Improving Air Quality in High-density Cities by Understanding Air Pollutant Dispersion and Urban Morphologies

Chao Yuan[1,2], Edward Ng[3], Leslie Norford[4]

[1] Massachusetts Institute of Technology, 77 Mass. Ave, Cambridge, MA, US. yuanc@mit.edu
[2] Singapore University of Technology and Design, 8 Somapah Rd, Singapore. yuanc@mit.edu
[3] The Chinese University of Hong Kong, Shatin, Hong Kong. edwardng@cuhk.edu.hk
[4] Massachusetts Institute of Technology, 77 Mass. Ave, Cambridge, MA, US. lnorford@mit.edu
dated: 27 June 2015

1. Introduction

Emissions from motor vehicles contribute to air pollution in urban areas, particularly at the street canyon level. The European Environment Agency (EEA) (2012) has reported seven types of pollutants that are primarily or secondarily related to road traffic emission. The risks associated with exposure to air pollution are relatively low for individuals but are a significant public health concern (Kunzli et al., 2000). Understanding the problem in densely populated cities is therefore paramount. To decrease traffic pollution, an improved vehicle emission control program has been implemented in Hong Kong by the Hong Kong SAR Government. Nonetheless, the roadside concentration of NO_2 continues to increase (Environmental Protection Department, 2011). High hourly, daily, and annual average concentrations of NO_2 have been recorded at the roadside stations in Central, Causeway Bay, and Mong Kok in Hong Kong. The reported higher concentration of NO_2 is the result of the larger NO_2 percentage in total traffic emissions (European Environment Agency, 2012; Grice et al., 2009) and of poorer urban air ventilation in high-density urban areas (Ng et al., 2011; Tominaga & Stathopoulos, 201). As shown in Figure 1, vehicles crowd the streets at these urban areas which are traffic hotspots and mostly occupied by high buildings. Therefore, apart from having control measures to decrease vehicle emissions, understanding pollutant dispersion as related to the urban planning and design is necessary to guide policymakers, planners, and architects to make evidence-based decisions.

Figure 1 Vehicle fleets in the deep street canyons of Mong Kok, Central and Causeway Bay in Hong Kong; high concentration of NO_2 is frequently measured at the roadside stations in these areas.

The Severe Acute Respiratory Syndrome (SARS) episode in 2003 triggered the Air Ventilation Assessment (AVA) study in Hong Kong. Since 2006, AVA has been implemented as a prerequisite for urban development and old-district redevelopment (Ng, 2009). The technical guideline, Sustainable Building Design Guidelines (APP-152), has also been drawn up by the Hong Kong Government. This guideline allows architects to evaluate the effects of their proposed building designs on the surrounding wind environments, and then to enhance urban environmental design (Hong Kong Building Department, 2006). We built up this study based on our previous parametric study (Yuan & Ng, 2012) to extend the understandings in AVA to the air pollutant dispersion issue. This study aims to provide insights on the air pollutant dispersion at the beginning stage of the design practice. These insights are helpful to avoid the mistakes that cannot be easily corrected at the late stages of the design process. The result of this study could change architecture design and urban planning from experience-based to more scientific and evidence-based decision making.

2. Method and Validation

In this study, we validated the Eulerian dispersion model using the wind tunnel data provided by Niigata Institute of Technology (Tominaga & Stathopoulos, 2011), and investigated the effects of the different turbulence models, i.e. RANS and LES, on air pollutant dispersion modelling. In RANS models, the standard and realizable κ-ε model, Reynolds stress model (RSM), shear-stress transport (SST) κ- ω model were included.

The model configurations were set to match those in the wind tunnel experiment (Tominaga & Stathopoulos, 2011). The H/W and H/L aspect ratios were 1.0 and 0.5, respectively, where H is the building height, W is the width of the street, and L is the length of the canopy. The input wind direction was perpendicular to the street canyon. Input wind velocity (U_x) and turbulence kinetic energy (TKE) profiles were set by a user-defined function.

