Wind Engineering Joint Usage/Research Center
FY2022 Research Result Report

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Research Theme:
The characteristics of turbulence and pollution diffusion inside urban street canyon based on vehicle canopy model

Representative Researcher: Yu Zhao

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1. Research Aim

With the development of China's economy, the number of vehicles on the street is increasing, resulting in traffic emissions become one of the main sources of pollution in high-density cities, and the stagnant air flow caused by dense high-rise buildings makes it difficult for air pollutants to spread. This coupling problem leads to frequent reports of with high air pollution concentrations in the urban canopy [1]. Due to the need of travel, people have to spend a longer time in the vehicle, and the external environment is one of the influencing factors of the micro-environment in the vehicle. The focus of air quality is gradually shifted from the indoor environment to the micro-environment [2] and the external environment in the vehicle. The main component of air pollution is atmospheric particulate matter (PM). PM will have a negative effect on human health [3]. Particulate matter is the pollutant with the most complex and harmful composition in the atmospheric environment [4].

At present, some scholars have vehicleried out a research on the pollutants inside and outside the vehicle. Yuan et al. 2019 [1] considered the influence of building height change on pollutant diffusion and established a semi-empirical multi-layer urban canopy model, which adopted the box model and was deduced according to the quality conservation in each layer. Zhao et al. 2021 [5] conducted on-site monitoring of Lianhuashan, Jiaojinshan and Shimen urban tunnels in Dalian. In order to assess the particulate pollution level, they conceived and applied the semi-parametric particle diffusion model. Liu 2015 [2] measured the urban roads, suburban roads and expressways in Guiyang, and found that the concentration of PM2.5 in the vehicle mainly depends on the overall environment outside the vehicle. Ge [6] conducted a research on the measurement and analysis of the concentration of air pollutants in the vehicle abroad, and found that the pollution level in the vehicle was affected by the temperature and the ventilation rate of the vehicle.

Moreover, some scholars have explored the pressure relationship inside and outside the vehicle through wind tunnel experiments [7]. In addition, wind tunnel experiments have also been widely used to investigate the distribution and airflow organization of pollutants in street canyons. For example, Christof Gromke et al. [8] used wind tunnel experiments to investigate the effect of trees on the diffusion of pollutants in urban street canyons, while Ziwei Mo et al. [9] studied the pollutant volume dispersion over the physical urban area. The main advantage using wind tunnels is the control of variables at will and economy in terms of time and money [10]. In fact, the major limitations of direct field experiments are, that all possible governing parameters are simultaneously operative; it is not easy to determine which are governing and which are secondary or insignificant parameters [11].

These are studies of pollutants inside and outside vehicles. Although some achievements have been made, there are few studies on the change law of pollutants in the valley and the influence of vehicle ventilation mode on the concentration of pollutants in the vehicle. Therefore, the author explores the change law of pollutants in the valley and the influence of different ventilation modes on the interior environment in this paper. To this end, the author using multilayer urban canopy structure theory of street valley pollutants concentration diffusion model, describe the traffic flow, natural wind and vehicle movement caused by airflow and other factors on the valley of grain mass concentration. Then, the measurement method of fixed and mobile measurement are used to analyze the pollution characteristics of the pollutants in the vehicle and the influence of the vehicle ventilation mode on the concentration of particulate matter. The study of traffic wind is an important issue in urban transportation planning, building design, and transportation safety. In order to study the differences in traffic wind effects among different vehicle models in street canyon environments, we conducted a series of wind tunnel experiments. Explore the distribution of street valley wind farms with different proportions of vehicle types, and further reveal the role of traffic wind in the transportation environment.

2. Research Method

2.1 Vehicle canyon model

As shown in Fig. 1, to explore the vehicle pollutant concentration change rule, on the street of vehicle emissions of particulate matter as pollution sources. Pollutants in the horizontal direction of the street valley will spread with the traffic wind and the natural wind, and the volume exchange of gas exists between the air above the vertical traffic flow layer and the upper layer of the street. The theory of multi-layer urban canopy structure is used in the vertical direction.

