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The influence of street layouts and viaduct settings on daily carbon monoxide exposure and intake fraction in idealized urban canyons

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ABSTRACT

Environmental concerns have been raised on the adverse health effects of vehicle emissions in micro-scale traffic-crowded street canyons, especially for pedestrians and residents living in near-road buildings. Viaduct design is sometimes used to improve transportation efficiency but possibly affects urban airflow and the resultant exposure risk, which have been rarely investigated so far. The personal intake fraction (*P_IF*) is defined as the average fraction of total emissions that is inhaled by each person of a population ($1\text{ppm}=1\times10^{-6}$), and the daily carbon monoxide (CO) pollutant exposure (E_t) is estimated by multiplying the average concentration of a specific micro-environment within one day. As a novelty, by considering time activity patterns and breathing rates in various micro-environments for three age groups, this paper introduces *IF* and E_t into computational fluid dynamic (CFD) simulation to quantify the impacts of street layouts (street width/ building height W/H=1, 1.5, 2), source location, viaduct settings and noise barriers on the source-exposure correlation when realistic CO sources are defined. Narrower streets experience larger P_*IF* (1.51-5.21 ppm) and CO exposure, and leeward-side buildings always attain higher vehicular pollutant exposure than windward-side. Cases with a viaduct experience smaller P_IF (3.25-1.46 ppm) than cases without a viaduct (P_IF=5.21-2.23 ppm) if the single ground-level CO source is elevated onto the viaduct. With two CO sources (both ground-level and viaduct-level), daily CO exposure rises 2.80-3.33 times but P_IF only change slightly. Noise barriers above a viaduct raise concentration between barriers, but slightly reduce vehicular exposure in near-road buildings. Because people spend most of their time indoors, vehicular pollutant exposure within near-road buildings can be 6-9 times that at pedestrian level. Although further studies are still required to provide practical guidelines, this paper provides effective methodologies to quantify the impacts of street/viaduct configurations on human exposure for urban design purpose.

***Capsule (Limit 185 Characters)**

Wider street and urban viaduct with a single elevated source could alleviate indoor exposure and building intake fraction. Adding noise barriers has no significant impact.

Keywords: Street canyon, Intake fraction, Daily pollutant exposure, Viaduct, Noise barrier

1. Introduction

Following the ongoing worldwide urbanization, traffic exhaust and non-exhaust emissions in cities constitute the major sources of urban air pollution, including fine particulate matter ($PM_{2.5}$), carbon monoxide, nitric oxide and benzene etc (Fenger, 1999; Pu and Yang, 2014).The population exposure to high air pollutant concentration is one of the major factors resulting in adverse health problems in cities (Luo et al., 2010; Zhou et al., 2013; Ji and Zhao, 2015), especially for sensitive groups like children and the elderly. Moreover, on average people spend more than 90% of their time indoors, the traditional epidemiology study linking mortality directly to outdoor pollution concentration may cause bias and give rise to exposure misclassification (Chen et al., 2012a,b) as outdoor air pollutants could penetrate indoors via doors/windows, ventilation systems and building cracks and cause indoor exposure to outdoor origins (Chen et al., 2012c; Ji and Zhao, 2015). Thus, improving the dispersion of vehicular pollutants in the urban environment can help improving urban air quality and reducing population exposure for both pedestrians and people living in near-road buildings (Zhang and Gu, 2013; Ng and Chau, 2014).

Extremely narrow street configurations, heavy traffic volumes and unfavourable meteorological conditions are the main reasons of serious vehicular street air pollution. As recently reviewed by the literature (Fernando et al., 2010; Kumar et al., 2011; Di Sabatino et al., 2013; Blocken, 2015; Meroney et al., 2016; Lateb et al., 2016), numerous field/wind tunnel experiments and computational fluid dynamic (CFD) simulations have contributed to understanding the impacts of urban design on the flow and urban air pollution. It has been widely confirmed as the most effective design approach to improve street pollutant dispersion by lowering street aspect ratios (street height/street width, H/W) in two-dimensional (2D) street canyons (Oke, 1988; Meroney et al., 1996; Vardoulakis et al., 2003; Li et al., 2006; Xie et al., 2006; Li et al., 2009; Liu and Wong, 2014; Zhong et al., 2015) and building packing densities in three-dimensional (3D) urban-like models (Chang and Meroney, 2003; Di Sabatino et al., 2007; Hang and Li, 2011; Buccolieri et al., 2010; Yang et al., 2013; Ramponi et al., 2015). Other key urban parameters include building height variations (Gu et al., 2011; Hang et al., 2012) and typical high-rise buildings (Zhang et al., 2015), ambient wind directions (Kanda, 2006; Yassin, 2013; Lin et al., 2014; Kwak et al., 2016), street vegetation (Buccolieri et al., 2011; Gromke and Blocken, 2015a and 2015b), building roof shape (Takano and Moonen, 2013; Liu et al., 2015), traffic-flow patterns (Thaker and Gokhale, 2016) and real-time boundary wind conditions (Zhang et al., 2011) etc. In addition, thermal buoyancy forces induced by wall heating and solar shading can significantly influence (Cai, 2012; Allegrini et al., 2014; Yang and Li, 2015; Cui et al., 2016; Nazarian and Kleissl, 2016) or dominate (Yang and Li, 2009; Luo and Li, 2011; Dallman et al., 2014; Wang and Li, 2016) urban airflows and pollutant dispersion if Richardson (Froude) number is relatively large (small),

