

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

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1 **Revision to Environmental Pollution 2016**

2
3 **The influence of street layouts and viaduct settings on daily carbon monoxide**
4 **exposure and intake fraction in idealized urban canyons**

5
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14
15 **ABSTRACT**

16 Environmental concerns have been raised on the adverse health effects of vehicle
17 emissions in micro-scale traffic-crowded street canyons, especially for pedestrians
18 and residents living in near-road buildings. Viaduct design is sometimes used to
19 improve transportation efficiency but possibly affects urban airflow and the resultant
20 exposure risk, which have been rarely investigated so far. The personal intake fraction
21 (P_{IF}) is defined as the average fraction of total emissions that is inhaled by each
22 person of a population ($1\text{ppm}=1 \times 10^{-6}$), and the daily carbon monoxide (CO)
23 pollutant exposure (E_t) is estimated by multiplying the average concentration of a
24 specific micro-environment within one day. As a novelty, by considering time activity
25 patterns and breathing rates in various micro-environments for three age groups, this
26 paper introduces IF and E_t into computational fluid dynamic (CFD) simulation to
27 quantify the impacts of street layouts (street width/ building height $W/H=1, 1.5, 2$),
28 source location, viaduct settings and noise barriers on the source-exposure correlation
29 when realistic CO sources are defined. Narrower streets experience larger P_{IF}
30 (1.51-5.21 ppm) and CO exposure, and leeward-side buildings always attain higher

31 vehicular pollutant exposure than windward-side. Cases with a viaduct experience
32 smaller P_{IF} (3.25-1.46 ppm) than cases without a viaduct (P_{IF} =5.21-2.23 ppm) if
33 the single ground-level CO source is elevated onto the viaduct. With two CO sources
34 (both ground-level and viaduct-level), daily CO exposure rises 2.80-3.33 times but
35 P_{IF} only change slightly. Noise barriers above a viaduct raise concentration between
36 barriers, but slightly reduce vehicular exposure in near-road buildings. Because
37 people spend most of their time indoors, vehicular pollutant exposure within
38 near-road buildings can be 6-9 times that at pedestrian level. Although further studies
39 are still required to provide practical guidelines, this paper provides effective
40 methodologies to quantify the impacts of street/viaduct configurations on human
41 exposure for urban design purpose.

42

43 ***Capsule (Limit 185 Characters)**

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

46

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

49

50 **1. Introduction**

51 Following the ongoing worldwide urbanization, traffic exhaust and non-exhaust
52 emissions in cities constitute the major sources of urban air pollution, including fine
53 particulate matter ($PM_{2.5}$), carbon monoxide, nitric oxide and benzene etc (Fenger,
54 1999; Pu and Yang, 2014).The population exposure to high air pollutant
55 concentration is one of the major factors resulting in adverse health problems in cities
56 (Luo et al., 2010; Zhou et al., 2013; Ji and Zhao, 2015), especially for sensitive
57 groups like children and the elderly. Moreover, on average people spend more than 90%
58 of their time indoors, the traditional epidemiology study linking mortality directly to
59 outdoor pollution concentration may cause bias and give rise to exposure
60 misclassification (Chen et al., 2012a,b) as outdoor air pollutants could penetrate

61 indoors via doors/windows, ventilation systems and building cracks and cause indoor
62 exposure to outdoor origins (Chen et al., 2012c; Ji and Zhao, 2015). Thus, improving
63 the dispersion of vehicular pollutants in the urban environment can help improving
64 urban air quality and reducing population exposure for both pedestrians and people
65 living in near-road buildings (Zhang and Gu, 2013; Ng and Chau, 2014).