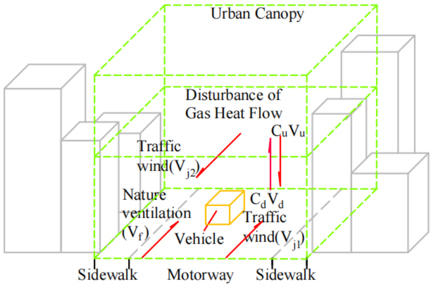


Fig.1. Model of concentration diffusion

According to the vertical height of the atmospheric boundary layer, it can be divided into canopy (from the ground to twice the average obstacle height), rough sublayer (2-5 times the average height of the obstacle) and inertial sublayer [12]. The vertical direction of the street valley is divided into two layers, the lower traffic flow layer and the urban canopy, which is deduced according to the quality conservation in each layer. There is vertical diffusion of pollutants in the lower traffic flow layer and the urban canopy, and the equation of pollutant concentration control is:

$$\dot{q}\lambda_e = u_d(C_1 - C_2)(1-\lambda_p) \tag{1}$$

Where $\dot{q}$ is the traffic-related pollutant emission flux (kg/(s·m^2); λ_e is a dimensionless parameter describing the ratio of the pollutant discharge area to the total plot; C_1 and C_2 are the concentrations of pollutants in the first and second layer, respectively, λ_{p1} is the site coverage of the first layer, and u_{d1} is the diffusion rate of pollutants between the first and the second layer.

For the diffusion velocity, the calculation method is provided as follows:

$$u_d = \frac{u^*}{\sqrt{2\pi}} \tag{2}$$

Where u^* is the friction velocity of the shear layer; and the ratio between u^* and the average wind speed at the top of the rough sublayer U_{ref} when the front density (windward area density) $\lambda_f \geq 0.4$ is a constant of 0.12 [1].

For λ_f, the calculation formula is listed as follows:

$$\lambda_f = \sum_{\theta=1}^{16} \lambda_{f(\theta)} P(\theta) \tag{3}$$

Where $\lambda_{f(\theta)}$ and $P(\theta)$ represent the front density and the annual wind probability at the θ angle, respectively (which can be obtained from the wind data climate statistics).

As the vehicle is running on the street, the following assumptions are made:

A. vehicle exhaust emissions are the only source of pollution on the streets;

B. Suppose that the wind speed in the urban canopy is uniform;

C. Each layer is distinguished by features: front density (windward area density) λ_f and site coverage λ_p where :

$$\lambda_p = \frac{A_F}{A_T} \tag{4}$$

D. Above the roof of the building, assume that the existence of pollutants is negligible, that is, the concentration of pollutant is 0;

E. Horizontal delivery to the target volume and an equal amount of air pollutants delivered from the target volume.

Based on the above five assumptions, the equation (5) is established:

$$V\frac{dC_d}{dt} = nC_pV_p - V_j(C_d - C_{j,0}) - V_f(C_d - C_{f,0}) + V_u(C_u - C_d) \tag{5}$$

Where V represents the volume of the target pedestrian area (m^3), V=LA_r, where L is the length of the valley (m), and A_r is the longitudinal cross-sectional area of the valley (m^2); C_d represents the pollutant concentration in the target area outside the vehicle (μg/m^3); n represents the number of vehicles, $n = QL/60v_c$, where Q is the number of vehicles recorded per minute, and v_c is the motor vehicle speed (m/s); C_p represents the concentration of pollutants in the vehicle exhaust (μg/m^3); V_p represents the vehicle exhaust volume; V_j represents the traffic wind flow; $C_{j,0}$ indicates the concentration of external pollution from the traffic wind (μg/m^3); V_f represents the natural wind flow, V_f=$v_0A_r cos\theta$, where θ is the wind Angle (dimensionless), v_0 is the natural wind speed (m/s); $C_{f,0}$ indicates the concentration of external contamination from the natural wind (μg/m^3); V_u represents the amount of air exchanged between the middle and upper layers of the valley (m^3/s); C_u represents the pollutant concentration in the upper layer of the valley (μg/m^3).