The adverse effects of vehicle emissions on people in near-road buildings require special concern (Zhou and Levy, 2008; Ng and Chau, 2014; Habilomatis and Chaloulakou, 2015) where the health risk is much higher than in other microenvironments. Most studies investigated the wind flow and emphasized spatial distribution of pollutant concentration in street canyons (e.g. Meroney et al., 1996; Xie et al., 2006; Li et al., 2009; Zhong et al., 2015) or near-road buildings (Kalaiarasan et al., 2009; Quang et al., 2012). However, the resultant pollutant exposure averaged over the population in the entire street canyon is more important for evaluating the overall impacts on people's health. Vehicular pollutant exposure is determined by three factors: the pollutant emission rate (mass per unit time) depending on traffic density, the capacity of pollutant dispersion associated with urban layouts and meteorological conditions, the distance of people from pollutant sources and time activity patterns. Furthermore, viaducts are sometimes used to improve transportation efficiency in traffic-crowded urban areas. Noise barriers at two sides of a viaduct are usually adopted to protect near-road residents from the adverse effects of noise, but possibly influence pollutant exposure. To date, there remains a shortage of studies reporting on how street layouts coupled with viaduct settings and noise barriers influence pollutant exposure in near-road buildings.

The concept of intake fraction (*IF*) represents the fraction of total pollutant emissions that is inhaled by a population (Bennett et al., 2002). Only a few studies estimated *IF* within micro-scale urban canyons (Zhou and Levy, 2008; Habilomatis and Chaloulakou, 2015). But the existing studies only considered realistic streets as case studies and did not examine how *IF* would be affected by street layouts and viaduct settings for design purpose. By conducting CFD simulations coupling with daily pollutant exposure, Ng and Chau (2014) assessed how the designs of building permeability and street setbacks influence daily population exposure inside idealized street canyons, but they did not look at the interactive flow between urban space and interior building space. As a novelty, this paper introduces two metrics, i.e., both intake fraction (*IF*) and daily pollutant exposure into CFD simulations to quantify the impacts of street aspect ratios, viaduct settings, noise barriers and source locations on vehicular exposure under neutral meteorological conditions, for street and viaduct design purpose.

The remainder of this paper is structured as follows: Section 2 describes the concepts of personal intake fraction (*P_IF*) and daily pollutant exposure. Section 3 introduces CFD setups and test cases investigated, while Section 4 presents CFD validation using wind tunnel data. Results are discussed in Section 5 and conclusions are drawn in Section 6.

2. Human exposure indices to vehicle emissions

2.1. Personal intake fraction (P_IF)

An intake fraction (*IF*) of 1 ppm (part per million) indicates that 1 g of air pollutants is inhaled by an exposed population from one ton of pollutants emitted from the source. Obviously *IF* depends on population density, but is independent of the pollutant release rate. *IF* has been widely used to determine the fraction of total emissions that is inhaled by a population at various scales. Indoor *IF* is commonly high (~2-20 $\times 10^3$ ppm) (Nazaroff, 2008) due to human's close proximity to pollutant sources. City-scale and regional-scale vehicular *IF* are relatively small, for example, *IF* of 1-10 ppm in US cities (Marshall et al., 2005) and 270 ppm in Hong Kong (Luo et al., 2010), and *IF* of primary $PM_{2.5}$ for the entire continental United States was reported at 0.12-25 ppm (Greco et al., 2007).

The high-resolution vehicular *IF* in micro-scale street canyons should be further emphasized. So far, only a few researchers examined street-scale *IF* for case studies. Recently, Habilomatis and Chaloulakou (2015) conducted CFD simulations to calculate *IF* of vehicular ultrafine particles in a 2D street canyon (*H*/*W*=1.5) of the central Athens in Greece reporting an overall *IF* of 371 ppm. By using modelling data (not CFD), Zhou and Levy (2008) investigated *IF* for a typical street canyon in midtown Manhattan, New York, obtaining an overall *IF* of 3000 ppm due to the high population density and poor urban ventilation. This paper aims to examine how idealized street layouts and viaduct settings affect vehicular pollutant distribution and its resultant exposure to inform future urban design.

