measured pollutants concentrations at location points (Mazzeo and Venegas, 2005; Solazzo *et al.*, 2007). Therefore, the VIT model in operational models would just partially represent the influence of VIT on pollutants concentrations at measurement points, but do not represent VIT itself (Kondo and Tomizuka, 2009).

Discussions on the Instantaneous Air Flow

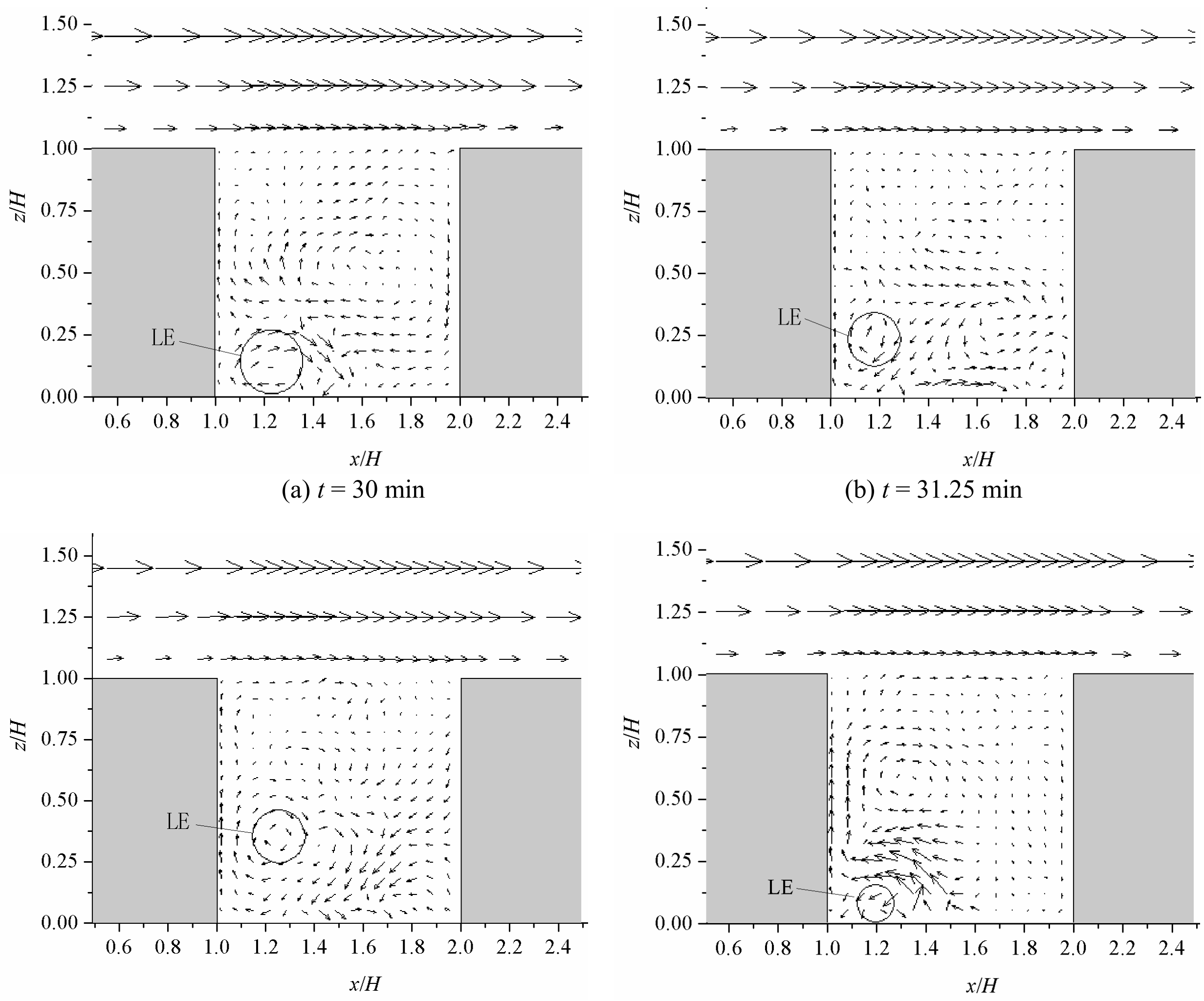
In our current numerical simulations, each moving vehicle was dynamically tracked, and each vehicle induced drag force was calculated. Thus instantaneous air flow field inside a street canyon with moving vehicles could be simulated. The supplementary material (S1) gives a short video to show the instantaneous air flow field on the pedestrian level in a street canyon.