Bringing each variable expression into (5), we could deduce the following formula:

$$LA_r\frac{dC_d}{dt} = \frac{QL}{60v_c}C_pv_ps - v_c\sqrt{nA_mA_r}(C_d - C_{j,0}) - v_0A_r\cos\theta(C_d - C_{f,0}) + A_s\frac{q\lambda_e}{\lambda_p - 1} \tag{6}$$

For (6), we could conclude the solution of C_d as follows:

$$C_d = (D + M\Delta te^{N\Delta t})e^{-N\Delta t} \tag{7}$$

Where D is a constant; M and N could represent as follows:

$$M = \frac{QC_pv_ps}{60A_rv_c} + \frac{v_c\sqrt{nA_mA_r}}{LA_r}C_{j,0} + \frac{v_0\cos\theta}{L}C_{f,0} + \frac{q\lambda_eA_s}{LA_r(\lambda_p - 1)} \tag{8}$$

$$N = \frac{v_c\sqrt{nA_mA_r}}{LA_r} + \frac{v_0\cos\theta}{L} \tag{9}$$

The Equation (7) was deduced under the assumption of spatial uniform distribution for pollutant. When considering the non-uniform distribution induced by traffic flow, natural wind, vehicle movement and other factors, the equation (7) could be corrected as follows:

$$C_d = \alpha(D + M\Delta te^{N\Delta t})e^{-N\Delta t} + \beta \tag{10}$$

Where α and β are the correction coefficient.

2.2 Field measurement

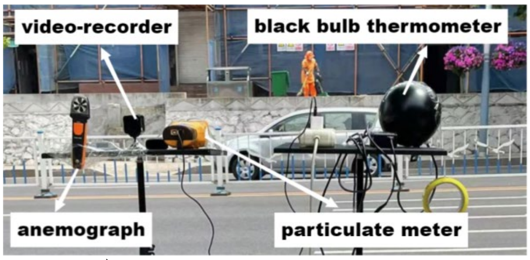
Furthermore, the accuracy of the vehicle canyon model when predicting the pollutant concentration inside street canyon needs to be verified by the measured data. Thus, an annual field measurement testing the pollutant diffusion patterns in three typical street canyons in Dalian, China was conducted. The details could be found in the following sections.

2.2.1 Measured object

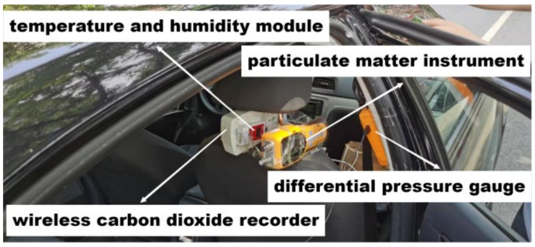
The measured objects of this paper are three typical kinds of streets in Dalian, Market Street (one-way, double row), Tangshan Street (two-way, four rows) and Shengli Road (two-way, six rows). The specific test path is consistent with the previous paper published by the research team, see the original [14].

2.2.2 Contents of the actual measurement

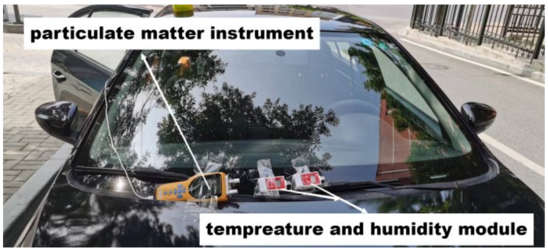
Fig. 2 shows the schematic diagram of the measuring point, including the fixed point of the street, the moving point inside the vehicle and the moving point outside the vehicle. The concentration of particulate matter inside and outside the vehicle is measured in four ventilation modes of confined circulation, inner circulation, external circulation and micro-window. Details of the measured performance parameters of the measured instrument are given in Table 1.



a) Sampling point on the street



b) Sampling point in the vehicle



c) Sampling point outside the vehicle

Fig. 2 Schematic diagram of measuring points

Table 1. Performance parameters of the measured instrument

Instrument name	Measurement parameter	Instrument performance parameters
Particulate instrument	PM0.3 PM1.0 PM2.5 PM10	Range：0-500mg/m³ Accuracy：≤±3% Resolution Ratio：1ug/m³ Interrecord Gap：1s
Video Recorder	vehicle Flowrate	Resolution Ratio：1080p

2.3 Wind tunnel experiment

2.3.1 Basic Principles

In urban environmental research, wind tunnel experiments are commonly used to study issues such as street canyon wind fields, traffic wind, and pollutant dispersion. For example, studying street canyon wind fields can be achieved by placing street canyon models in a wind tunnel and measuring wind field parameters under different conditions such as wind speed and direction to analyze the variations in the wind field within the street canyon. Traffic wind studies can be conducted by placing vehicle models in the wind tunnel and measuring wind field parameters under different conditions such as vehicle speed and quantity to analyze the impact of traffic on the wind field. For pollutant dispersion studies, pollutants can be injected into the wind tunnel and pollutant concentration distribution can be measured to analyze pollutant dispersion under different conditions.