For a specific vehicular pollutant, the intake fraction (*IF*) is defined as below

(Zhou and Levy, 2008; Luo et al., 2010; Habilomatis and Chaloulakou, 2015):

$$IF = \sum_{i}^{N} \sum_{j}^{M} P_i \times Br_{i,j} \times \Delta t_{i,j} \times Ce_j / m \qquad (1)$$

where m is the total emission rate over the period considered (kg), N is the number of population groups defined and M is the number of different microenvironments considered, P_i is the total number of people exposed in the i^{th} population group; Br_{ij} is the average volumetric breathing rate for individuals in the i^{th} population group (m^3/s) in the microenvironment j; $\triangle t_{ij}$ is the time spent in the microenvironment j for people group of i(s)**;** and Ce_j is the pollutant concentration attributable to traffic emissions in the microenvironment j (kg/m^3).

As referred to the literature (Chau et al., 2002; Allan et al., 2008), breathing rates in four micro-environmental categories (M=4) for three age groups (N=3) were defined (Fig. A1a in Appendix): indoors at home (j=1), other indoor locations (j=2), near vehicles (j=3), and other outdoor locations away from vehicles (j=M=4). The 2004 population census data for the Hong Kong (Luo et al., 2010) were adopted (Fig. A1b). Moreover, some assumptions were further proposed: The near-road buildings were residential, and only j=1 (Indoors at home) and j=3 (near vehicles, i.e. pedestrian level) were considered to assess *IF* for local residents and pedestrians (Fig. A1a).

Because *IF* for the entire population rises linearly with the increasing population density, this paper proposes the average personal intake fraction (*P_IF*) for a virtual person. This virtual person has an average breathing rate TBr_j combining the population subgroups for each time-activity pattern j (j=1 and 3). Thus *P_IF* is independent of population density.

$$P\_IF = IF / \sum_{i}^{N} P_i = \sum_{j}^{M} TBr_j \times \Delta t_j \times Ce_j / m \qquad (2)$$

Here $\triangle t_j$ is the time spent in the microenvironment j for the entire population.

2.2. Daily Pollutant exposure of CO (E_t)

The daily pollutant exposure is defined as the extent of human beings' contact with different air pollutants within one day which is estimated indirectly by multiplying the average concentration of a specific micro-environment within the time people spend in it. Different from the intake fraction, daily pollutant exposure depends on the realistic pollutant emission rates. Mathematically, for a specific population subgroup, it is calculated as below (Ng and Chau, 2014):

$$E_t = \sum_{j=1}^{M} E_{t,j} = \sum_{j=1}^{M} C_{real,j,k} \times t_j \qquad (3)$$

where $E_{t,\mathrm{j}}$ is the daily pollutant exposure (mg/m^3/day) of the j^{th} microenvironment, and j=1, 2, 3, 4 representing the time activity pattern in Fig. A1a. Thus, E_t is the total pollutant exposure for all microenvironments. $C_{real,j,k}$ is the exposed pollutant concentration in the j^{th} microenvironment at the k^{th} side (leeward or windward side). Similarly, we only considered the time t_{j} people spend indoors at home (j=1) or near vehicles (j=3) within a day (Fig. A1a) assuming near-road buildings are residential.

3. CFD methodologies

3.1. Description of CFD test cases and flow modelling

Large Eddy Simulations (LES) are known to perform better in predicting turbulence than the Reynolds-Averaged Navier-Stokes (RANS) approaches in urban airflows and pollutant dispersion modelling (Kanda, 2006; Gu et al., 2011; Li et al., 2009 and 2015; Liu et al., 2014 and 2015; Zhong et al., 2015). But there are still challenges to LES applications including the much longer computational time, the development of advanced sub-grid scale models, the difficulty in specifying appropriate time-dependent inlet and wall boundary conditions. We are aware that steady RANS turbulence models have deficiencies in predicting turbulence, for example they fail to predict the sizes of reattachment lengths behind buildings and under-predict the velocity in weak wind regions (Yoshie et al., 2007). In spite of its limitations, the RNG k-ε model (Yakhot and Orszag, 1986) has been successfully validated in predicting mean airflows and pollutant dispersion in urban-like models (e.g.Tominaga and Stathopoulos, 2013; Ho et al., 2015; Blocken, 2015; Meroney, 2016; Habilomatis and Chaloulakou, 2015) and those coupling indoor-outdoor airflows (e.g. Gao et al., 2008; van Hooff and Blocken, 2010 and 2013; Ramponi and Blocken, 2012; Jin et al., 2015; Hang et al., 2016). Thus CFD software Ansys FLUENT (Fluent, 2006) with the RNG k-ε model was used to solve the steady-state isothermal urban airflows. The governing equations were discretized by a finite volume method with the second order upwind scheme. The SIMPLE scheme was used for the pressure and velocity coupling.

