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Study on the Impact of Different Traffic Pollutant Sources Caused by Rural Highway Planning on Residents' Health Based on CFD Simulation Technology

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Abstract. China's transportation network is very well developed, and usually, one or more busy highways pass through villages. Carbon monoxide from vehicle exhaust has important effects on the residents' health, such as reducing the ability of blood to transport oxygen. Therefore, how to plan highways passing through villages is very important for green village construction and sustainable development. This study used CFD techniques to simulate the effects of two types of highways passing through villages and three highway types (two-way two-lane, two-way four-lane, and two-way six-lane) on pollutant dispersion and the health of the residents under the most unfavorable risks. The results of the study show that the highway passing through the middle of the village has a greater impact on the residents' health than passing through the edge of the village. The two-lane highway type passing through the middle of the village and the two- and four-lane highway types passing through the edge of the village did not result in pollutant concentrations exceeding 4 mg/m3 in the villages. The higher traffic volume types with more than six lanes of highway should be built away from the villages, and auxiliary roads can be constructed to connect the villages to facilitate the residents' travel.

Keywords. Highway planning, Traffic pollutants, Residents' health, CFD simulation

1. Introduction

As part of the rural revitalization strategy, it is crucial to address the environmental health issues prevalent in rural areas [1]. The impacts of traffic pollution, industrial emissions, and burning on the health of rural residents have received widespread attention [2-3]. China's well-developed transportation network system allows villages to be surrounded by one or even more highways with heavy traffic. Vehicle emissions inevitably have an impact on the health of village residents [4], especially when the village is downwind of the highway.

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Courtyards and streets are important places for rural residents to engage in activities such as walking and cooling off in the shade. Therefore, air quality in rural outdoor spaces is very important for the health of rural residents. In the past, one of the main sources of air pollutants in the countryside was the burning of firewood [5]. However, with the implementation of environmental protection policies in northern China, more and more households are using natural gas as a cooking fuel [6]. Nowadays, the number of automobiles per 100 households in rural China is 17.4, which is 13.18 times higher than that in 2000. Therefore, automobile exhaust is another important factor that threatens the health of urban and rural residents today.

Computational Fluid Dynamics (CFD) has emerged as a valuable tool for studying pollutant transportation in various environments. CFD method is more cost-effective and flexible than on-site measurements or wind tunnel experiments [7]. At present, many researchers have used CFD technology to investigate the impact of building morphology, traffic pollutants, and greening on the physical environment of urban neighborhoods. Xu et al. [8] simulated pollutant transport at the urban neighborhood scale and provided some suggestions for public building design from the perspective of ventilation capacity. In addition, the design of roadside green belts was quantitatively investigated by considering traffic heat using the CFD method by Xi et al. [9]. Therefore, CFD simulations provide insight into the wind flow field and concentration distribution of pollutants emitted by vehicles.

In order to assess the impact of pollutants from heavy traffic on the health of village residents, this study investigated the exposure of villages to pollution when they are located downwind of the highway. Three traffic pollutant source intensities and Two highway locations were investigated. The conclusions of this study can provide some suggestions for highway planning around villages and the outdoor activities of residents.

2. Methods

2.1. Description of Case Studies

Tianjin, as the core city of China's capital economic zone and the second largest city in northern China, has a population of 13.73 million and covers an area of 11,966.45 square kilometers. Traditional villages in North China are typically composed of hundreds of regularly arranged single-story courtyard houses. The courtyards are the main space for outdoor activities for residents. In addition, streets are outdoor spaces for residents to shop, such as markets, and to walk after dinner and socialize with other residents [10]. Therefore, the air quality of the rural outdoor environment is very important for the health of the residents.