A wind tunnel is a device used in aerodynamic research to study the effects of air moving past solid objects. Wind tunnels consist of several components, including a powerful fan or blower to generate airflow, a test section or chamber where the model or object is placed, and instrumentation to measure the flow parameters such as air speed, pressure, and temperature.

In the context of studying urban environmental wind fields, the wind tunnel experiment can be performed as follows:

(1) Set up the wind tunnel with the appropriate instrumentation, including sensors for measuring air speed, temperature, and pressure.
(2) Construct a scale model of the urban environment, which could include street canyons, buildings, and other structures. The model should be placed in the test section of the wind tunnel.
(3) Adjust the fan or blower to generate a flow of air at the desired speed and direction.
(4) Measure the flow parameters at various points within the model to obtain a detailed picture of the wind flow in the urban environment.
(5) Change the parameters of the model or the wind tunnel settings to simulate different scenarios and observe their effects on the flow field.

Wind tunnel experiments can provide valuable insights into the complex behavior of urban environmental wind fields, and can be used to study a wide range of phenomena including street canyon effects, pollutant dispersion, and wind loads on buildings.

2.3.2 Measurement Cases

In the experiment, we selected large and small vehicle models with different quantity ratios and measured the wind fields they experienced at different wind speeds. Specifically, we set the quantity ratios of large and small vehicle models to 10:0, 6:4, 5:5, 4:6, and 0:10, and conducted the experiments at different wind speeds. The details of the experimental case are given in Table 2. To measure the wind fields, we used a pitot tube anemometer and placed it at the rear end of the wind tunnel test section, corresponding to the position of pedestrians breathing in the street. The anemometer was connected to a data acquisition system to record the wind speed data. The vehicle and street canyon model is shown in Fig. 3.

Table 2. Cases of wind tunnel experiments

Cases	Number of large vehicles	Number of small cars	wind speed (m/s)
1	0	10	4
2	0	10	5
3	0	10	6
4	4	6	5
5	5	5	5
6	6	4	5
7	10	0	5
8	2	0	5
9	1	1	5
10	0	2	5

Fig. 3. The vehicle and street canyon model

3. Research Result

3.1 Field measurement results

3.1.1 Traffic flow

Fig. 4 is the graph of the change of traffic flow over time. In order to reduce the error caused by the discontinuity of traffic flow over time in the measurement process, the traffic flow data is counted in the unit of 10 minutes. As can be seen from the figure that the trend of traffic flow in the three different lanes over time varies less. Within 10 minutes, the traffic flow of one-way double-row roads is about 70 vehicles, the two-way four-row is about 165 and about 500 in the two-way six-row. It can be seen that the traffic flow is positively correlated with the number of motor vehicle lanes. The traffic flow has an obvious evening peak. The maximum traffic flow of each lane within 10min is 119,229 and 615, respectively, which occurs in the evening rush hour of 15:30-17:00.

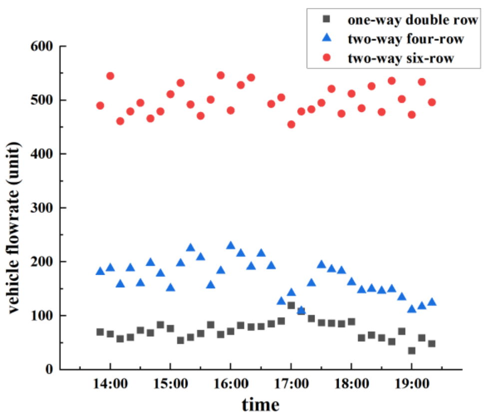


Fig. 4. Graph of traffic flow over time during the measurement

3.1.2 Particles in the street canyon

Fig. 5 shows the variation of PM2.5 concentration over time at moving points outside the vehicle during the test period. The PM2.5 concentration outside the vehicle is mainly affected by factors such as lane type and vehicle speed, etc. In the figure, the highest PM2.5 concentration outside the vehicle appeared at 18:10 on June 18, with a value of 42.08ug /m³. The concentration is close to the maximum PM2.5 concentration limit of 50ug /m³ issued by the 2022 edition of Indoor Air Quality Standards, indicating poor air quality. In the figure, the lowest point occurred at 18:50 on June 16th, when the vehicle was in the initial state, with a value of 19.98ug /m³.

