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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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A B S T R A C T

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 ($1\ \text{ppm} = 1 \times 10^{-6}$), 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.

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

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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, 2009; Xie et al., 2006; 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, 2015), 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 × 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):

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

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 ith population group; Br_{ij} is the average volumetric breathing rate for individuals in the ith population group (m^3/s) in the microenvironment j; Δt_{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

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