Instantaneous air flow fields in a urban street canyon with moving vehicles are shown in Fig. 5. Generally, air flow inside an urban street canyon without moving vehicle is dominated by a main air recirculation vortex (Cui *et al.*, 2004). This air recirculation vortex inside the street canyon is generated by the strong shear layer on top of the street canyon and the down draft near the windward wall. Therefore, the horizontal wind velocities in the upper area of a street canyon are usually larger than those in the bottom area of a street canyon, while vertical wind velocities near the windward wall are larger than those near the leeward wall (Cui *et al.*, 2004).

Fig. 5 shows the instantaneous air flow field on the spanwise middle cross section ($y = H$) of a road at different time in a street canyon under low background wind velocity condition (Case VS2). When compared with air flow field in a street canyon without moving vehicles, instantaneous air flow fields are shown to have clear variations with moving vehicles inside a street canyon. Instantaneous wind velocities at the bottom of the street canyon are larger than those in the upper area, while instantaneous wind velocities near the leeward wall are larger than those near the windward wall. Therefore, in Case VS2, the main energy source of air flow inside a street canyon is originated from moving vehicles, but not from the strong shear layer on top of a street canyon. The intensity of the main air recirculation vortex is weaker than the intensity of induced air flow caused by moving vehicles inside a street canyon. The induced air

Table 2. Comparison of the VIT with different models.

		VS1	VS2	VS3	VS4	VS5
LES results in current work, σ_{w0} ($m\ s^{-1}$)	Averaged in the total canyon area	0.384	0.398	0.444	0.404	0.370
	Averaged in the lower half of the canyon area	0.490	0.540	0.557	0.474	0.499
Empirical model in WinOSPM, σ_{w0} ($m\ s^{-1}$) (Solazzo *et al.*, 2007)		0.135	0.269	0.135	0.269	0.330
Theoretical model, (Di Sabatino *et al.*, 2003)	c_2	-	0.798	-	0.909	0.641
	c_3	1.475	-	1.677	-	-
Parameter and value	n_v	0.2	0.05	0.2	0.05	0.0333



(a) t = 30 min (b) t = 31.25 min (c) t = 32.5 min (d) t = 33.75 min

Fig. 5. Instantaneous air flow fields on the spanwise middle cross section at different time in Case VS2 (a, t = 30 min; b, t = 31.25 min; c, t = 32.5 min; d, t = 33.75 min).

flow by moving vehicles was shown to incline to the leeward wall, affected by the main air recirculation vortex within a street canyon, resulting in higher wind velocities at the bottom part and near the leeward wall of a street canyon.

Local eddies (LE) are remarkable features of instantaneous air flow fields inside a street canyon with moving vehicles, as illustrated in Fig. 5. LEs can be found in other cases as well, as shown in Fig. 6. LEs would mainly occur at the bottom area and near the leeward wall of a street canyon. The wind velocities of these local eddies in the regime are larger than those of the main air recirculation vortex. Therefore, these LEs are not the secondary vortices in the corner regions that are driven by the main air recirculation within a street canyon (Michioka *et al.*, 2010; Zhang *et al.*, 2015), that could be induced by moving vehicles.

CONCLUSIONS

In our current work, a Lagrangian scheme for calculating vehicle drag forces has been developed to study effects of moving vehicles on air flow and turbulence in an urban street canyon, under different background wind and traffic conditions. Our simulated results were validated against wind tunnel experimental results, including variations of average wind velocities and turbulence inside a street canyon with/without moving vehicles.