Fig. 1 depicts full-scale urban models investigated by CFD simulations. The height of all buildings stays as constant as H=24 m (y direction), and the width of target street canyon varies from W=24, 36 to 48 m (W/H=1, 1.5, 2) with its span-wise (or lateral) length of L=12 m (y direction). There are two identical street canyons (W'=24 m) neighbour to the target street canyon with one in the upstream and the other in the downstream to explicitly reproduce roughness elements. There are eight-storey buildings at both leeward and windward sides with a door at the first floor (2 m tall, 4 m wide) and windows (1 m tall, 4 m wide) at the other storeys. Each storey is 3m high with the room height of 2.7 m and room floor thickness of 0.3 m. For cases with a viaduct, the width of the viaduct is fixed as W_b=16 m. The viaduct is elevated as 9 m above the ground, and its thickness is 1m. In addition, there are noise barriers installed at the sides of the viaduct. Two barrier heights are considered, i.e., 2m and 4m respectively. The birds' eye view in cases with a viaduct are depicted in Fig. A2. The model description in test cases without a viaduct is also displayed in Fig. 1. At two lateral domain boundaries, symmetrical boundary conditions are assumed. We are aware that, an idealized 2D street canyon with symmetrical lateral boundary condition represents a simplified urban geometry of an infinitely long street with a perpendicular approaching wind to street axis, but it can serve as a platform to synthesize the physical and chemical processes found in the urban environment which is currently still and commonly investigated (Allegrini et al., 2014; Ho et al., 2015; Liu et al., 2014 and 2015; Li et al., 2015; Zhong et al., 2015). The similar 2D urban model coupling indoor and outdoor airflows have been adopted by Gao et al. (2008) and Hang et al. (2016).

All test cases are summarized in Table 1. Three kind of street canyons with W/H

=1, 1.5 or 2 (*H*=24 m) are included, and four types of viaduct settings are considered, i.e. with no viaduct (Case Nv[*W/H*]), with viaduct but no noise barriers (Case V[*W/H*]), with viaduct and barrier 1 (2 m tall, Case Vb1[*W/H*]), with viaduct and barrier 2 (4 m tall, Case Vb2[*W/H*]). The grid size normal to wall surfaces is 0.1 m (0.004*H*) which is based on the grid independence study in the CFD validation case. CFD grid arrangement in cases with a viaduct is depicted in Fig. A2. The total number of hexahedral cells is about 1.3 million to 2.1 million. For Case Nv[1], we also used a finer grid arrangement with grid size of 0.05m at wall surfaces to perform a mesh-dependency test, finding that CFD results change little with the finer grid.

No-slip wall boundary condition with standard wall function was applied for near-wall treatment. Zero normal gradient conditions were used at the domain top (i.e. symmetry), domain outlet (i.e. outflow) and two lateral domain boundaries (i.e. symmetry). At the domain inlet, a power-law velocity profile was applied as below.

$$U_0(z) = U_{ref}\left(\frac{z-H}{z_{ref}}\right)^{\alpha} \tag{4a}$$

$$k_{in}(z) = (U_{in}(z) \times I_{in})^2 \tag{4b}$$

$$\varepsilon_{in}(z) = \frac{C_{\mu}^{3/4} k_i^{3/2}}{\kappa z} \tag{4c}$$

where U_{ref}=3 m/s is the reference velocity, *H*=24 m and z_{ref} is the reference height of 40 m. The power-law exponent of α=0.22 denotes the underlying surface roughness depending on the terrain category of a medium-dense urban area. I_{in}= 0.1 is turbulence intensity, C_{μ} =0.09 and κ is the von Karman constant (κ=0.41).

The reference Reynolds number based on the building height ($\mathrm{Re} = U_{ref} H / \nu$, ν is the kinematic viscosity, *H*=24 m) is about 4.8×10^6 and that based on the room window height is 19733 ($\mathrm{Re} = U_{ref} h_w / \nu$, h_w=0.1 m). Both are much greater than 11000 to ensure Reynolds number independence (Snyder, 1972).

3.2. CFD setups in dispersion modelling

In this study, carbon monoxide (CO) was selected as a vehicular pollutant being emitted from volumetric sources in the target street canyon. For cases with a viaduct (Fig. 1), there are two situations of CO sources: (1.) a single CO source (Source 1) is fixed above the viaduct (i.e. viaduct-level only, no source near the ground), (2.) two CO sources are present at viaduct-level (Source 1) and ground-level (Source 2, near the ground). The geometry sizes and emission rates of CO sources are fixed as constants (width W_b=16 m, length L=12 m). Ng and Chau (2014) adopted a realistic total traffic emission of carbon monoxide (CO) with the release rate of 6503.6 (g/h) by counting traffic numbers in a realistic street (source length=street length=180 m) in Mongkok, Hong Kong, as proposed by Xia and Shao (2005). This paper utilizes the same emission rate per unit street length (36.1 g/h/m, source length L=12m, Fig. 1) for each CO source. Obviously with two CO sources the total realistic CO emission rate doubles. For cases without a viaduct, only ground-level Source 2 exists within the pedestrian regions (z=0 to 2 m, Fig. 1).