66 Extremely narrow street configurations, heavy traffic volumes and unfavourable
67 meteorological conditions are the main reasons of serious vehicular street air pollution.
68 As recently reviewed by the literature (Fernando et al., 2010; Kumar et al., 2011; Di
69 Sabatino et al., 2013; Blocken, 2015; Meroney et al., 2016; Lateb et al., 2016),
70 numerous field/wind tunnel experiments and computational fluid dynamic (CFD)
71 simulations have contributed to understanding the impacts of urban design on the flow
72 and urban air pollution. It has been widely confirmed as the most effective design
73 approach to improve street pollutant dispersion by lowering street aspect ratios (street
74 height/street width, H/W) in two-dimensional (2D) street canyons (Oke, 1988;
75 Meroney et al., 1996; Vardoulakis et al., 2003; Li et al., 2006; Xie et al., 2006; Li et
76 al., 2009; Liu and Wong, 2014; Zhong et al., 2015) and building packing densities in
77 three-dimensional (3D) urban-like models (Chang and Meroney, 2003; Di Sabatino et
78 al., 2007; Hang and Li, 2011; Buccolieri et al., 2010; Yang et al., 2013; Ramponi et al.,
79 2015). Other key urban parameters include building height variations (Gu et al., 2011;
80 Hang et al., 2012) and typical high-rise buildings (Zhang et al., 2015), ambient wind
81 directions (Kanda, 2006; Yassin, 2013; Lin et al., 2014; Kwak et al., 2016), street
82 vegetation (Buccolieri et al., 2011; Gromke and Blocken, 2015a and 2015b), building
83 roof shape (Takano and Moonen, 2013; Liu et al., 2015), traffic-flow patterns (Thaker
84 and Gokhale, 2016) and real-time boundary wind conditions (Zhang et al., 2011) etc.
85 In addition, thermal buoyancy forces induced by wall heating and solar shading can
86 significantly influence (Cai, 2012; Allegrini et al., 2014; Yang and Li, 2015; Cui et al.,
87 2016; Nazarian and Kleissl, 2016) or dominate (Yang and Li, 2009; Luo and Li, 2011;
88 Dallman et al., 2014; Wang and Li, 2016) urban airflows and pollutant dispersion if
89 Richardson (Froude) number is relatively large (small),

90 The adverse effects of vehicle emissions on people in near-road buildings require

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

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

121 design purpose.

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

127

128 **2. Human exposure indices to vehicle emissions**

129 **2.1. Personal intake fraction (P_{IF})**

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

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

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

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

$$152 \quad IF = \sum_i^N \sum_j^M P_i \times Br_{i,j} \times \Delta t_{i,j} \times Ce_j / m \quad (1)$$

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

160 As referred to the literature (Chau et al., 2002; Allan et al., 2008), breathing rates
161 in four micro-environmental categories ($M=4$) for three age groups ($N=3$) were
162 defined (Fig. A1a in Appendix): indoors at home ($j=1$), other indoor locations ($j=2$),
163 near vehicles ($j=3$), and other outdoor locations away from vehicles ($j=M=4$). The
164 2004 population census data for the Hong Kong (Luo et al., 2010) were adopted (Fig.
165 A1b). Moreover, some assumptions were further proposed: The near-road buildings
166 were residential, and only $j=1$ (Indoors at home) and $j=3$ (near vehicles, i.e.
167 pedestrian level) were considered to assess IF for local residents and pedestrians (Fig.
168 A1a).

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

$$174 \quad P_IF = IF / \sum_i^N P_i = \sum_j^M TBr_j \times \Delta t_j \times Ce_j / m \quad (2)$$

175 Here Δt_j is the time spent in the microenvironment j for the entire population.

176

177 **2.2. Daily Pollutant exposure of CO (E_t)**

178 The daily pollutant exposure is defined as the extent of human beings' contact

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

$$184 \quad E_t = \sum_{j=1}^M E_{t,j} = \sum_{j=1}^M C_{real,j,k} \times t_j \quad (3)$$

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

191

192 **3. CFD methodologies**

193 **3.1. Description of CFD test cases and flow modelling**

194 Large Eddy Simulations (LES) are known to perform better in predicting
195 turbulence than the Reynolds-Averaged Navier-Stokes (RANS) approaches in urban
196 airflows and pollutant dispersion modelling (Kanda, 2006; Gu et al., 2011; Li et al.,
197 2009 and 2015; Liu et al., 2014 and 2015; Zhong et al., 2015). But there are still
198 challenges to LES applications including the much longer computational time, the
199 development of advanced sub-grid scale models, the difficulty in specifying appropriate
200 time-dependent inlet and wall boundary conditions. We are aware that steady RANS
201 turbulence models have deficiencies in predicting turbulence, for example they fail to
202 predict the sizes of reattachment lengths behind buildings and under-predict the
203 velocity in weak wind regions (Yoshie et al., 2007). In spite of its limitations, the
204 RNG $k-\varepsilon$ model (Yakhot and Orszag, 1986) has been successfully validated in
205 predicting mean airflows and pollutant dispersion in urban-like models (e.g. Tominaga
206 and Stathopoulos, 2013; Ho et al., 2015; Blocken, 2015; Meroney, 2016; Habilomatis
207 and Chaloulakou, 2015) and those coupling indoor-outdoor airflows (e.g. Gao et al.,

208 2008; van Hooff and Blocken, 2010 and 2013; Ramponi and Blocken, 2012; Jin et al.,
209 2015; Hang et al., 2016). Thus CFD software Ansys FLUENT (Fluent, 2006) with the
210 RNG $k-\varepsilon$ model was used to solve the steady-state isothermal urban airflows. The
211 governing equations were discretized by a finite volume method with the second order
212 upwind scheme. The SIMPLE scheme was used for the pressure and velocity
213 coupling.

