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Mitigating particulate matter exposure at bus stations using green infrastructure

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ABSTRACT

With the rapid urbanization, traffic volume and road density have significantly increased. Urban residents are encountering high exposure risks to roadside particulate matters emitted from traffic (e.g., $PM_{2.5}$), especially at bus stations where vulnerable passenger groups like children are at higher risks. Using green infrastructure such as green hedge is an effective strategy to mitigate exposure risks to $PM_{2.5}$. However, rare studies have explored the effectiveness of such strategy at bus stations. This study investigated the influence of different green hedge heights (0.5, 1.0, and 1.5 m) on $PM_{2.5}$ deposition and passengers' health risk at bus stations, under different incoming wind directions. Field surveys were conducted to analyze the passengers' demographics and waiting time. Based on the simulation method, it can be found that green hedges at the heights between 1.0 m and 1.5 m proved more effective in blocking $PM_{2.5}$ compared with that of 0.5 m. Without green hedges, passengers faced average daily exposure risks between 10^{-6} and 10^{-4}. After using green hedges, risks were largely decreased by approximately 62 %, reaching the safety threshold below 10^{-6}. Improvement strategies including control of passengers' locations, optimaztion of entrance and exit of bus station, and integration of green hedges and belts were further proposed. This study can provide valuable insights into effective roadside greening initiatives for creating a healthy urban environment.

1. Introduction

With the rapid process of urbanization, the construction scale of urban infrastructures such as transportation has subsequently expanded (Wang. et al., 2024), leading to urban residents increasingly exposed to particulate pollutants (de Nazelle et al., 2017; Zheng and Yang, 2023). According to the data compiled by the World Health Organization on particulate matters in about 3000 cities/towns worldwide (WHO, 2016), only 16 % of the global population evaluated is exposed to air quality that meets the guidelines. Fine particulate matter, $PM_{2.5}$ (particles with an aerodynamic diameter of $\leq 2.5\ \mu m$), is a significant factor in urban air pollution, profoundly impacting the human health and contributing to the incidence and mortality rates of cardiopulmonary diseases (Tahery et al., 2021; Heal et al., 2012). The Global Burden of Disease Study has classified $PM_{2.5}$ as the seventh largest risk factor for death globally (Jiang et al., 2021), and it ranks as the fourth largest risk factor for death in China.

Traffic pollution is the primary source affecting the level of $PM_{2.5}$ in urban areas (Karagulian et al., 2015; Tominaga & Stathopoulos, 2011; Qiu et al., 2017). $PM_{2.5}$ in approximately 90 % of cities can be attributed to traffic vehicle emissions and fossil fuel combustion (Thurston, 2022; Dabrowski, 2022). $PM_{2.5}$ concentrations along the traffic routes are relatively high, such as at bus stations (Hess et al., 2010), where passengers waiting for buses are at increased exposure risks to high levels of roadside pollution, leading to autonomic nervous system disorders and cardiovascular diseases (Wei et al., 2019).

Numerous scholars have conducted the research on roadside particulate matters. In recent years, improvements in traffic emission control technology and fuel quality have greatly reduced the roadside $PM_{2.5}$ concentration exhausted by vehicles. However, non-exhaust emission is

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still a significantly contributor to $PM_{2.5}$, and has gradually increased compared to exhausted ones. Non-exhaust emissions mainly include tire wear (Mayer et al., 2024), brake wear (Zhang et al., 2024), clutch wear, asphalt road wear, as well as dust resuspension (Riddar & Rudolphi, 2013; Budai & Clement, 2018). For example, microscopic analysis by Weinbruch et al. (2014) revealed that the main sources of road particles included three aspects of exhaust, wear, and resuspension, with the proportions of 22 % 22 %, and 56 %, respectively, compared to urban background concentration of particles. Thus, whether it is exhaust emissions or non-exhaust emissions from traffic, roadside $PM_{2.5}$ level is consistently high.

Bus stations are hotspots for high levels of roadside $PM_{2.5}$ exposure, particularly affecting vulnerable passenger groups like children and the elderly during peak hours. Even short commutes can pose significant health risks due to daily exposure (Kaur et al., 2007; Nogueira et al., 2019). An overview of previous research on particle exposure and health risk at bus stations is shown in Table 1. Children usually face a higher risk of exposure to roadside particles than adults, as they inhale more pollutants per body weight and have higher respiratory intake during light to moderate activities (Adams & Requia, 2017; Kumar et al., 2017; Rivas et al., 2018). Liu et al. (2021) investigated particle exposure at seven bus stations in a megacity center and also found significantly higher exposure levels of particles at these bus stations than those at their surroundings, primarily due to a large traffic volume (Zhong et al., 2021). Yang et al. (2021) assessed $PM_{2.5}$ exposure levels in various modes of transportation, with buses showing the highest exposure level. Lan et al. (2024) conducted an observation experiment in Guangzhou and found that passengers at stations in street canyons may be exposed to high particle concentrations during 82 % of their waiting time. Velasco and Tan (2016) measured particle exposure level at five Singapore bus stations and found that exposure levels at these stations were largely 3 times higher than local authority reports. These previous studies consistently revealed that passengers at bus stations may be exposed to high levels of roadside particles. Such exposure can lead to nasal and throat irritation, inflammation, and diseases especially for the elderly and children with weak immunity.