The governing equation of time-averaged CO concentration C (kg/m^3) is:

$$\bar{u}_j \frac{\partial C}{\partial x_j} - \frac{\partial}{\partial x_j}((D_m + D_t)\frac{\partial C}{\partial x_j}) = S \tag{5}$$

where $\bar{u}_j$ is the time-averaged velocity component, S is the CO emission rate, D_m and D_t are the molecular and turbulent diffusivity of pollutants. Here $D_t = \nu_t / Sc_t$, ν_t is the kinematic eddy viscosity and Sc_t is turbulent Schmidt number (Sc_t=0.7) (Hang et al., 2012; Di Sabatino et al., 2007).

For the boundary condition of Eq. (5), the zero normal flux condition was set at wall surfaces, and zero normal gradient conditions at the domain outlet and domain roof. At the domain inlet, the concentration was defined as zero. It is worth mentioning that, in present CFD simulations, the density of air is 1.177 kg/m^3 (average molecular weight 28.966) which is a little greater than the density of CO 1.138 kg/m^3 (average molecular weight 28.011). Thus the buoyancy effects due to the density difference is little.

After Eq. (5) was solved, the personal intake fraction and daily CO exposure were analysed. Here we mainly considered two microenvironments (Fig. A1a), in near-road buildings (indoors at home) and for pedestrian regions (near vehicles).

4. CFD validation studies

4.1 CFD Validation of single-sided ventilation flow modelling

Wind tunnel data from the literature (Jiang et al., 2003) were used to evaluate the numerical accuracy of isothermal flows in single-sided ventilation by coupling indoor and outdoor airflows. As depicted in Fig. A3, the dimension of the reduced-scale cubic building is 0.25m×0.25m×0.25m, with a wall thickness of 0.006 m and opening size of 0.125 m×0.084 m at both windward-side or leeward-side walls. The time-averaged stream-wise velocity U and vertical velocity V along 10 vertical lines at the building centre section were measured by a laser Doppler anemometer (Jiang et al., 2003). In CFD simulations (Fig. A3a), full-scale models with a building size of 2.5m×2.5m×2.5m and opening size of 1.25m×0.84m were used (scale ratio is 10:1). x, y and z are the stream-wise, span-wise (lateral) and vertical directions. $x/H=0$ is the location of the windward building surface. The computational domain has a downstream length of $28H$, an upstream length of $6H$, a lateral length of $7.5H$ on both sides, and a height of $6H$.

At the domain inlet, the vertical profiles of stream-wise velocity $U_0(z)$, turbulent kinetic energy (k) and its dissipation rate (ε) were adopted the same as in the wind tunnel (Jiang et al., 2003).

$$U_0(z) = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right) \tag{6a}$$

$$k_{in}(z) = u_*^{\,2} / \sqrt{C_\mu} \tag{6b}$$

$$\varepsilon_{in}(z) = C_\mu^{3/4} k^{3/2} / (\kappa z) \tag{6c}$$

where u_* is the friction velocity which equals 1.068m/s, z_0 is the aerodynamic roughness height equalling 0.05 m in the full-scale CFD model.

The RNG k-ε model with a standard wall function was adopted to solve the turbulence. To ensure grid independency, the medium and fine grid arrangements were used with the smallest grid size of $\triangle x=\triangle y=\triangle z=0.1$ m and 0.05 m at wall surfaces respectively. For the medium and fine grid, the hexahedral meshes of 0.49 and 1.14 million are produced (Fig. A3a). All the other CFD setups are similar to subsection 2.1.

Figs. A3b and A3c show the vertical profiles $U(z)/U_{ref}$ along the vertical lines at x=-0.04H, x=0.5H for windward single-sided ventilation, and at x=0.5H, x=1.04H for leeward single-sided ventilation. Here U_{ref} is the reference velocity (10 m/s). The predicted $U(z)/U_{ref}$ profiles match wind tunnel data well for regions below and near the roof level. The grid independence study shows little difference between two grid arrangements. These facts confirm the RNG k-ε model with medium grids (minimum grids of $\triangle x=\triangle y=\triangle z=0.1$m) performs well in predicting single-sided ventilation airflows.