Vehicle pollutants are most detrimental to the health of residents when the village is located downwind of the highway. Therefore, this study summarized two typical types of village locations downwind of a highway, one where the highway passes through the village and one where the highway is located at the edge of the village, as shown in Figure 1(a). As shown in Figure 1(b), two-way two-lane, two-way four-lane, and two-way six-lane have different traffic volumes, i.e., different areas of automobile emissions (referred to as the pollutant source intensity in this study). According to the Code for Design of Urban Road Engineering in China, pedestrian lanes and bicycle lanes are set to 4 m and 3.5 m, respectively. In this study, the width of one motor vehicle lane is set to be 3.75 m, so the total width of the two-way two lanes, two-way four lanes, and two-way six lanes are set to 7.5, 15, and 22.5 m, respectively, which is the area where the pollutants are released from the motor vehicles. In summary, six cases were simulated using the CFD method to obtain the distribution of pollutants in the village and to evaluate the health impacts on the residents, as shown in Table 1.

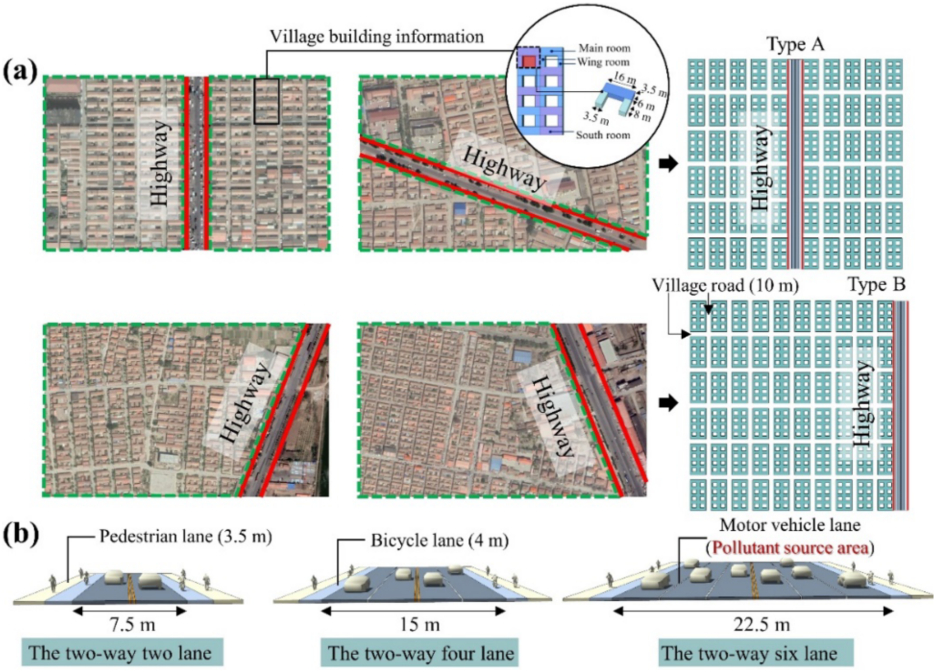

Figure 1. The investigation cases used in this study include (a) two types of urban highways passing through the village and (b) three highway types with different lanes.

Table 1. Six cases with different highway locations and highway types were investigated.

Name	Highway location	Highway type
Case C-2	Center	Two lanes
Case C-4	Center	Four lanes
Case C-6	Center	Six lanes
Case S-2	Edge	Two lanes
Case S-4	Edge	Four lanes
Case S-6	Edge	Six lanes

Note: The Center represents the highway passing through the middle of the village; the Edge represents the highway passing by the edge of the village.