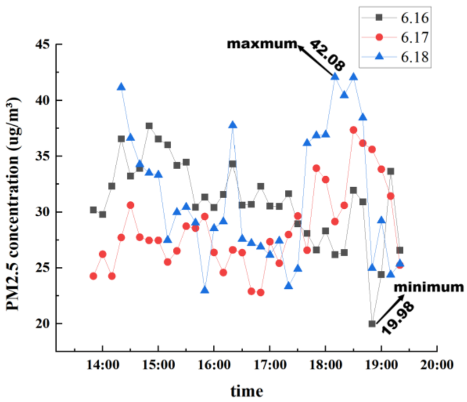


Fig. 5. PM2.5 changes over time at moving points outside the vehicle during the test

3.1.3 Parameters inside the vehicle

1. Particles

During the measurement period, in order to explore the influence of the vehicle ventilation mode on the concentration of PM2.5 particles in the vehicle, the vehicle uses four ventilation modes of confined model, external circulation, inner circulation and micro-window model to drive on the lane.

Figure 6 is a plot of the vehicle PM2.5 concentration over time during the measurement, The concentration of particulate matter in the vehicle constantly changes with the vehicle ventilation mode and lane type. The highest point of PM2.5 concentration in the figure appeared at 18:10 on June 18 and the vehicle is in micro-window model. The numerical value was 37.40 ug / m³, compared with the maximum limit of PM2.5 concentration of 50 ug / m³ released by China's Air Indoor Quality Standard 2022 edition, the concentration value of PM2.5 particles in the vehicle was within the limit range. The lowest point in the figure appears at 16 June at 18:10, the vehicle is in inner circulation . The numerical value was 3.43 ug / m³.

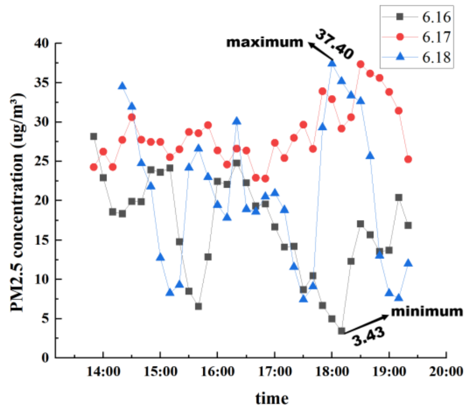


Fig. 6. PM2.5 changes over time in the vehicle during the measurement

2. Influence of ventilation mode on particulate matter in the vehicle

Fig.7 is a comparative map of PM2.5 concentration in different ventilation modes, and the following comparative analysis according to Fig. 5.

One-way double-row channel

The average concentration of PM2.5 in the four ventilation modes of confined, external circulation, inner circulation and micro-window is 16.57 ug / m³, 20.99 ug / m³, 13.82 ug / m³ and 23.90 ug / m³, respectively. The concentration value in the vehicle is within the range stipulated in the 2022 edition of the Air Indoor Quality Standard, and the air quality in the vehicle is good. In this lane, the highest concentration value is in the micro-window mode, followed by the external circulation and confined model, and the lowest is in inner circulation.

Two-way four-row channel

The change pattern of PM2.5 concentration in the four ventilation modes is consistent with that of the one-way double-row channel. With the one-way double row as the benchmark, the concentration of PM2.5 in the vehicle increased by 21.49% and 11.02% respectively under the external circulation and micro-window, and under the inner circulation and confined, the concentration of PM2.5 in the vehicle decreased by 35.75% and 0.66% respectively.