4.2 CFD Validation of pollutant dispersion modelling in 2D street canyons

Meroney et al. (1996) conducted wind tunnel experiments of pollutant dispersion in 2D street canyons with a perpendicular wind to its street axis (Fig. A4 in Appendix). There were 28 parallel 2D street canyons (uniform building height $H=W=B$=60mm) with 20 street canyons upstream to the target street canyon and 8 downstream. A steady line tracer gas (ethane) source exists in the target street. In CFD simulations, the same model geometry and boundary conditions with wind tunnel experiments were adopted (Fig. A4). The total grid number was 372.889. No slip wall boundary condition was set at wall surfaces. The normalized concentration is defined as $K=\bar{c}\,UHL/Q$, where $\bar{c}$ is the measured tracer gas concentration, L is line source length and Q is the source emission rate, U is wind velocity measured in the free stream at 0.50 m above wind tunnel floor. With V_{in}=3m/s at the domain inlet, Fig. A4 shows the CFD validation profiles of K along windward and leeward walls. As expected windward K is much lower than that leeward K. Numerical K predicted by the RNG k-ε model agree with wind tunnel data generally well.

5. Results and discussion

5.1. Effects of aspect ratio, viaduct and noise barriers on flow and dispersion

Figs. 2 and 3 display streamline, velocity and CO concentration in the lateral centre plane in some example test cases. Note that for cases with a viaduct, two situations are included, i.e. with only a single elevated CO source or two CO sources at the viaduct-level and ground-level. Obviously, as *W*/*H*=1 or 2, the single clockwise main vortex exists with different locations of vortex centre (Fig. 2), and the leeward-side concentration is always much higher than that on the windward-side (Fig. 3). Wider streets (*W*=2*H*=48 m) always experience much lower concentrations than narrower streets with *W*=*H*=24 m, no matter with or without a viaduct (Fig. 3). These findings are similar to those in the literature representing different types of flow regions in the street canyon (e.g. Oke, 1988; Meroney et al., 1996; Xie et al., 2006; Allegrini et al., 2014). In addition, the existence of a viaduct slightly elevates or changes the vortex centre (Fig. 2). Since the single CO source is elevated onto the viaduct, the high-pollution region is raised onto the viaduct level (Fig. 3), moreover, CO concentration in the leeward-side building becomes much lower than that without a viaduct (Fig. 3) because the elevated viaduct reduce the distance of source to street roof level and improve pollutant dispersion out of the street canyon. In principle, it can be regarded as an introduction of a new horizontal surface with the street canyon, therefore the street canyon is divided into two parts vertically. Therefore, the effective aspect ratio is reduced by the elevated viaduct surface. If noise barriers are fixed on viaducts (Case Vb2[*W*/*H*]), due to their shelter effect the velocity above viaducts and between barriers is relatively small (Fig 2), a much higher pollutant concentration is expected between the barriers (Fig. 3), Therefore, a higher exposure to drivers in the vehicles on the urban viaduct can be envisaged, but noise barriers seem not to raise CO concentration in the near-road buildings.

In cases with a viaduct, we also consider two CO sources (ground-level and viaduct-level), assuming the total realistic pollutant emission rate doubles due to the increase of the traffic capacity. As two examples, Fig. 3 also shows CO concentration in the lateral centre plane in Case Vb2[1] and Vb2[2] with the viaduct and two CO sources (W/H=1 or 2). Obviously, in contrast to those with the single elevated source, even the flow is the same, CO concentration with two sources is much higher. For a street of W=H=24 m, the leeward-side rooms at the first and second floors are polluted more seriously than the upper floors. For a wider street (W=2H=48 m), vertical gradient of CO concentration for rooms in both windward and leeward sides are small.

5.2. Effects of aspect ratios, viaduct and noise barriers on daily CO exposure

Vertical profiles of indoor daily CO exposure at various heights

Fig. 4 displays the spatially-averaged indoor daily CO exposure at each floor of near-road buildings with a single ground-level or viaduct-level CO source. Obviously, wider streets (W/H=1, 1.5, 2) are prone to smaller CO exposure for each floor, and leeward-side CO exposures are always greater than windward-side. More importantly, in contrast to Case Nv[W/H] without a viaduct (single ground-level source), cases with a viaduct (single viaduct-level source) always attain smaller leeward-side CO exposure but greater windward-side CO exposure. For cases with a viaduct, Figs. 4 also compares daily CO exposure in each floor with single source and with two sources. As W/H=1, 1.5 and 2, two sources obviously produce much greater daily CO exposure than single source. Moreover noise barriers only slightly affect daily CO exposure in near-road buildings. CO exposure decreases slightly towards upper levels..

Total CO exposure (E_t), for indoors (E_{indoor}) and at pedestrian level (E_{ped})

Figs. 5-6 and Table 2 display the average daily CO exposure in the entire near-road buildings (E_{indoor}) and that at the pedestrian level (E_{ped}) with one source or two sources as well as their ratios in all test cases.