We used ethylene (C_4H_4) as the tracer gas, and set the tracer concentration as 1000 ppm to duplicate the settings in the wind tunnel experiment. The tracer gas was released from the point source with a wind velocity W_s (W_s/U_b = 0.12, U_b is the input wind velocity at the building height, 3.8 m/s). All CFD simulation settings, such as the domain size and the grid size ratio, followed the Architectural Institute of Japan (AIJ) guidelines (Tominaga, et al., 2008).

We plotted the simulation results in Figure 2. Compared with an LES model with best accuracy, all RANS models overestimated the concentrations at upper lines (e.g. X/H=0.5, Figure 2b). Among the RANS models, the SST κ- ω model best performed especially at the windward side of the street canyon. The special near-wall region (the shear layer) treatment by the standard κ- ω model (Menter, Kuntz, & Langtry, 2003) was considered helpful for modelling the air pollutant dispersion near surface regions. Balancing the computational cost and accuracy, we selected the SST κ- ω model as the preferred turbulence model to simulate the air pollutant dispersion in the parametric study.
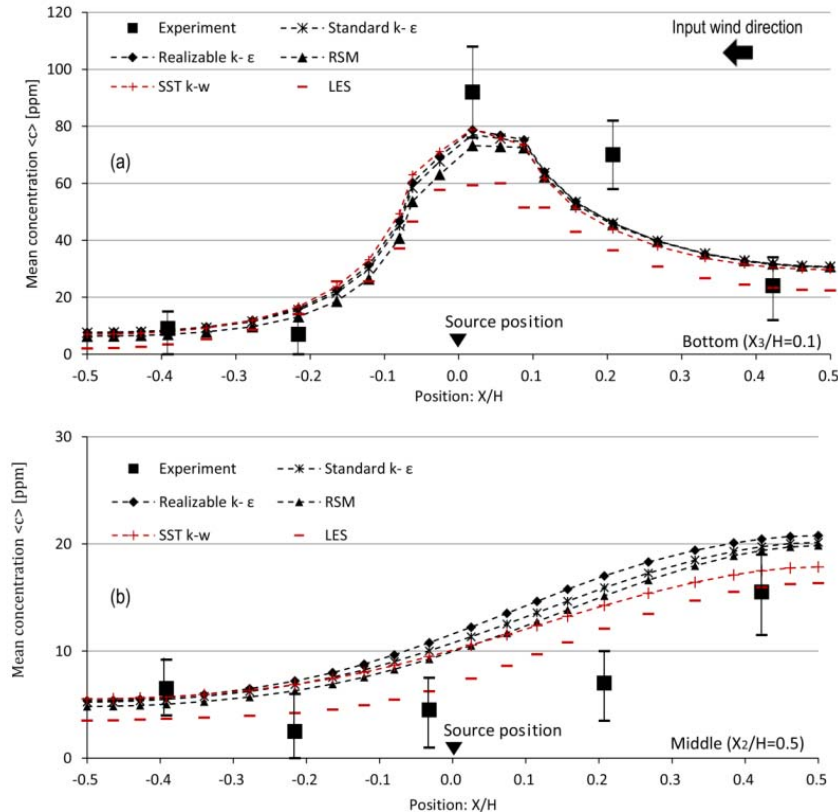

Figure 2 Cross-comparisons of time-averaged concentrations <c> at the street canyon between the wind tunnel experiment and different turbulent models: a) <c> at the bottom line; b) <c> at the middle line.

Table 1 Eight simulation scenarios with different building geometries and permeability

Cases	Building geometry		Land use density	Urban permeability			Performance
	Parameters	H (m)	Plot ratio	P	λ_p	λ_i	Percentage of 'pollutant concentration ratio >1'
1	Current urban form	60	8.9	0.9	0.7	0.9	100%
2	Future urban form	95	14	0.9	0.8	0.9	75%
3	Building setback	105	14	0.9	0.5	0.7	70% (Unsuitable)
4	Building separation	137	14	0.7	0.6	0.5	29% (Good)
5	Stepped podium void	109	14	0.8	0.6	0.7	75% (Unsuitable)
6	Building porosity	133	14	0.7	0.8	0.7	33% (Good)
7	Building separation & Build setback	146	14	0.7	0.4	0.3	0% (Excellent)
8	Building separation & Stepped building void	150	14	0.6	0.4	0.4	0% (Excellent)

Note: H: building height; P: permeability of buildings (P = sum of frontal area/Area of the assessment zone) (Hong Kong Building Department, 2006); λ_p: site coverage ratio; λ_i: integrated permeability which is defined in section 4.2.