2.2. CFD Simulation Method

The boundary conditions of CFD simulation are very important for the accuracy of the simulation results. Figure 2 shows the computational domain and boundary conditions of the CFD model. The distance of the building complex from the inlet, outlet, and side boundaries is 20H (H is the height of the rural building) and the distance from the top boundary is 5H, which satisfies the wind engineering simulation criteria of the Architectural Institute of Japan [11]. The wind speed, turbulent kinetic energy (k_z, m^2/s^2), and turbulent dissipation rate (ε_z, m^2/s^3) at the inlet boundary were defined by Eqs. (1)-(3).

$$U_Z = \frac{U^*_{ABL}}{k} \ln\left(\frac{z+z_0}{z_0}\right) \tag{1}$$

$$k_z = \frac{{U^*_{ABL}}^2}{\sqrt{C_\mu}} \tag{2}$$

$$\varepsilon_Z = \frac{{U^*_{ABL}}^3}{k(z+z_0)} \tag{3}$$

where U_z (m/s) is the wind speed at the height of z (m), and z_0 is the roughness length (set to 0.03 in this study). k is the von Karman constant (0.41) [12] and C_μ is a constant (0.09). The friction velocity of the atmospheric boundary layer (U^*_{ABL}) can be calculated by Eq. (4):

$$U^*_{ABL} = \frac{kU_r}{ln\left(\frac{z_r+z_0}{z_0}\right)} \tag{4}$$

where U_r (m/s) is the wind speed at the reference height z_r (10 m). Based on the local meteorological conditions in the study case, U_r was set to 3 m/s. In order to assess the most unfavorable scenario of pollutants to the village environment, the village was set downwind from the highway, i.e., the wind direction was perpendicular to the highway and the village.

In addition, carbon monoxide (CO) was selected as a pollutant emitted from automobiles on highways. The release areas of pollutant sources differ for the three different highway types; see Section 2.1. The governing equation of time-averaged CO concentration is shown as Eq. (5).

$$\overline{u_J}\frac{\partial c}{\partial x_j} - \frac{\partial}{\partial x_j}\left[(D_m + D_t)\frac{\partial c}{\partial x_j}\right] = S \tag{5}$$

where $\overline{u_J}$ is the time-averaged velocity component of direction j, and C is the CO concentration (kg/m^3). D_m and D_t are the molecular and turbulent diffusivity of pollutants, respectively. *S* is the CO emission rate. *S* was assumed as 1.25×10^{-6} kg/(m^3·s) according to the realistic emission rate of vehicle-exhausted pollutants [4]. The grid resolution is also very important for the accuracy of the CFD simulation results. In this study, the minimum grid size is set to 0.1 m, and the number of grid layers between two edge lines is at least 5. Boundary layer grids were also added to the wall boundaries to properly simulate the wind flow field near the wall. Reynolds-averaged Navier-Stokes (RANS) method is employed to calculate the turbulent wind field with a standard k-ε turbulence model. The mass, momentum, turbulent kinetic energy, and turbulent dissipation rate were discretized with the second-order upwind scheme. The Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm was used for the pressure-velocity coupling. The residuals for all variables need to be less than 10^{-4} to complete the calculation.

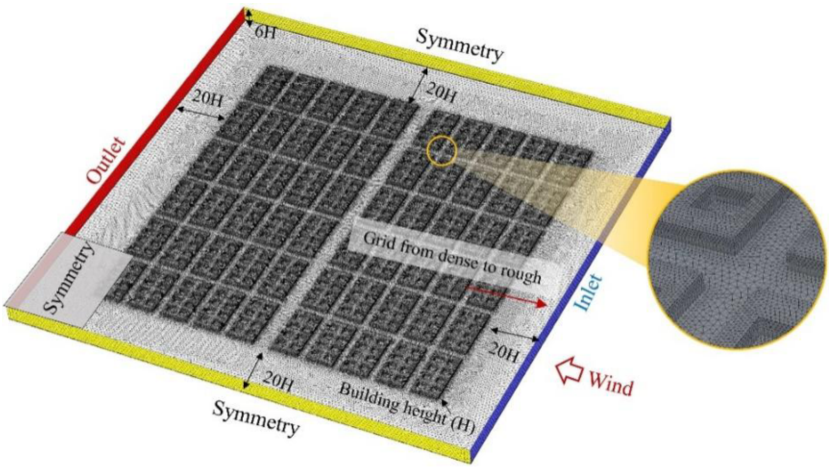

Figure 2. Computational domain dimensions and boundary condition settings.