When only one single CO source is presented on the elevated viaduct, viaduct settings (V, Vb1, Vb2) could attain much smaller CO exposure both indoors and at pedestrian level than those without a viaduct (Nv), accounting for only 60-75% of total CO exposure for non-viaduct cases (Table 2). Meanwhile, the ratios of leeward-side CO exposure to windward-side ($E_{leeward1}$/ $E_{windward1}$) are 3.34-3.96 in cases without viaduct, but this ratio in cases with viaducts are only 1.16-1.23 (Table 2). These results confirm that, viaduct settings significantly weaken the exposure ratio $E_{leeward1}/E_{windward1}$ by reducing leeward-side CO exposure and raising windward-side CO exposure. Furthermore, Figs. 5 and 6 also show that widening the street (from W/H=1 to 2) could potentially reduce total daily CO exposure for all the cases. Finally, noise barriers (Vb1, Vb2) do not have significant impact on the daily CO exposure for the viaduct settings (Figs. 5-6), however, it should be noted that they may increase the in-vehicle exposure on the viaduct although it is not the focus of current study.

When there exist two CO sources (both at the pedestrian and viaduct levels), the total CO exposure ($E_{t2}=E_{indoor2}+E_{ped2}$) can be 2.67-3.33 times as great as those with a single CO source ($E_{t1}=E_{indoor1}+E_{ped1}$) (Fig. 5 and Table 2), and $E_{leeward2}$/ $E_{windward2}$ with two sources are 2.40 to 3.52, which is much greater than $E_{leeward1}$/ $E_{windward1}$(1.16 to 1.23) with a single source (Table 2). Irrespective of the number of CO sources, $E_{indoors}$ are always 6-9 times of E_{ped} since people spend much shorter time outdoors (at pedestrian level) than indoors (Fig. 5 and Table 2), highlighting the importance of necessity to include indoor exposure to outdoor origins into the traditional epidemiological pollution exposure study.

5.3. Effects of aspect ratios, viaduct and noise barriers on intake fraction

Personal intake fraction (*P_IF*) are depicted in Fig. 7 and Table2. For all cases investigated, wider streets (or greater W/H) experience smaller *P_IF* .

For cases with the single CO source, the values of *P_IF* for non-viaduct cases (Nv[W/H]) are 5.21, 3.06 and 2.23 ppm respectively for W/H=1, 1.5, 2. With viaduct setting and a single elevated CO source (V[W/H]), *P_IF* exhibits smaller values (1.46-3.59 ppm). Moreover, the introduction of noise barrier on the viaduct (Vb1[W/H] and Vb2[W/H]) show similar *P_IF* as those without noise barrier (V[W/H]) but are still much smaller than non-viaduct cases (Nv[W/H]).

If two CO sources are introduced in cases with viaduct settings, personal intake fraction (P_IF_2) is obviously greater than the one with a single source(P_IF_1). The ratio of P_IF_2/P_IF_1 ranges from 1.34 to 1.66, which is only half of the CO exposure ratio E_{t2}/ E_{t1}(2.67 to 3.33). It is reasonable that the intake fraction is an index normalized by the total pollutant emission rate whereas CO exposure is not. No matter one source or two sources, noise barriers (Vb1[W/H], Vb2[W/H]) seem to have little influence on personal intake fraction.

Finally, if it is assumed that 10 persons are living on each floor of the near-road buildings (8 floors, 160 persons), the total intake fraction (Table 2) ranges from 230 ppm to 834 ppm in cases with one source and 387 ppm to 913 ppm for cases with two sources. Our results are comparable to those in a street canyon (H/W=1.5) in the central Athens urban area, Greece (371 ppm) (Habilomatis and Chaloulakou, 2015), but much smaller than that in a typical deep street canyon in midtown Manhattan, New York (3,000 ppm), where a much larger population density was studied (Zhou and Levy, 2008). In this regard, the newly developed index of personal intake fraction show strong merits of independency of population density and emission rate, and is mainly decided by urban layouts and meteorological conditions, allowing comparison among different design strategies.

5.4 Limitations

It should be noted that we assumed the near-road buildings are residential-type. The current CO exposure evaluation possibly changes if different assumptions are adopted, for example the near-road buildings are office-type or mixture of office/residential types, or age subgroups and time patterns differ from Figs. 1b-1c. Although further investigations are still required to provide practical guidelines, this paper is one of the first attempts to quantify the significant source-exposure relationship influenced by the key factors of street layouts, configurations of viaducts/noise barriers. The findings can provide meaningful reference for decision makers and urban planners in formulating appropriate street and viaduct design policies to reduce near-road pollutant exposures. The methodologies adopted are confirmed promising and effective to assess the effects of various urban layouts and meteorological conditions on vehicular human exposure in more kinds of realistic/idealized urban models, for sustainable urban design purpose.