214 Fig. 1 depicts full-scale urban models investigated by CFD simulations. The
215 height of all buildings stays as constant as $H=24$ m (y direction), and the width of
216 target street canyon varies from $W=24, 36$ to 48 m ($W/H=1, 1.5, 2$) with its span-wise
217 (or lateral) length of $L=12$ m (y direction). There are two identical street canyons
218 ($W'=24$ m) neighbour to the target street canyon with one in the upstream and the
219 other in the downstream to explicitly reproduce roughness elements. There are
220 eight-storey buildings at both leeward and windward sides with a door at the first
221 floor (2 m tall, 4 m wide) and windows (1 m tall, 4 m wide) at the other storeys. Each
222 storey is 3m high with the room height of 2.7 m and room floor thickness of 0.3 m.
223 For cases with a viaduct, the width of the viaduct is fixed as $W_b=16$ m. The viaduct is
224 elevated as 9 m above the ground, and its thickness is 1m. In addition, there are noise
225 barriers installed at the sides of the viaduct. Two barrier heights are considered, i.e.,
226 2m and 4m respectively. The birds' eye view in cases with a viaduct are depicted in
227 Fig. A2. The model description in test cases without a viaduct is also displayed in Fig.
228 1. At two lateral domain boundaries, symmetrical boundary conditions are assumed.
229 We are aware that, an idealized 2D street canyon with symmetrical lateral boundary
230 condition represents a simplified urban geometry of an infinitely long street with a
231 perpendicular approaching wind to street axis, but it can serve as a platform to
232 synthesize the physical and chemical processes found in the urban environment which
233 is currently still and commonly investigated (Allegrini et al., 2014; Ho et al., 2015;
234 Liu et al., 2014 and 2015; Li et al., 2015; Zhong et al., 2015). The similar 2D urban
235 model coupling indoor and outdoor airflows have been adopted by Gao et al. (2008)
236 and Hang et al. (2016).

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

238 =1, 1.5 or 2 ($H=24$ m) are included, and four types of viaduct settings are considered,
 239 i.e. with no viaduct (Case Nv[W/H]), with viaduct but no noise barriers (Case
 240 V[W/H]), with viaduct and barrier 1 (2 m tall, Case Vb1[W/H]), with viaduct and
 241 barrier 2 (4 m tall, Case Vb2[W/H]). The grid size normal to wall surfaces is 0.1 m
 242 ($0.004H$) which is based on the grid independence study in the CFD validation case.
 243 CFD grid arrangement in cases with a viaduct is depicted in Fig. A2. The total number
 244 of hexahedral cells is about 1.3 million to 2.1 million. For Case Nv[1], we also used a
 245 finer grid arrangement with grid size of 0.05m at wall surfaces to perform a
 246 mesh-dependency test, finding that CFD results change little with the finer grid.

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

$$251 \quad U_0(z) = U_{ref} \left(\frac{z-H}{z_{ref}} \right)^\alpha \quad (4a)$$

$$252 \quad k_{in}(z) = (U_{in}(z) \times I_{in})^2 \quad (4b)$$

$$253 \quad \varepsilon_{in}(z) = \frac{C_\mu^{3/4} k_i^{3/2}}{\kappa z} \quad (4c)$$

254 where $U_{ref}=3$ m/s is the reference velocity, $H=24$ m and z_{ref} is the reference height of
 255 40 m. The power-law exponent of $\alpha=0.22$ denotes the underlying surface roughness
 256 depending on the terrain category of a medium-dense urban area. $I_{in}=0.1$ is turbulence
 257 intensity, $C_\mu=0.09$ and κ is the von Karman constant ($\kappa=0.41$).

258 The reference Reynolds number based on the building height ($Re = U_{ref}H / \nu$, ν
 259 is the kinematic viscosity, $H=24$ m) is about 4.8×10^6 and that based on the room
 260 window height is 19733 ($Re = U_{ref}h_w / \nu$, $h_w=0.1$ m). Both are much greater than
 261 11000 to ensure Reynolds number independence (Snyder, 1972).