Two-way six-row channel

The change law of PM2.5 concentration in the four ventilation modes is consistent with that of the one-way double-row road and the two-way four-row road. With the one-way double row as the benchmark, the PM2.5 concentration decreased by 10.92% and 22.07% respectively under confined and inner circulation, and the external circulation and micro-opening increased by 6.91% and 4.48% respectively.

To sum up, the concentration of PM2.5 in the vehicle changes the highest is in the micro-window mode, followed by the external circulation, confined model and the lowest is in inner circulation. In the micro window and external circulation mode, external particles will enter the vehicle, increasing the concentration of PM2.5 in the vehicle, and the micro window will enter more particles. In the inner circulation, the vehicle does not exchange gas with the vehicle, but the vehicle filter will purify the air in the vehicle and reduce the PM2.5 concentration in the vehicle, so the concentration is lower than in the confined model. Therefore, PM2.5 concentration: micro-window external circulation> confined model> inner circulation.

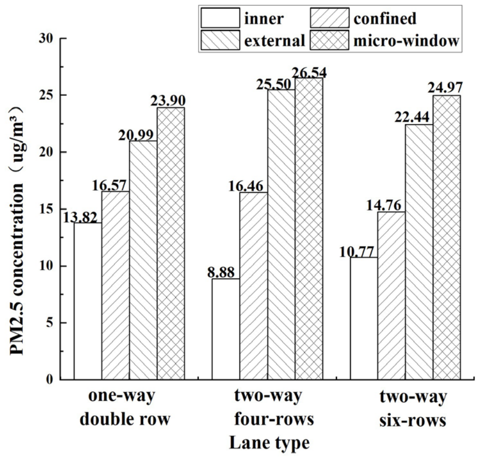


Fig. 7. Comparison diagram of PM2.5 concentration in different ventilation modes

3.1.4 Correlation analysis of particulate matter inside and outside the vehicle

Fig. 8 is the change pattern of the concentration of PM2.5 outside the vehicle. It can be seen from the figure that the PM2.5 concentration inside the vehicle is correlated with the PM2.5 concentration outside the vehicle when the vehicle uses four ventilation modes. In the micro-window and external circulation mode, the inner vehicle PM2.5 concentration was positively correlated with the outer vehicle PM2.5 concentration, and the linear fitting coefficient R^2 is 0.55 and 0.23, respectively. In the confined and inner cycle mode, the correlation of PM2.5 concentration inside and outside the vehicle is very low, and the linear fitting coefficient R^2 is 0.03 and 0 respectively

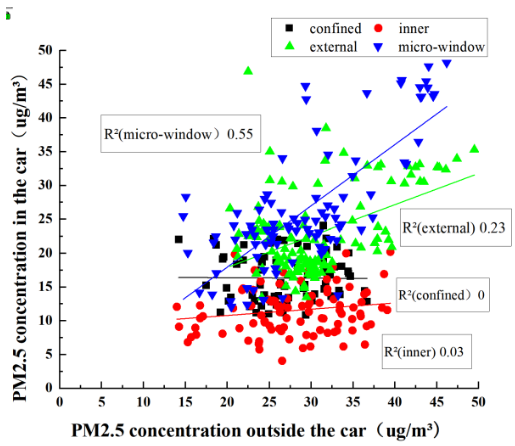


Fig.8.Correlation analysis diagram of PM2.5 concentration inside and outside the vehicle

3.2 Wind tunnel experiment results

In the experimental results, we normalized the data obtained from the wind tunnel experiment and plotted the wind profiles at different inflow velocities. The wind profiles showed good overlap, indicating the reliability of the experimental data (Fig.9). By observing the wind fields formed by models of different vehicle proportions at the same wind speed, we found significant differences in the wind fields. We further applied a weighted average method to the wind field data obtained from the models of large and small vehicles and found that this method could effectively capture the mixed wind field when different vehicle sizes coexist, thereby characterizing the influence of traffic wind when different vehicle types are mixed and obtaining a more accurate and comprehensive description of the traffic wind effect. Fig. 10 shows that vehicles in street canyons can have a significant impact on the sidewalk wind field. The difference between large and small vehicles is around 24%. The vehicle canopy model with a mixture of large vehicles and small vehicles can be approximately calculated using the weighted average method.