3. Parametric Study

The parametric study was at the urban scale and established based on urban conditions in Mong Kok (Figure 3), a high-density metropolitan area in Hong Kong. As shown in Figure 3, we established eight simulation scenarios with different building geometries and urban permeability. The details of the simulation scenarios are tabulated in Table 1. The permeability of buildings (P) (Hong Kong Building Department, 2006) and site coverage ratio (λ_p) represent the vertical and horizontal permeability respectively. High values of P and λ_p indicate low urban permeability. It should be noted that we set plot ratios in Cases 3-8 to be the same as that of Case 2 to avoid design strategies decreasing the land use density.
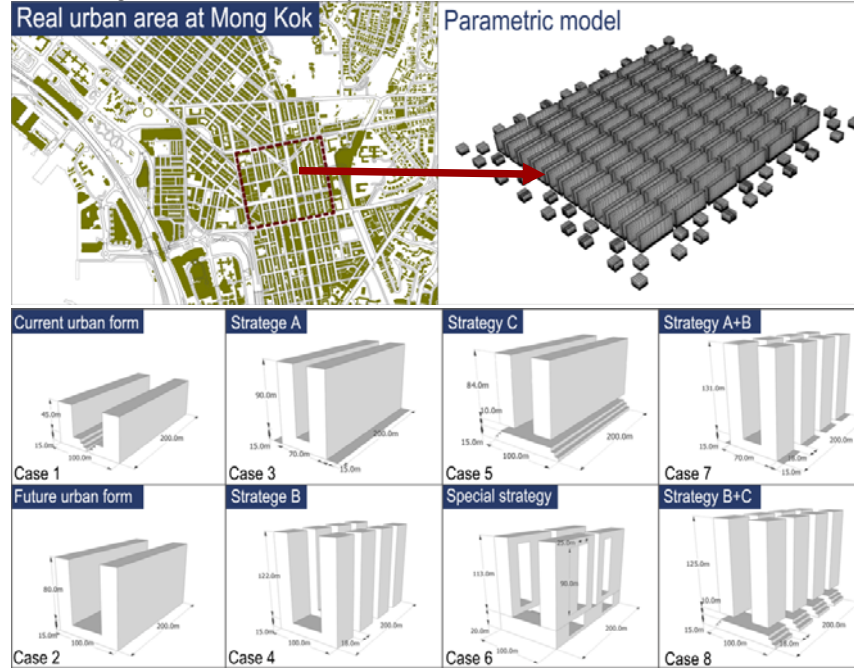

Figure 3 Urban area in Mong Kok, corresponding parametric model, and eight strategy cases.

4. Result Analysis and Discussion

We used the normalized pollutant concentration ($\bar{c}$) as the index to analyze the effects of different building geometries and permeability on air pollutant dispersion in the street canyon. This is given by:

$$\bar{c} = \frac{<c>}{<c_0>} \qquad (1)$$

where $<c>$ is the time-averaged concentration of NO_2 and $<c_0>$ is the reference emission concentration, 1000 ppm, the norm of $<c>$. Given the definition of $\bar{c}$, we set the threshold value of $\bar{c}$ as 1.0, which means that, if the value of $\bar{c}$ is less than 1.0, air pollutants disperse and do not concentrate in the street canyon.