262

263 **3.2. CFD setups in dispersion modelling**

264 In this study, carbon monoxide (CO) was selected as a vehicular pollutant being

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

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

$$279 \quad \bar{u}_j \frac{\partial C}{\partial x_j} - \frac{\partial}{\partial x_j} ((D_m + D_t) \frac{\partial C}{\partial x_j}) = S \quad (5)$$

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

284 For the boundary condition of Eq. (5), the zero normal flux condition was set at
 285 wall surfaces, and zero normal gradient conditions at the domain outlet and domain
 286 roof. At the domain inlet, the concentration was defined as zero. It is worth
 287 mentioning that, in present CFD simulations, the density of air is $1.177 \text{ kg}/\text{m}^3$
 288 (average molecular weight 28.966) which is a little greater than the density of CO
 289 $1.138 \text{ kg}/\text{m}^3$ (average molecular weight 28.011). Thus the buoyancy effects due to the
 290 density difference is little.

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

294

295 4. CFD validation studies

296 4.1 CFD Validation of single-sided ventilation flow modelling

297 Wind tunnel data from the literature (Jiang et al., 2003) were used to evaluate the
 298 numerical accuracy of isothermal flows in single-sided ventilation by coupling indoor
 299 and outdoor airflows. As depicted in Fig. A3, the dimension of the reduced-scale
 300 cubic building is 0.25m×0.25m×0.25m, with a wall thickness of 0.006 m and opening
 301 size of 0.125 m×0.084 m at both windward-side or leeward-side walls. The
 302 time-averaged stream-wise velocity U and vertical velocity V along 10 vertical lines at
 303 the building centre section were measured by a laser Doppler anemometer (Jiang et al.,
 304 2003). In CFD simulations (Fig. A3a), full-scale models with a building size of
 305 2.5m×2.5m×2.5m and opening size of 1.25m×0.84m were used (scale ratio is 10:1). x ,
 306 y and z are the stream-wise, span-wise (lateral) and vertical directions. $x/H=0$ is the
 307 location of the windward building surface. The computational domain has a
 308 downstream length of $28H$, an upstream length of $6H$, a lateral length of $7.5H$ on both
 309 sides, and a height of $6H$.

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

$$313 \quad U_0(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad (6a)$$

$$314 \quad k_{in}(z) = u_*^2 / \sqrt{C_\mu} \quad (6b)$$

$$315 \quad \varepsilon_{in}(z) = C_\mu^{3/4} k^{3/2} / (\kappa z) \quad (6c)$$

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

318 The RNG k - ε model with a standard wall function was adopted to solve the

319 turbulence. To ensure grid independency, the medium and fine grid arrangements
320 were used with the smallest grid size of $\Delta x = \Delta y = \Delta z = 0.1$ m and 0.05 m at wall
321 surfaces respectively. For the medium and fine grid, the hexahedral meshes of 0.49
322 and 1.14 million are produced (Fig. A3a). All the other CFD setups are similar to
323 subsection 2.1.

324 Figs. A3b and A3c show the vertical profiles $U(z)/U_{ref}$ along the vertical lines at
325 $x = -0.04H$, $x = 0.5H$ for windward single-sided ventilation, and at $x = 0.5H$, $x = 1.04H$ for
326 leeward single-sided ventilation. Here U_{ref} is the reference velocity (10 m/s). The
327 predicted $U(z)/U_{ref}$ profiles match wind tunnel data well for regions below and near
328 the roof level. The grid independence study shows little difference between two grid
329 arrangements. These facts confirm the RNG $k-\varepsilon$ model with medium grids (minimum
330 grids of $\Delta x = \Delta y = \Delta z = 0.1$ m) performs well in predicting single-sided ventilation
331 airflows.