2.3. Analysis Indices

The average values of pollutant concentration at the pedestrian level (0-2 m) in courtyard spaces were calculated to evaluate the health risk of residents. The individual intake fraction (*IF*) was calculated using Eq. (6) [13].

$$IF = \frac{\bar{C} \cdot BR_i \cdot T_i}{E} \tag{6}$$

where BR_i is the breathing rate, 2.85 m^3/h [14]. T_i is the time spent on some activities (h); one hour was assumed in this study. *E* is the pollutant emissions from the study area (*S* × emission volume × one hour, kg).

3. Results and Discussion

3.1. Pollutant Contours

Pollutant contours of villages under the influence of automobile exhaust pollutants are shown in Figure 3. When the highway passes through the middle of the village, the part of the village located downwind of the highway is significantly polluted by vehicle emissions, as shown in Figure 3a, while pollutant concentration upwind of the highway is almost zero. Different highway types have different levels of pollution in villages, and the degree of pollution in the part of the village located downwind of the highway is significantly higher than that in the case of a six-lane highway when the highway passes through the village than that in the case of a four-lane and six-lane highway. As shown in Figure 3b, when the entire village is located downwind of the highway, the entire village is exposed to vehicle exhaust pollutants. However, many areas of the village are in areas of low pollutant concentrations. In order to precisely evaluate the impacts of pollutants on the village, quantitative analysis is discussed in Section 3.2.

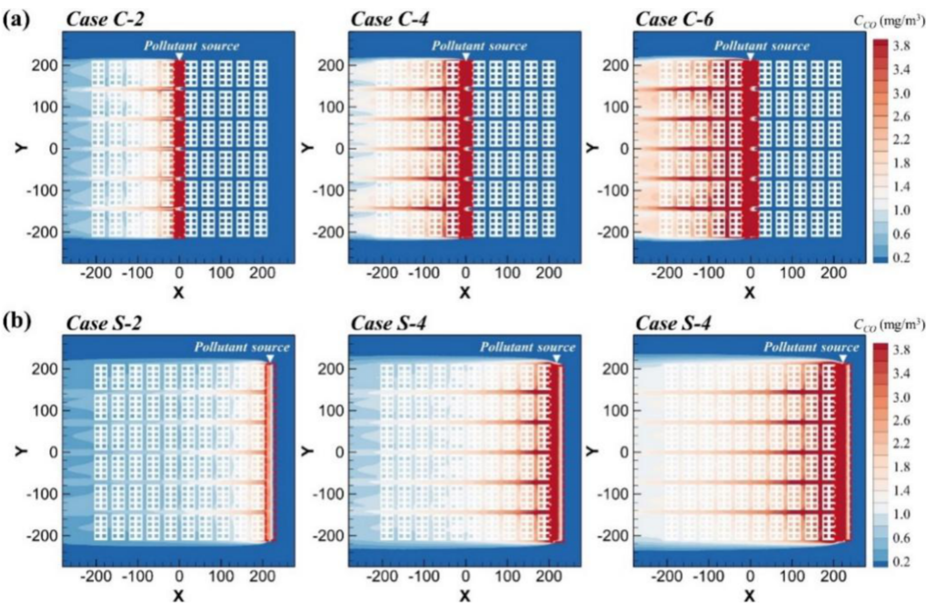

Figure 3. Pollutant contours of the study village for (a) highway passes through the village and (b) highway is located at the edge of the village

3.2. Impacts of Traffic Pollutants on Village

3.2.1. CO Concentration of Courtyard

As is shown in Figure 1, eight courtyard houses form a small cluster in the village of Tianjin. Thus, a village can be seen as consisting of many courtyard house clusters. In this study, the average concentration of pollutants at the pedestrian level of each cluster was calculated, and the calculation results are shown in Figure 4. The US Air quality standard is one of the most stringent air quality standards in the world, and it considers a CO concentration below 4 mg/m^3 to be good air quality. Using this as a standard to quantify the impact of the highway on the village courtyard, it is found that CO concentration in column E of Case C-4 exceeds the air quality standard when the highway passes through the middle of the village, as shown in Figure 4a. Similarly, for Case C-6, the CO concentration in column E still exceeded the air quality standard, and the whole village has a higher concentration of pollutants than in Case C-4.