Moving vehicles were shown to produce significant effects on wind turbulence as was illustrated by vertical distributions of average wind velocities and turbulence on a spanwise middle cross section of a road by our simulation. However, the effect on average wind velocities was low within a street canyon. Especially, VIT at the lower portion and near the leeward wall of a street canyon is larger than those in other areas of a street canyon.

Comparison with theoretical and empirical VIT models has shown that our simulations could predict higher VIT values than empirical model simulated using WinOSPM and would give slightly lower VIT values than the theoretical model. Some local eddies were found in the instantaneous air flow field within the street canyon; and these could be induced by moving vehicles.

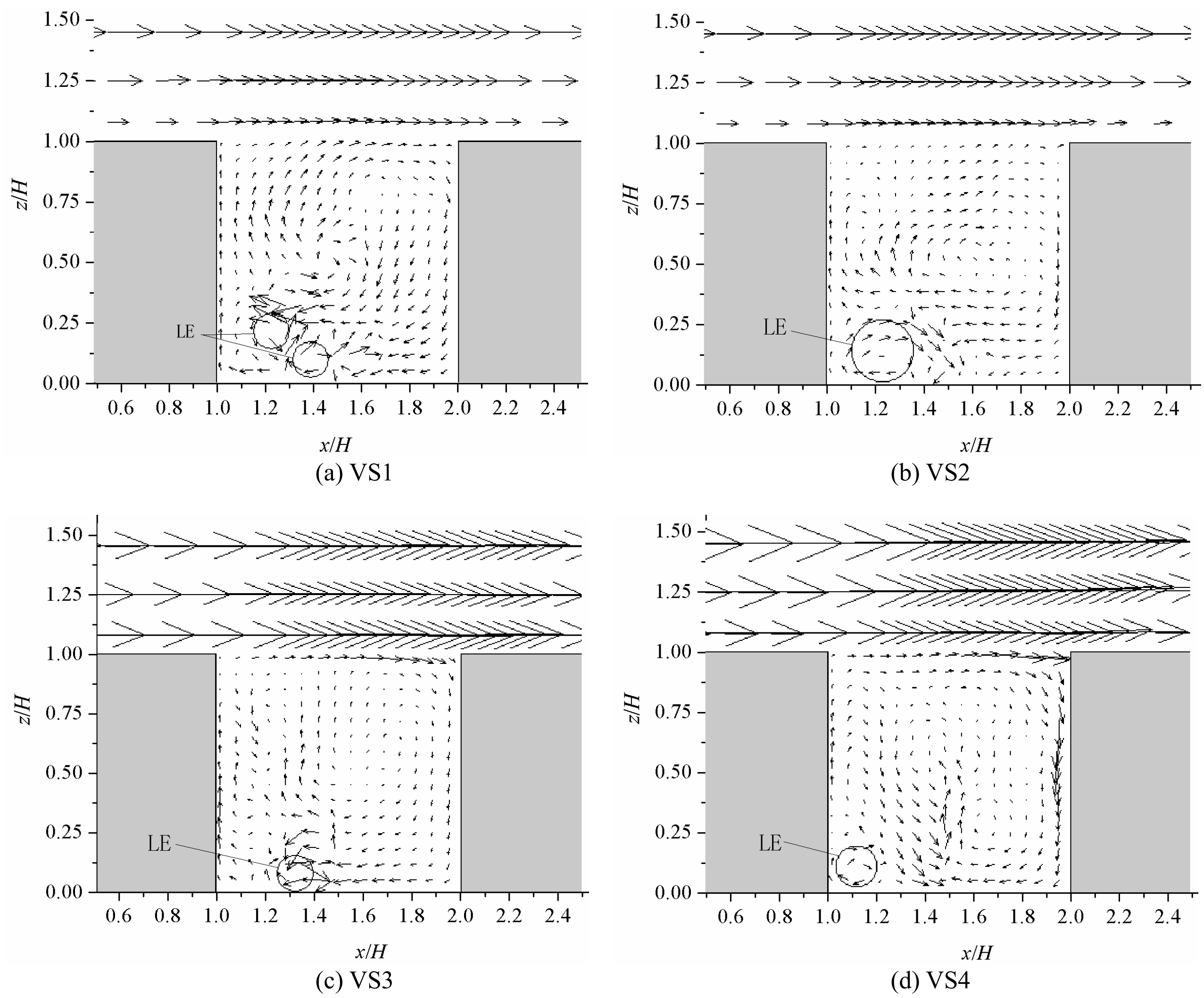


Fig. 6. Instantaneous air flow fields on the spanwise middle cross section at t = 30 min in Cases VS1-VS4.