332

333 4.2 CFD Validation of pollutant dispersion modelling in 2D street canyons

334 Meroney et al. (1996) conducted wind tunnel experiments of pollutant dispersion
335 in 2D street canyons with a perpendicular wind to its street axis (Fig. A4 in Appendix).
336 There were 28 parallel 2D street canyons (uniform building height $H = W = B = 60$ mm)
337 with 20 street canyons upstream to the target street canyon and 8 downstream. A
338 steady line tracer gas (ethane) source exists in the target street. In CFD simulations,
339 the same model geometry and boundary conditions with wind tunnel experiments
340 were adopted (Fig. A4). The total grid number was 372,889. No slip wall boundary
341 condition was set at wall surfaces. The normalized concentration is defined as $K = \bar{c}$
342 UHL/Q , where \bar{c} is the measured tracer gas concentration, L is line source length
343 and Q is the source emission rate, U is wind velocity measured in the free stream at
344 0.50 m above wind tunnel floor. With $V_{in} = 3$ m/s at the domain inlet, Fig. A4 shows the
345 CFD validation profiles of K along windward and leeward walls. As expected
346 windward K is much lower than that leeward K . Numerical K predicted by the RNG
347 $k-\varepsilon$ model agree with wind tunnel data generally well.

348

349 **5. Results and discussion**

350 *5.1. Effects of aspect ratio, viaduct and noise barriers on flow and dispersion*

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

375 In cases with a viaduct, we also consider two CO sources (ground-level and
376 viaduct-level), assuming the total realistic pollutant emission rate doubles due to the
377 increase of the traffic capacity. As two examples, Fig. 3 also shows CO concentration

378 in the lateral centre plane in Case Vb2[1] and Vb2[2] with the viaduct and two CO
379 sources ($W/H=1$ or 2). Obviously, in contrast to those with the single elevated source,
380 even the flow is the same, CO concentration with two sources is much higher. For a
381 street of $W=H=24$ m, the leeward-side rooms at the first and second floors are
382 polluted more seriously than the upper floors. For a wider street ($W=2H=48$ m),
383 vertical gradient of CO concentration for rooms in both windward and leeward sides
384 are small.

385

386 **5.2. Effects of aspect ratios, viaduct and noise barriers on daily CO exposure**

387 ***Vertical profiles of indoor daily CO exposure at various heights***

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

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

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

404 When only one single CO source is presented on the elevated viaduct, viaduct
405 settings (V, Vb1, Vb2) could attain much smaller CO exposure both indoors and at
406 pedestrian level than those without a viaduct (Nv), accounting for only 60-75% of
407 total CO exposure for non-viaduct cases (Table 2). Meanwhile, the ratios of

408 leeward-side CO exposure to windward-side ($E_{leeward1}/E_{windward1}$) are 3.34-3.96 in
409 cases without viaduct, but this ratio in cases with viaducts are only 1.16-1.23 (Table
410 2). These results confirm that, viaduct settings significantly weaken the exposure ratio
411 $E_{leeward1}/E_{windward1}$ by reducing leeward-side CO exposure and raising windward-side
412 CO exposure. Furthermore, Figs. 5 and 6 also show that widening the street (from
413 $W/H=1$ to 2) could potentially reduce total daily CO exposure for all the cases. Finally,
414 noise barriers (Vb1, Vb2) do not have significant impact on the daily CO exposure for
415 the viaduct settings (Figs. 5-6), however, it should be noted that they may increase the
416 in-vehicle exposure on the viaduct although it is not the focus of current study.

417 When there exist two CO sources (both at the pedestrian and viaduct levels), the
418 total CO exposure ($E_{t2}=E_{indoor2}+E_{ped2}$) can be 2.67-3.33 times as great as those with a
419 single CO source ($E_{t1}=E_{indoor1}+E_{ped1}$) (Fig. 5 and Table 2), and $E_{leeward2}/E_{windward2}$ with
420 two sources are 2.40 to 3.52, which is much greater than $E_{leeward1}/E_{windward1}$ (1.16 to
421 1.23) with a single source (Table 2). Irrespective of the number of CO sources, $E_{indoors}$
422 are always 6-9 times of E_{ped} since people spend much shorter time outdoors (at
423 pedestrian level) than indoors (Fig. 5 and Table 2), highlighting the importance of
424 necessity to include indoor exposure to outdoor origins into the traditional
425 epidemiological pollution exposure study.

426

427 **5.3. Effects of aspect ratios, viaduct and noise barriers on intake fraction**

428 Personal intake fraction (P_{IF}) are depicted in Fig. 7 and Table 2. For all cases
429 investigated, wider streets (or greater W/H) experience smaller P_{IF} .