As shown in Figure 4b, when the highway passes from the edge of the village (i.e., the whole village is located downwind of the highway), the CO concentration of Case S-2 and Case S-4 does not exceed 4 mg/m^3. For the six-lane highway type, the CO concentration of the downwind first column exceeded 4mg/m^3, but the pollutant concentration was lower than that of Case C-6. Therefore, from the perspective of CO concentration, if the highway passes through the middle of the village, only Case C-2 can not make the pollutant concentration of the village courtyard exceed the air quality standard; if the highway passes through the edge of the village, neither Case S-2 nor Case S-4 can make the pollutant concentration of the village courtyard exceed the air quality standard.

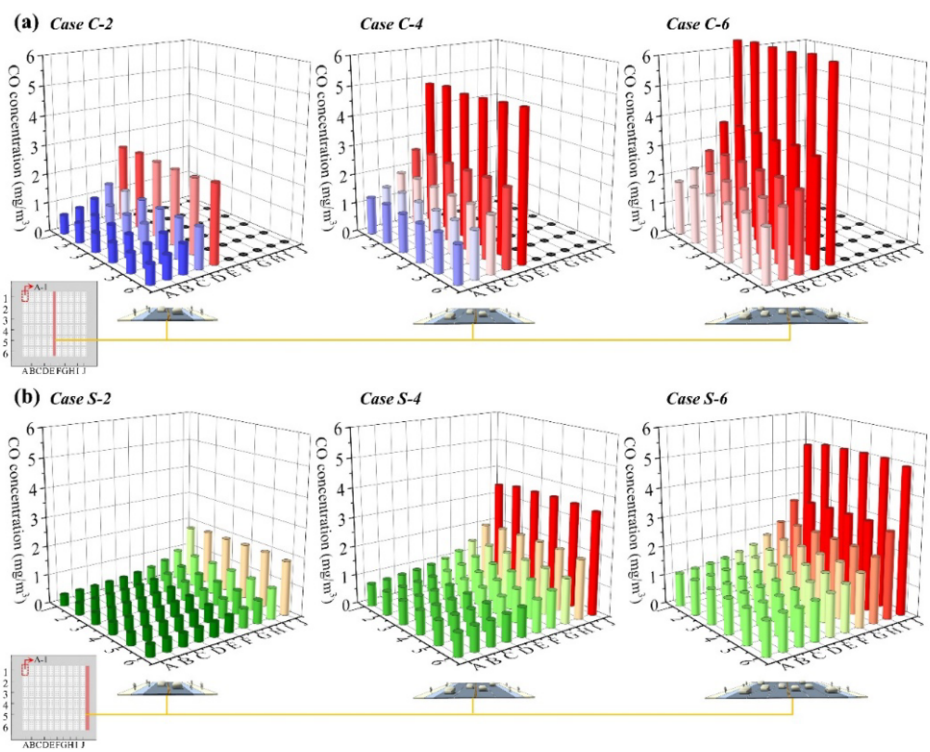

Figure 4. CO concentration of courtyards at the pedestrian level (2 m). (a) highway passes through the village, and (b) highway is located at the edge of the village