Our simulations mainly emphasize the cases with all windows open, allowing most potential of indoor-outdoor air exchange, however, in the reality, the windows may be closed or partly closed due to various reasons such as protection from the outside noise and cold air in the winter, using air conditioners in hot summer and desirable human behaviour among the others. The status of the windows may have significant impact on the penetration of outdoor pollutions and therefore alter the magnitude of indoor exposure to outdoor pollutants, for example, previous studies have found the installation of air-conditioners and close of the windows in winter is linked to the reduced risk to the mortality due to exposure to outdoor pollution (Chen et al., 2012a,b). Future work has been planned to consider such issue by integrating CFD and multi-zone building airflow modelling.

6. Conclusions

The present work is devoted to investigating the relationship of urban design and CO exposure both indoors and at pedestrian level to urban vehicular CO emissions, addressing the gap between the urban planning and pollution exposure field. Validated by wind tunnel data, CFD simulations are preformed to assess the effect of widening street (W/H=1, 1.5, 2 as the road-side building height H=24 m) and introducing viaducts and noise barriers on pollutant dispersion and vehicular human exposure when realistic CO sources are defined. As a novelty, both personal intake fraction (*P_IF*) and daily CO exposure (E_t) are used to quantify vehicular pollutant exposure. *P_IF* is a dimensionless index for overall exposure which is independent of the pollutant emission rate, but CO exposure depends on realistic pollutant emission rates and can show spatial distributions of exposure at various floor heights in near-road buildings.

The simulation results show that wider streets experience smaller *P_IF* and CO exposure, and leeward-side buildings always attain less vehicular pollutant exposure than windward-side. In contrast to cases without a viaduct (*P_IF*=5.21-2.23 ppm as W/H=1, 1.5, 2), the viaduct can lead to smaller *P_IF* (3.25-1.46 ppm) if the single pollutant source is elevated onto the viaduct level. Noise barriers on viaducts can significantly raise CO concentration above the viaduct and between the barriers, but slightly reduce pollutant exposure in near-road buildings. Assuming that 10 persons are living on each floor (8 floors, totalling 160 persons in two near-road buildings), the total intake fractions range from 230-913 ppm, which are the same order with that (371 ppm) in a street canyon (H/W=1.5) of the central Athens urban area in Greece (Habilomatis and Chaloulakou, 2015), but are much smaller than that (3,000 ppm) in a deep street canyon in midtown Manhattan, New York, with a large population density (Zhou and Levy, 2008). Because people spend most of their time indoors, pollutant exposure in near-road buildings can be 5-8 times greater than that at the pedestrian level of street canyons. Finally, the introduction of a viaduct tends to reduce pollutant exposure in leeward-side buildings but slightly raises that of windward-side. If there are two CO sources (ground-level, viaduct-level) in cases with a viaduct, overall CO exposure is much greater (2.80-3.33 times) than cases with a single elevated source above a viaduct. The ratios of leeward-side and windward-side exposure with two CO sources (2.40-3.52) are much greater than those with a single CO source (1.16-1.23).

Conflict of interest

The authors declare no competing financial interest.

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Table list

Table 1. Summary of test cases investigated by CFD simulations.

Table 2. Daily CO exposure, personal intake fraction (*P_IF*) and total intake fraction (*IF*) in Cases Nv[*W*/*H*], V[*W*/*H*] and Vb2[*W*/*H*].

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Fig. 1. CFD domain and model descriptions with or without viaduct.

Fig. 2. Streamline and velocity in the lateral centre plane in Cases Nv[1], Nv[2], Vb2[1], Vb2[2].

Fig. 3. Concentration in the lateral centre plane in Cases Nv[1], Nv[2], V[1], V[2], Vb2[1], Vb2[2] with the single CO source or two CO sources.

Fig. 4. Indoor daily CO exposure at different floors in some example cases Nv[*W*/*H*], V[*W*/*H*] and Vb2[*W*/*H*] with the single pollutant source or with two CO sources.

Fig. 5. Daily CO exposure of E_{indoor} , E_{ped} and their ratios in Cases Nv[*W*/*H*], V[*W*/*H*] and Vb2[*W*/*H*].

Fig. 6. Overall daily CO exposure E_t in Cases Nv[*W*/*H*], V[*W*/*H*] and Vb2[*W*/*H*] with one source or two sources.

Appendix

Fig. A1. (a) Time patterns/breathing rate for various age subgroups in four microenvironments (Chau et al., 2002; Allan et al., 2008), (b) the 2004 census data of Hong Kong population in Luo et al. (2010).

Fig. A2. (a) Birds' eye view in cases with viaduct, (b) CFD grid arrangements.

Fig. A3. (a) CFD setup in the validation case. Vertical profiles of $U(z)/U_{ref}$ along vertical lines at the centre section of building model at (b) x=-0.04H and x=0.5H for windward single-sided ventilation case, (c) x=1.04H and x=0.5H for leeward single-sided ventilation case.