ACKNOWLEDGEMENTS

This study was funded by the Fundamental Research Funds for the Central Universities Project (xjj2014054), the National Nature Science Foundation of China (No. 51508458) and the 12th Five Year Science and Technology Support Key Project of China (2012BAJ15B06).

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

REFERENCE

Ahmad, K., Khare, M. and Chaudhry, K.K. (2002). Model vehicle movement system in wind tunnels for exhaust dispersion studies under various urban street configurations. *J. Wind Eng. Ind. Aerodyn.* 90: 1051–1064.

Cheng, Y., Yu, C.W.F., Huang, Y., Zhang, Y.W., Gao, Y., Yau, P.S., Chan, C.S. and Lee, S.C. (2012). Particle counts and size distributions in the roadside environment. *Indoor Built Environ.* 21: 633–641.

Cui, Z.Q., Cai, X.M. and Baker C.J. (2004). Large-eddy simulation of turbulent flow in a street canyon. *Q. J. R. Meteorolog. Soc.* 130: 1373–1394.

Depaul, F.T. and Sheih, C.M. (1986). Measurements of wind velocities in a street canyon. *Atmos. Environ.* 20: 455–459.

Di Sabatino, S., Kastner-Klein, P., Berkowicz, R., Britter, R.E. and Fedorovich, E. (2003). The modelling of turbulence from traffic in urban dispersion models - Part I: Theoretical considerations. *Environ. Fluid Mech.* 3: 129–143.

Gu, Z.L., Zhang, Y.W. and Lei, K.B. (2010). Large eddy simulation of flow in a street canyon with tree planting under various atmosperic instability conditions. *Sci. China Ser. E: Technol. Sci.* 53: 1928–1937.

Jicha, M., Pospisil, J. and Katolicky, J. (2000). Dispersion of pollutants in street canyon under traffic induced flow and turbulence. *Environ. Monit. Assess.* 65: 343–351.

Jicha, M., Katolicky, J. and Pospisil, J. (2002). Dispersion of pollutants in a street canyon and street intersection under traffic-induced flow and turbulence using a low Re k-epsilon model. *Int. J. Environ. Pollut.* 18: 160–170.

Kanda I., Uehara K., Yamao Y., Yoshikawa Y. and Morikawa T. (2006). A wind-tunnel study on exhaust gas dispersion from road vehicles--Part I: Velocity and concentration fields behind single vehicles. *J. Wind Eng. Ind. Aerodyn.* 94: 639–658.

Kastner-Klein P., Fedorovich E., Sini J.F. and Mestayer P.G. (2000a). Experimental and numerical verification of similarity concept for dispersion of car exhaust gases in urban street canyon. *Environ. Monit. Assess.* 65: 353–361.

Kastner-Klein, P., Berkowicz, R. and Plate, E.J. (2000b). Modelling of vehicle-induced turbulence in air pollution studies for streets. *Int. J. Environ. Pollut.* 14: 496–507.

Kastner-Klein, P., Fedorovich, E. and Rotach, M.W. (2001). A wind tunnel study of organised and turbulent air motions in urban street canyons. *J. Wind Eng. Ind. Aerodyn.* 89: 849–861.

Kastner-Klein, P., Fedorovich, E., Ketzel, M., Berkowicz, R. and Britter, R. (2003). The modelling of turbulence from traffic in urban dispersion models - Part II: Evaluation against laboratory and full-scale concentration measurements in street canyons. *Environ. Fluid Mech.* 3: 145–172.