3.2.2. Intake Fraction of Residents

Similar to the distribution of CO concentration, the IF value in the first column downwind from the highway has higher IF values. When the highway passes through the middle of the village, the IF values of courtyards in the village are shown in Figure 5a. The contaminated situations for Case C-6 are higher than those for Case C-2 and Case C-4. The IF values in column E of Case C-6 are 23% and 59% higher than those of Case C-4 and Case C-2. Column J has the highest IFs when the highway passes over the edge of the village, as shown in Figure 5b. The IFs for Case S-6 are significantly higher than those for Case S-2 and Case S-4. In addition, the IFs for Case S-2 are very low, significantly lower than those for the other five cases. The maximum IF values for Case S-6 (column J) and the maximum IF values for Case C-4 (column E) are similar in value. Overall, highways passing through the middle of villages have a greater impact on the health of residents than those passing through the edges of villages.

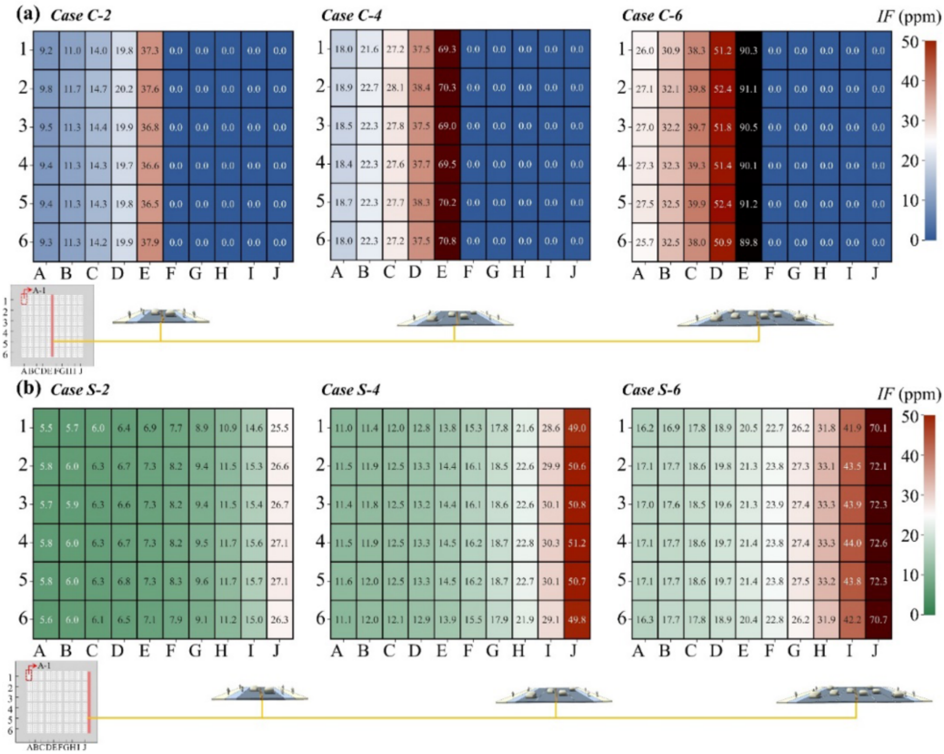

Figure 5. Intake fraction (IF) of residents for (a) highway passes through the village and (b) highway is located at the edge of the village

4. Conclusion

CO in automobile exhaust significantly impacts human health; for example, high concentrations of carbon monoxide can reduce the ability of blood to transport oxygen and cause tissue hypoxia. This study used CFD simulation techniques to analyze the effects of two types of highways passing through the village and three highway types (two-way two-lane, two-way four-lane, and two-way six-lane) on the air quality within the village. The CO concentration and intake fraction of village courtyards were analyzed to quantify the impact on residents' health. The results of this study can provide a reference for the future planning and construction of highways around rural areas from the perspective of pollutant diffusion and residents' health.