4.1 Building scale analysis

Simulated contours of $\bar{c}$ at the vertical sections are shown in Figure 4. First, the results in Cases 1-2 indicated that mitigation strategies for the air pollutant dispersion are necessary in the high-density urban planning and design. In the current urban condition (Case 1), given that most of the pedestrian-level normalized concentrations ($\bar{c}$) in the street with emission sources were larger than 1.0, air pollutants in Case 1 could be seriously concentrated in the deep street canyon. Furthermore, if keeping the current planning and design strategies, the future urban development (Case 2) could further worsen the air quality. Second, the results in Case 3-8 indicated that the air pollutant can be dispersed in high-density cities if appropriate strategies are applied. Among them, Cases 4-6 promote the convection effect and Case 3 promotes the turbulence diffusion. Cases 7-8 are the multiple strategies. The performances of these strategies were quantitatively investigated and listed in Table 1. In the design and planning process, urban designers should choose appropriate strategies based on the particular concerns in different projects. It should be emphasized that, although a high building porosity off ground level cannot increase the pedestrian level wind speed (Yuan and Ng, 2012), it can still decrease pedestrian-level air pollutant concentrations as shown in Case 6. It means that the pedestrian-level traffic-related pollutant concentration depends on the permeability of the entire street canyon.

4.2 Urban scale analysis

In the urban scale, we conducted a linear regression analysis to weight the effect of building permeability (P) and site coverage ratio λ_p (Table 1) on the time-averaged pollutant concentration. Based on the results shown in Figure 5, it is clear that the time-averaged concentration depends more strongly on the permeability of buildings (P) than on the site coverage ratio (λ_p), as the R^2 for P, 0.78, is larger than the R^2 for λ_p, 0.47.
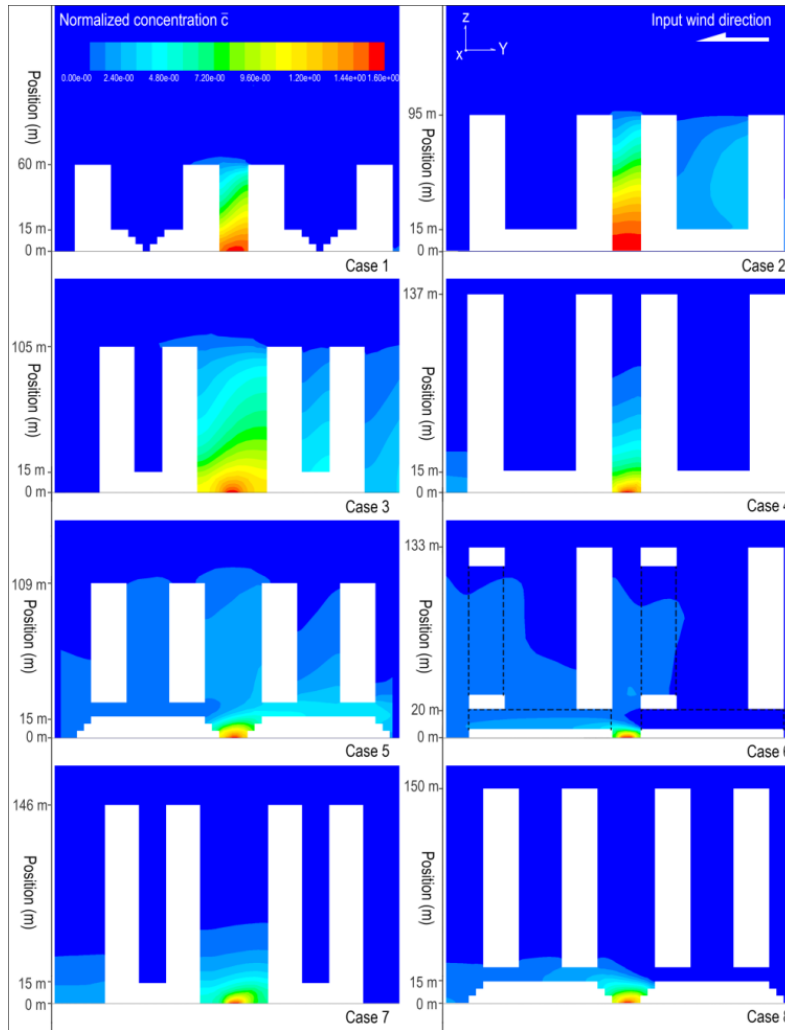
Figure 4 Contour of $\bar{c}$ at the vertical sections in Cases 1-8.
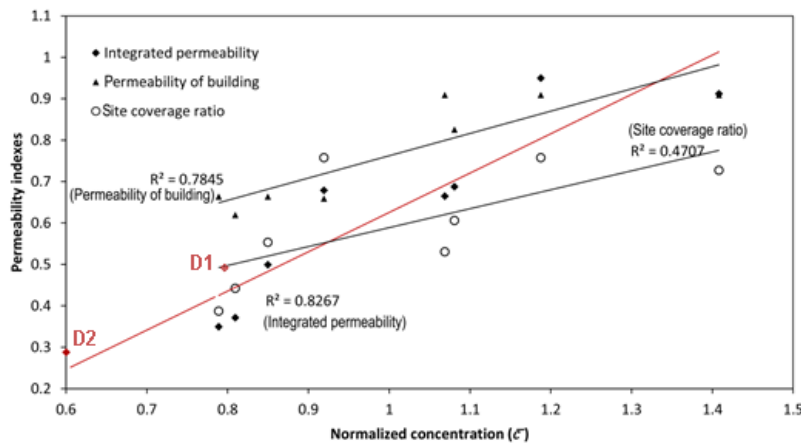

