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A modeling investigation of the impact of street and building configurations on personal air pollutant exposure in isolated deep urban canyons

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HIGHLIGHTS

- Indirect exposure approach was used to evaluate canyon air quality.
- Certain building spacing and setback configurations could reduce personal exposures.
- Building setbacks were the best option in lowering personal exposures.
- Decision making hierarchy guides the canyon planning in high density urban cities.

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ABSTRACT

This study evaluated the effectiveness of different configurations for two building design elements, namely building permeability and setback, proposed for mitigating air pollutant exposure problems in isolated deep canyons by using an indirect exposure approach. The indirect approach predicted the exposures of three different population subgroups (i.e. pedestrians, shop vendors and residents) by multiplying the pollutant concentrations with the duration of exposure within a specific micro-environment. In this study, the pollutant concentrations for different configurations were predicted using a computational fluid dynamics model. The model was constructed based on the Reynolds-Averaged Navier–Stokes (RANS) equations with the standard k–ε turbulence model. Fifty-one canyon configurations with aspect ratios of 2, 4, 6 and different building permeability values (ratio of building spacing to the building façade length) or different types of building setback (recess of a high building from the road) were examined. The findings indicated that personal exposures of shop vendors were extremely high if they were present inside a canyon without any setback or separation between buildings and when the prevailing wind was perpendicular to the canyon axis. Building separation and building setbacks were effective in reducing personal air exposures in canyons with perpendicular wind, although their effectiveness varied with different configurations. Increasing the permeability value from 0 to 10% significantly lowered the personal exposures on the different population subgroups. Likewise, the personal exposures could also be reduced by the introduction of building setbacks despite their effects being strongly influenced by the aspect ratio of a canyon. Equivalent findings were observed if the reduction in the total development floor area (the total floor area permitted to be developed within a particular site area) was also considered. These findings were employed to formulate a hierarchy decision making model to guide the planning of deep canyons in high density urban cities.

1. Introduction

Air pollution problems, which are among the major challenges confronting sustainable city development, are further aggravated by the growing number of vehicles on roads. These problems become even worse in dense city centers, where tall buildings are situated along narrow roads producing so-called 'street canyon' effects. Canyon effects can reduce the ventilation effectiveness along roads and elevate the pollutant concentrations at a pedestrian level (Bady et al., 2008; Chan et al., 2003; DePaul and Sheih, 1986).

Numerous efforts have been made to understand the air flow and pollutant dispersion patterns in street canyons. Previous studies have employed either field measurements (Ghenu et al., 2008; Kumar et al., 2008, 2009; Murena and Favale, 2007; Murena and Vorraro, 2003), computational simulations (as reviewed by Ahmad et al. (2005) and Li et al. (2006)), or wind tunnel measurements (Bady et al., 2011; Gromke and Ruck, 2007; Uehara et al., 2000).

To mitigate the problem of near-road air quality, some urban planning strategies have been investigated in terms of their effects

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on dispersion patterns and pollutant concentrations. More recently, a new concept, 'city breathability', was introduced to evaluate the capabilities of proposed strategies to ventilate a city by diluting and removing pollutants (Buccolieri et al., 2010; Hang et al., 2012; Panagiotou et al., 2013). Round shaped city forms were recommended as they induced better ventilation performance than regular city forms (Hang et al., 2009a,b). Lowering the building packing density within a city could reduce the pollutant concentrations at street level (Buccolieri et al., 2010; Di Sabatino et al., 2007a; Mfula et al., 2005). Roadway geometry can also modify urban air quality. A road elevated from the ground level could improve the urban air quality on flat terrains (Heist et al., 2009). A sloping road with noise barriers erected on two sides produced a higher reduction of ground-level pollutant concentrations (Heist et al., 2009). Furthermore, attempts have also been made to examine how the air quality in street canyons can be enhanced by geometrical street design. Some building geometries like slanted or triangular shaped roofs (Kastner-Klein et al., 2004; Theodoridis and Moussiopoulos, 2000; Xie et al., 2005) and step-up canyons (Assimakopoulos et al., 2003; Chan et al., 2001) could enhance the ventilation and dilution processes inside street canyons. Street intersections induced changes in both air flow and pollutant dispersion patterns by creating additional vortices (Wang and McNamara, 2007; Yassin et al., 2008). For instance, skew-shaped street intersections created a roll-type vortex near its vicinity which increased its wind velocity to produce a low exposure environment (Yassin et al., 2008). More recently, passive control measures have become a subject of active exploration for their potentials in reducing exposures (Gallagher et al., 2012; McNabola, 2010). It was determined that street parking systems (Gallagher et al., 2011), noise barriers (Baldauf et al., 2008; Finn et al., 2010; Ning et al., 2010), and near-road structures such as low boundary walls (Bowker et al., 2007; McNabola et al., 2009) could be employed as passive controls to improve local air quality. In contrast, vegetation was found to exert adverse impacts on local air quality inside street canyons (Buccolieri et al., 2009, 2011; Gromke et al., 2008; Gromke and Ruck, 2007, 2012; Ries and Eichhorn, 2001; Salim et al., 2011).