From the perspective of CO concentration, if the highway passes through the middle of the village, the two-lane highway type does not make the pollutant concentration of the village courtyard exceed the air quality standard; if the highway passes through the edge of the village, the two-lane and four-lane road type does not make the pollutant concentration of the village courtyard exceed the air quality standard. Similarly, the intake fraction also shows a similar distribution pattern to the CO concentration. The six-lane highway that passes through the middle of the village poses the greatest risk to residents. Therefore, traffic routes with traffic flow lower than the requirements of the above highway types can be built on the edge of the village. For the wider and busier highway construction needs, the highway can be built far away from the village and constructing auxiliary roads to the village to meet the travel needs of residents. In addition, setting up a pollutant insulation panel may also be a good way to insulate the pollutants. The impact of the isolation panels on highway pollutants will be analyzed in detail using CFD simulations in the future.

References

[1] X. Zeng, Y. Zhao, and Z. Cheng, Development and research of rural renewable energy management and ecological management information system under the background of beautiful rural revitalization strategy, *Sustainable Computing: Informatics and Systems* **30** (2021), 100553.

[2] Q. Deng, C. Lu, Y. Yu, Y. Li, J. Sundell, and D. Norbäck, Early life exposure to traffic-related air pollution and allergic rhinitis in preschool children, *Respiratory Medicine* **121** (2016), 67-73.

[3] S. Cai, Q. Li, S. Wang, J. Chen, D. Ding, B. Zhao, D. Yang, and J. Hao, Pollutant emissions from residential combustion and reduction strategies estimated via a village-based emission inventory in Beijing, *Environmental Pollution* **238** (2018), 230-237.

[4] H. Yang, T. Chen, Y. Lin, R. Buccolieri, M. Mattsson, M. Zhang, J. Hang, and Q. Wang, Integrated impacts of tree planting and street aspect ratios on CO dispersion and personal exposure in full-scale street canyons, *Building and Environment* **169** (2020), 106529.

[5] J.J. Zhang, and K.R. Smith, Household air pollution from coal and biomass fuels in China: measurements, health impacts, and interventions, *Environmental health perspectives* **115** (2007), 848-855.

[6] L. Li, F. Fan, and X. Liu, Determinants of rural household clean energy adoption intention: Evidence from 72 typical villages in ecologically fragile regions of western China, *Journal of Cleaner Production* **347** (2022), 131296.

[7] B. Blocken, 50 years of Computational Wind Engineering: Past, present and future, *Journal of Wind Engineering and Industrial Aerodynamics* **129** (2014), 69-102.

[8] F. Xu, Z. Gao, J. Zhang, Y. Hu, and W. Ding, Influence of typical street-side public building morphologies on the ventilation performance of streets and squares, *Building and Environment* **221** (2022), 109331.

[9] C. Xi, C. Ren, R. Zhang, J. Wang, Z. Feng, F. Haghighat, and S.J. Cao, Nature-based solution for urban traffic heat mitigation facing carbon neutrality: sustainable design of roadside green belts, *Applied Energy* **343** (2023), 121197.

[10] F. Xu, Z. Gao, Y. Xing, Z. Wu, J. Zhang, Y. Liao, and Y. Hu, The effect of village morphological variation caused by economic development on residents' health and rural ventilation in Tianjin, *Buildings* **12** (2022), 1393.

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

[12] P.J. Richards, and R.P. Hoxey, Appropriate boundary conditions for computational wind engineering models using the k-e turbulence model, *Computational Wind Engineering 1* **46-47**(1993), 145–153.

[13] L. He, J. Hang, X.Wang, B. Lin, X. Li, and G. Lan, Numerical investigations of flow and passive pollutant exposure in high-rise deep street canyons with various street aspect ratios and viaduct settings, *Science of the Total Environment* **584** (2017), 189-206.

[14] X. Du, Y. Wu, L. Fu, S. Wang, S. Zhang, and J. Hao, Intake fraction of PM2.5 and NOx from vehicle emissions in Beijing based on personal exposure data, Atmospheric Environment 57 (2012), 233-243.