Figure 5 Linear relationships between pedestrian level air pollutant concentration and permeability indexes, P, λ_P, λ_i (Table 1). The values of two real urban Cases, D1 and D2, were also plotted. (Significant level: 95%)

To better predict time-averaged concentration $\bar{c}$ in high-density urban areas, we developed and calculated the integrated permeability (λ_i) based on Counihan's roughness model (Grimmond & Oke, 1999) as follows:

$$\lambda_i = (C_1 \cdot \lambda_P - C_2) \cdot P \qquad (2)$$

The coefficients C_1 (1.4352) and C_2 (0.0463) were for the contribution of λ_P, given that the horizontal permeability λ_P is less important than the vertical permeability P. The values of λ_i in eight cases were given in Table 1. As shown in Figure 5, a strong relationship between λ_i and time-averaged $\bar{c}$ (R^2=0.83) indicated that λ_i is a better urban permeability index than P and λ_p to estimate traffic air pollutant dispersion. This analysis result makes possible to map the traffic air pollutant concentration in urban areas in GIS by calculating λ_i by pixel.

5. Implementation

We conducted a real case study at Mong Kok to illustrate that suggested design strategies are feasible in real urban design practices. As shown in Figure 6, based on the current urban morphology (D1), we made an urban design (D2) by using mitigation design strategies in Table 1 to improve the local air quality. To avoid reducing the land use efficiency, the plot ratio in these two cases was same, 8.3. The site coverage ratio λ_P in D1 and D2 were 0.51 and 0.42, respectively. The values of averaged building permeability (P) at the total site area were 0.7 in D1 and 0.5 in D2, as shown in Figure 6. Based on Equation 2, we calculated the urban permeability λ_i at these two cases, which is 0.48 in D1 and 0.27 in D2.
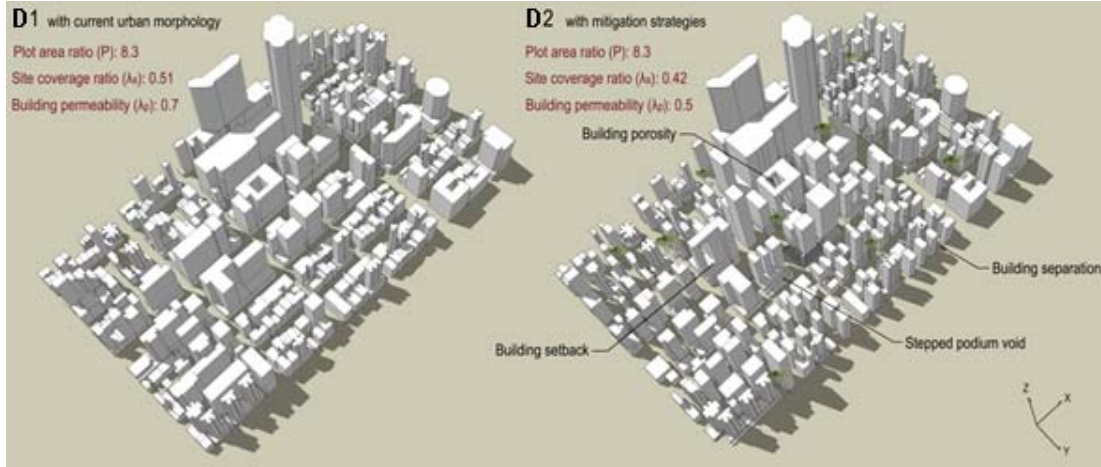