Katolicky, J. and Jicha, M. (2005). Eulerian-Largangian model for traffic dynamics and its impact on operational ventilation of road tunnels. *J. Wind Eng. Ind. Aerodyn.* 93: 61–77.

Kondo, H. and Tomizuka, T. (2009). A numerical experiment of roadside diffusion under traffic-produced flow and turbulence. *Atmos. Environ.* 43: 4137–4147.

Li, X.X., Liu, C.H., Leung, D.Y.C. and Lam, K.M. (2008). Physical modeling of flow field inside urban street canyons. *J. Appl. Meteorol. Clim.* 41: 2058–2067.

Mazzeo, N.A. and Venegas, L.E. (2005). Evaluation of turbulence from traffic using experimental data obtained in a street canyon. *Int. J. Environ. Pollut.* 25: 164–176.

Michioka, T., Sato, A., Takimoto, H. and Kanda, M. (2010). Large-eddy simulation for the mechanism of pollutant removal from a two-dimensional street canyon. *Boundary Layer Meteorol.* 138: 1–19.

Oke, T.R. (1988). Street design and urban canopy layer climate. *Energy Build.* 11: 103–113.

Perry, R. and Gee, I.L. (1994). Vehicle emissions and effects on air quality: Indoors and outdoors. *Indoor Built Environ.* 3: 224–236.

Qin, Y. and Kot, S.C. (1993). Dispersion of vehicular emission in street canyons, Guangzhou City, South China (P.R.C.). *Atmos. Environ.* 27: 283–291.

Sharma, P. and Khare, M. (2001). Modelling of vehicular exhausts-A review. *Transp. Res. D* 6: 179–198.

Solazzo, E., Cai, X. and Vardoulakis, S. (2008). Modelling wind flow and vehicle-induced turbulence in urban streets. *Atmos. Environ.* 42: 4918–4931.

Solazzo, E., Vardoulakis, S. and Cai, X. (2007). Evaluation of traffic-producing turbulence schemes within Operational Street Pollution Models using roadside measurements. *Atmos. Environ.* 41: 5357–5370.

Xie, X.M., Huang, Z. and Wang, J.S. (2005). Thermal effects on vehicle emission dispersion in an urban street canyon. *Transp. Res. D* 10: 197–212.

Zhang, Y.W., Gu, Z.L., Lee, S.C., Fu, T.M. and Ho, K.F. (2011). Numerical simulation and in situ investigation of fine particle dispersion in an actual deep street canyon in Hong Kong. *Indoor Built Environ.* 20: 206–216.

Zhang, Y.W., Gu, Z.L., Cheng, Y., Shen, Z.X., Dong, J.G. and Lee, S.C. (2012a). Measurement of diurnal variations of $PM_{2.5}$ mass concentrations and factors affecting pollutant dispersion in urban street canyons under weak-wind conditions in Xi'an. *Aerosol Air Qual. Res.* 12: 1261–1268.

Zhang, Y.W., Gu, Z.L. and Yu, C. (2012b). Time-series numerical simulation of wind flow within urban canopy layer and its integration effect for prediction of pollutant concentration variation. *Indoor Built Environ.* 21: 355–357.

Zhang, Y.W., Gu, Z.L., Wang, Z.S. and Yu, C.W.F. (2013a). Revisit of wind flows between wind tunnels and real canyons – The viewpoint of reynolds dynamic similarity. *Indoor Built Environ.* 22: 467–470.

Zhang, Y.W., Gu, Z.L., Wang, Z.S., Cheng, Y. and Lee, S.C. (2013b). Advanced in the fine scale simulation of urban wind environment. *Indoor Built Environ.* 22: 332–336.

Zhang, Y.W., Zhang, H.W. and Gu, Z.L. (2015). Large eddy simulation of the wind field of urban street canyon induced by moving vehicles. *Environ. Sci. Technol.* 38: 64–69 (in Chinese).

Received for review, May 24, 2016
Revised, October 16, 2016
Accepted, October 26, 2016