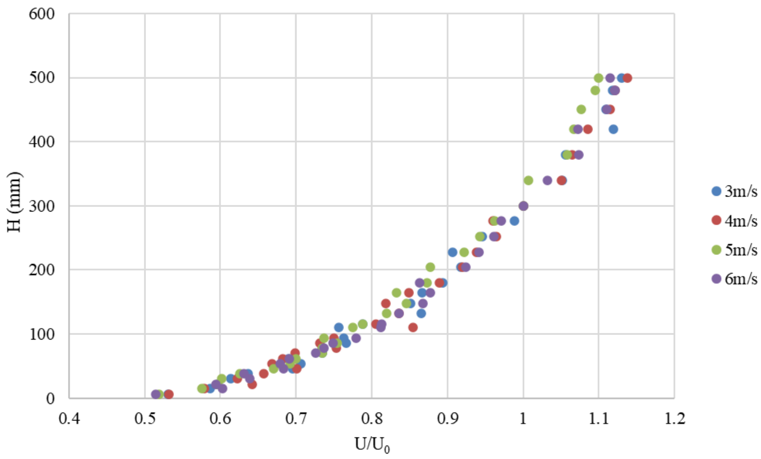


Fig.9. Wind profile along the height direction

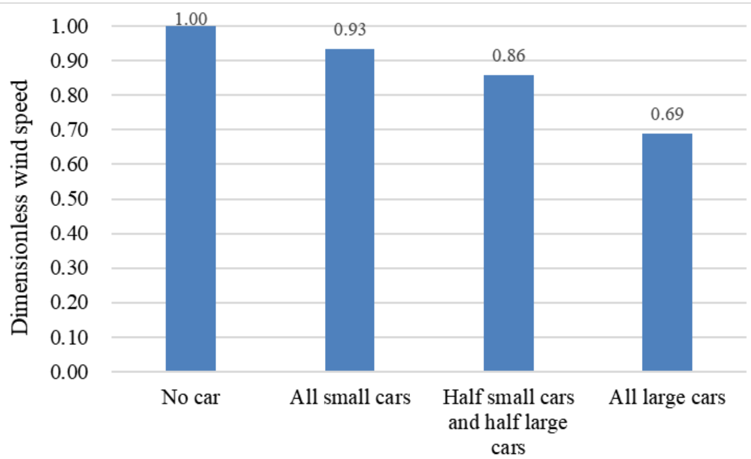


Fig.10. Dimensionless wind speed in pedestrian breathing zone

4. Published Paper etc.

As the field measurement and wind tunnel experiment were finished at March, this year, the data process of the field measurement and wind tunnel experiment is now undergoing. In the next future, the representative researcher Yu Zhao and collaborate researcher Yingli Xuan will prepare 1 or 2 papers to be published in the international Journals such as Building and Environment, Sustainable Cities and Society, etc.

[Presentations at academic societies]

1. **Yu Zhao**, Seasonal patterns of thermal environment and particle at typical street canyons in Dalian, China. 2022 年度 東京工芸大学 風工学研究拠点 共同利用・共同研究 研究集会

5. Research Group

1. Representative Researcher

Yu Zhao, Lecturer, Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian, China

2. Collaborate Researchers

1.	Yingli Xuan	Tokyo Polytechnic University	Assistant Professor
2.	Xiaocheng Song	Dalian University	Associate Professor
3.	Tianyi Zhao	Dalian University of Technology	Associate Professor
4.	Chaowen Jiang	Dalian University of Technology	Doctoral candidate

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6. Abstract (half page)

Research Theme

The characteristics of turbulence and pollution diffusion inside urban street canyon based on vehicle canopy model

Representative Researcher (Affiliation)

Yu Zhao, Dalian University of Technology, Dalian, China

Summary・Figures

In recent decades, China's urbanization process has developed rapidly, and the scale of urban population has expanded rapidly. The problems of urban pollution have become major issues affecting the health and safety of urban population, which has been widely concerned by the whole society. The wind, turbulence, thermal environment and pollution levels in street canyon have become several important factors affecting the health of pedestrians inside. The project focused on the abovementioned issues by employing field measurement and wind tunnel experiment. The results indicated that the pollutant concentration in the target area outside the vehicle is a function of time. The weighted average method can effectively be used to calculate the mixed wind field when different vehicle sizes coexist, thereby characterizing the impact of traffic wind when different vehicle types are mixed.