Figure 6 Case study of urban redevelopment at Mong Kok. D1: current urban area of Mong Kok; D2: urban redevelopment of Mong Kok with mitigation strategies.
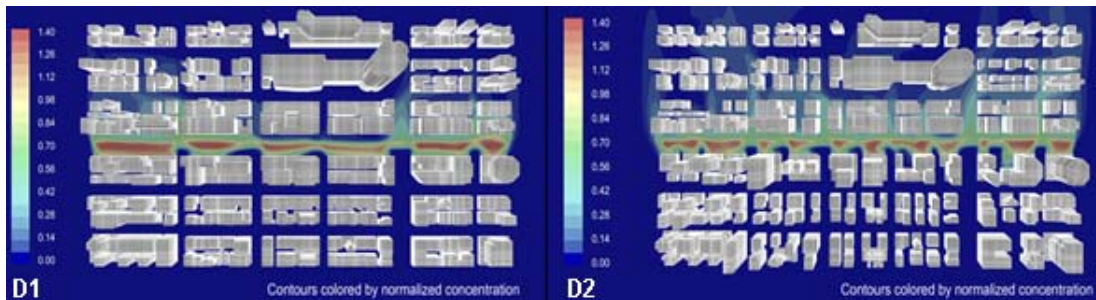

Figure 7 Simulation results. The mitigation strategies in D2 could significantly increase the wind permeability and decrease the traffic air pollutant concentration.
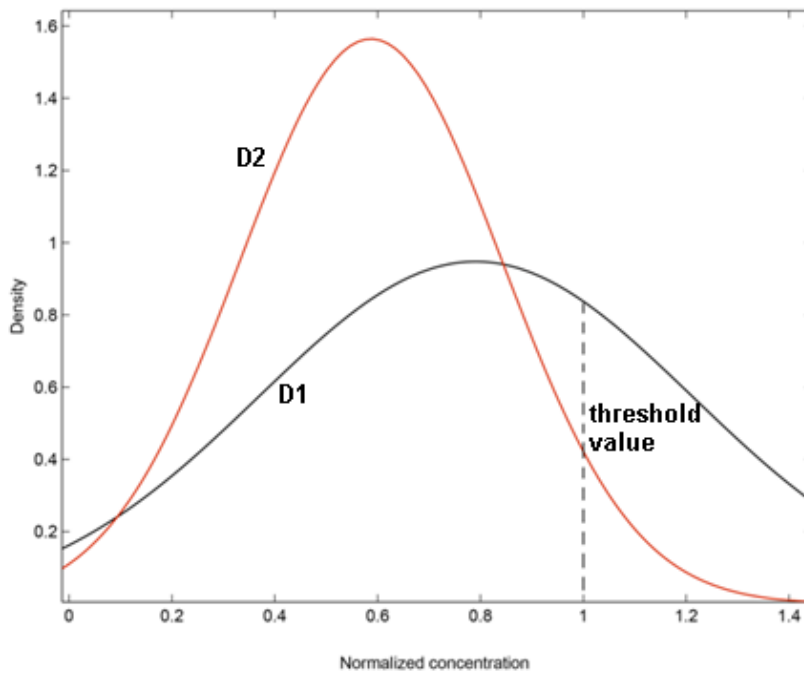

Figure 8 Normal distribution fit of the normalized concentrations in D1 and D2.