430 For cases with the single CO source, the values of P_{IF} for non-viaduct cases
431 (Nv[W/H]) are 5.21, 3.06 and 2.23 ppm respectively for $W/H=1, 1.5, 2$. With viaduct
432 setting and a single elevated CO source (V[W/H]), P_{IF} exhibits smaller values
433 (1.46-3.59 ppm). Moreover, the introduction of noise barrier on the viaduct (Vb1[W/H]
434 and Vb2[W/H]) show similar P_{IF} as those without noise barrier (V[W/H]) but are
435 still much smaller than non-viaduct cases (Nv[W/H]).

436 If two CO sources are introduced in cases with viaduct settings, personal intake
437 fraction (P_{IF2}) is obviously greater than the one with a single source (P_{IF1}). The

438 ratio of P_{IF_2}/P_{IF_1} ranges from 1.34 to 1.66, which is only half of the CO exposure
439 ratio E_{t2}/E_{t1} (2.67 to 3.33). It is reasonable that the intake fraction is an index
440 normalized by the total pollutant emission rate whereas CO exposure is not. No matter
441 one source or two sources, noise barriers ($Vb1[W/H]$, $Vb2[W/H]$) seem to have little
442 influence on personal intake fraction.

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

454

455 **5.4 Limitations**

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

468 realistic/idealized urban models, for sustainable urban design purpose.

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

480

481 **6. Conclusions**

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

494 The simulation results show that wider streets experience smaller P_{IF} and CO
495 exposure, and leeward-side buildings always attain less vehicular pollutant exposure
496 than windward-side. In contrast to cases without a viaduct ($P_{IF}=5.21-2.23$ ppm as
497 $W/H=1, 1.5, 2$), the viaduct can lead to smaller P_{IF} (3.25-1.46 ppm) if the single

498 pollutant source is elevated onto the viaduct level. Noise barriers on viaducts can
499 significantly raise CO concentration above the viaduct and between the barriers, but
500 slightly reduce pollutant exposure in near-road buildings. Assuming that 10 persons
501 are living on each floor (8 floors, totalling 160 persons in two near-road buildings),
502 the total intake fractions range from 230-913 ppm, which are the same order with that
503 (371 ppm) in a street canyon ($H/W=1.5$) of the central Athens urban area in Greece
504 (Habilomatis and Chaloulakou, 2015), but are much smaller than that (3,000 ppm) in
505 a deep street canyon in midtown Manhattan, New York, with a large population
506 density (Zhou and Levy, 2008). Because people spend most of their time indoors,
507 pollutant exposure in near-road buildings can be 5-8 times greater than that at the
508 pedestrian level of street canyons. Finally, the introduction of a viaduct tends to
509 reduce pollutant exposure in leeward-side buildings but slightly raises that of
510 windward-side. If there are two CO sources (ground-level, viaduct-level) in cases
511 with a viaduct, overall CO exposure is much greater (2.80-3.33 times) than cases with
512 a single elevated source above a viaduct. The ratios of leeward-side and
513 windward-side exposure with two CO sources (2.40-3.52) are much greater than those
514 with a single CO source (1.16-1.23).

515

516 **Conflict of interest**

517 The authors declare no competing financial interest.

518

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524

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737 **Table list**

738 [Table 1](#). Summary of test cases investigated by CFD simulations.

739 [Table 2](#). Daily CO exposure, personal intake fraction (P_{IF}) and total intake fraction
740 (IF) in Cases $Nv[W/H]$, $V[W/H]$ and $Vb2[W/H]$.

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742 **Figure list**

743 [Fig. 1](#). CFD domain and model descriptions with or without viaduct.

744 [Fig. 2](#). Streamline and velocity in the lateral centre plane in Cases $Nv[1]$, $Nv[2]$,
745 $Vb2[1]$, $Vb2[2]$.

746 [Fig. 3](#). Concentration in the lateral centre plane in Cases $Nv[1]$, $Nv[2]$, $V[1]$, $V[2]$,
747 $Vb2[1]$, $Vb2[2]$ with the single CO source or two CO sources.

748 [Fig. 4](#). Indoor daily CO exposure at different floors in some example cases $Nv[W/H]$,
749 $V[W/H]$ and $Vb2[W/H]$ with the single pollutant source or with two CO sources.

750 [Fig. 5](#). Daily CO exposure of E_{indoor} , E_{ped} and their ratios in Cases $Nv[W/H]$, $V[W/H]$
751 and $Vb2[W/H]$.

752 [Fig. 6](#). Overall daily CO exposure E_t in Cases $Nv[W/H]$, $V[W/H]$ and $Vb2[W/H]$ with
753 one source or two sources.

754

755 **Appendix**

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

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

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