Besides understanding air flow and dispersion patterns or city breathability, many field measurement campaigns have been organized to understand how the pedestrian exposures were influenced by site characteristics (Greaves et al., 2008; Kaur et al., 2005). Despite this, there remains a shortage of studies carried out to assess the relationships between street and building configurations and personal exposures for different population subgroups. Although Zhou and Levy (2008) estimated the exposure factor values for different population subgroups within an urban canyon, they did not examine how the exposure factors would be varied by different street and building configurations. Accordingly, our study aims at investigating the impacts of different street and building configurations on the personal exposures of different

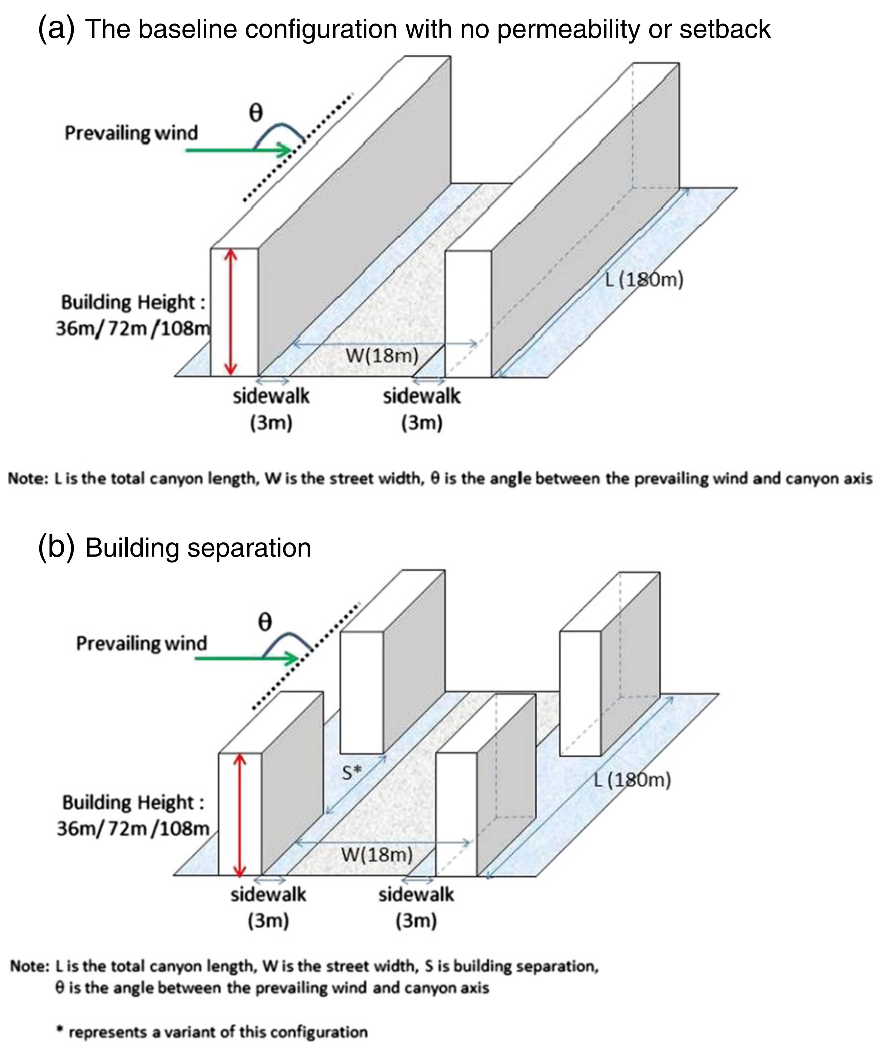

Fig. 1. Sketches of the studied configurations: (a) baseline; (b) building separation; (c) a vertical setback; and (d) a horizontal setback.