We simulated and compared the air pollutant concentrations in the above two cases by using CFD. The comparison results in Figure 7 showed that the mitigation strategies in D2 can significantly increase the wind permeability and decrease the traffic air pollutant concentration. As shown in Figure 8, the probability of high concentration ($\bar{c}$>1.0) in D2 was far less than in D1. Correspondingly, the time-averaged normalized concentration ($\bar{c}$) at the street with the emission source decreased from 0.79 in D1 to 0.59 in D2. These results were plotted in Figure 5 and are consistent with the understanding from the parametric study. It means that, in the practical urban planning, planners can decrease the local traffic-related air pollutant concentration by decreasing the local value of λ_i.

6. Conclusion

Hong Kong Planning Standards and Guidelines (HKPSG) points out that '*In the preparation of land use plans, due consideration should be given to the location of major polluting uses with a view to improving the regional air quality.*' and '*Concentrations of NO_2 and particulates are high, particularly at the older urban areas where motor vehicle usage is intense and vehicle exhausts are trapped between narrow roads and tall buildings*' (Chapter 9, Hong Kong Planning Department, 2011). But the specific mitigation strategies in the building design are still missing to make 'due consideration'. In this study, we conducted a parametric study and clarified the effect of different building morphologies and permeability on the outdoor air quality. Consequently, architects and urban planners can modify their design and planning to alleviate the effect of proposed projects on the outdoor air quality in the process of practical design and planning.

Acknowledgment

For more information of this study, please refer to:
Yuan, C., Ng, E., Norford, L.K., 2014: Improving air quality in high-density cities by understanding the relationship between air pollutant dispersion and urban morphologies, *Building and Environment*. 71: 245-258.

References

Environmental Protection Department. 2011: Air quality in Hong Kong 2011 - A report on the results from the air quality monitoring network (AQMN). Hong Kong: The Government of the Hong Kong Special Administrative Region.

Grice, S., Stedman, J., Kent, A., Hobson, M., Norris, J., Abbott, J., & Cooke, S. 2009: Recent trends and projections of primary NO_2 emissions in Europe. *Atmospheric Environment*, 43(13): 2154-2167.

Grimmond, C. S. B., & Oke, T. R. 1999: Aerodynamic Properties of Urban Areas Derived from Analysis of Surface Form. *Journal of applied meteorology*, 38: 1262-1292.

Hong Kong Building Department. 2006: Sustainable building design guidelines Practical note for authorized persons, registered structure engineers and registered geotechnical engineers. Hong Kong: APP-152.

Hong Kong Planning Department. 2011: Hong Kong Planning Standards and Guidelines. The government of the Hong Kong Special Administrative Region

Kunzli, N., Kaiser, R., Medina, S., Studnicka, M., Chanel, O., Filliger, P., Sommer, H. 2000: Public-health impact of outdoor and traffic-related air pollution: a European assessment. Lancet, 356(9232): 795-801.

Menter, F. R., Kuntz, M., & Langtry, R. 2003: Ten years of Industrial Experience with the SST Turbulence Model. Turbulence, Heat and Mass Transfer 4: 625-632.

Ng, E. 2009: Policies and Technical Guidelines for Urban Planning of High Density Cities – Air Ventilation Assessment (AVA) of Hong Kong. Building and Environment, 44: 1478–1488.

Ng, E., Yuan, C., Chen, L., Ren, C., & Fung, J. C. H. 2011: Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: a study in Hong Kong. *Landscape and Urban planning*, 101(1): 59-74.

Tominaga, Y., & Stathopoulos, T. 2011: CFD modelling of pollution dispersion in a street canyon: Comparison between LES and RANS. *Journal of Wind Engineering and Industrial Aerodynamics*, 99(4): 340-348.

Tominaga, Y., & Stathopoulos, T. 2012: CFD modelling of pollution dispersion in building array: Evaluation of turbulent scalar flux modelling in RANS model using LES results. *Journal of Wind Engineering and Industrial Aerodynamics*, 104: 484-491.

Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa, M., Shirasawa, T., 2008: AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, 96: 1749-1761.

Yuan, C., & Ng, E. 2012: Building porosity for better urban ventilation in high-density cities - A computational parametric study. *Building and Environment*, 50: 176-189.