Reducing the particle exposure at bus stations is crucial (Ricardo et al., 2020). The particle concentration for stations in open environments (such as crossroads) was found to be lower than that in narrow street canyons. It is preferable to optimize bus station locations such as placing them on roads with open space at one side rather than on roads with high-rise buildings at both sides (Lan, Jin, & Zhu, 2024). However, bus route and station setups are typically mature and stationary, especially in the central areas of large cities, making it difficult to rearrange bus station location. Green infrastructure such as green hedge has proven a more effective strategy to reduce exposure risks to roadside $PM_{2.5}$ (Li et al., 2023; Xiao et al., 2024; Zheng et al., 2024). Barwise et al. (2021) studied the impact of roadside hedges on reducing the spread of particles to sidewalks and lowering exposure risk. Kumar et al. have conducted the substantial research on the green hedges in urban streets (Al-Dabbous & Kumar, 2014; Kumar et al., 2022, 2024; Ottosen & Kumar, 2020). However, rare studies have considered the effect of green hedges on depositing particles and mitigating the exposure level at stations (Liu et al., 2018).

Thus, this research mainly investigates the impact of different green hedge heights (0.5, 1.0, and 1.5 m) on $PM_{2.5}$ deposition and exposure risk at bus stations for passengers. Fig. 1 shows the main contents of this study. Different passenger groups (children and adults) and their waiting time are surveyed at real bus stations. Different wind directions are also considered in the simulation of particle concentrations. Then, health risks are evaluated and compared based on the particle concentrations using green hedges and without using green hedges. Finally, optimization strategies are proposed to improve the mitigation effects of hedges on roadside particles from traffic. This study provides valuable insights into effective roadside greening initiatives for creating a healthy urban environment.

2. Methodology

In this study, on-site survey was conducted to obtain the types of passengers and their waiting time at 11 bus stations in Nanjing city. The particle concentration at each station was measured to validate the simulation model. Then, simulation method was used to analyze the influence of different green hedge heights (0.5 m, 1.0 m, and 1.5 m) and wind directions (0°, 30°, and 60°) on $PM_{2.5}$ diffusion at different breathing heights of passengers. Based on the simulation of particle concentration, health risk assessment model was employed to calculate the exposure risk of passengers.

2.1. Survey at bus stations

The survey was conducted in Hongwu Road and Hongwu North Road, Xuanwu District, Nanjing city, Jiangsu Province, China (see Fig. 2). This site is located in urban center area of Nanjing. On-site

Table 1
Literature review on particle exposure and health risk at bus stations.

Author (year)	Research contents	Particle types	Main results	Mitigation strategies	Number of passengers
Lan et al. (2024)	To conduct a study on ultrafine particle (UFP) exposure at bus stations with varying styles	UFP	The particle exposure levels at the bus station were notably higher when compared to those at its surrounding areas, particularly in narrow street canyons.	Placing the bus station in an open environment to facilitate the diffusion of particles	8
Yang et al. (2021)	Impacts of different transportation modes on particle matter exposure was studied.	$PM_{2.5}$	Buses registered the highest levels of particle concentration.	Transitioning the bus transportation system from diesel to more eco-friendly alternatives like compressed natural gas or electricity	/
Velasco and Tan (2016)	Portable sensors were used to evaluate the particle exposure level at bus stations during rush hours.	PM_1; $PM_{2.5}$; PM_{10}	On average, the particle level at bus stops was found to be 3.5 times higher than the ambient level.	/	5
Zhong et al. (2021)	Exploring the level of particle exposure for individuals at bus stations in the center of megacities	$PM_{2.5}$; PM_{10}	Differences in particle exposure characteristics at bus stations can be clearly observed in both space and time.	/	7
Liu et al. (2021)	To explore the exposure level of urban residents to particles while waiting at bus stations	$PM_{2.5}$; PM_{10}	Exploring the extent to which city residents were exposed to particles at bus stations situated in different land types	/	12
Xu et al. (2019)	To determine the harm of particle deposition in human bronchus	Particulate matter (10 nm-1 μm)	People who commute by bus may pose a cancer risk, and excess lifetime cancer risk (ELCR) all exceeded recommended limits.	/	1

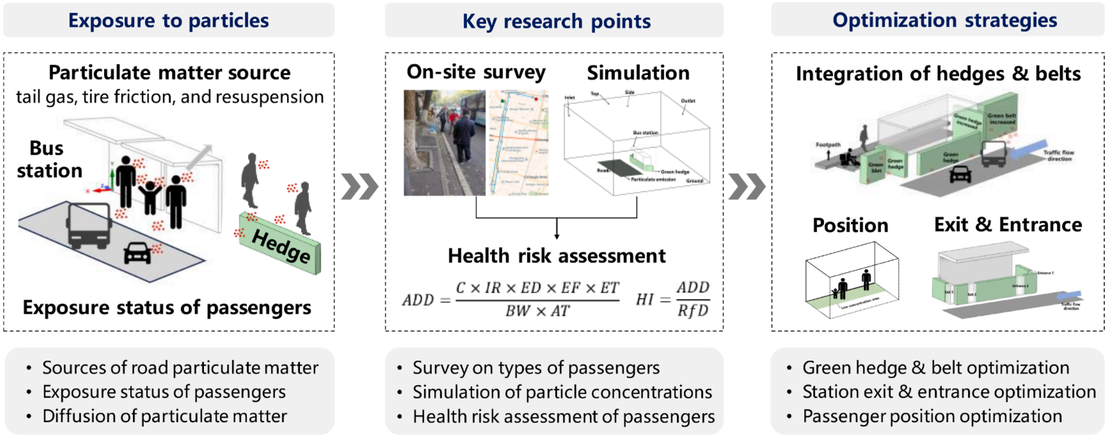

Fig. 1. Main contents of this study.

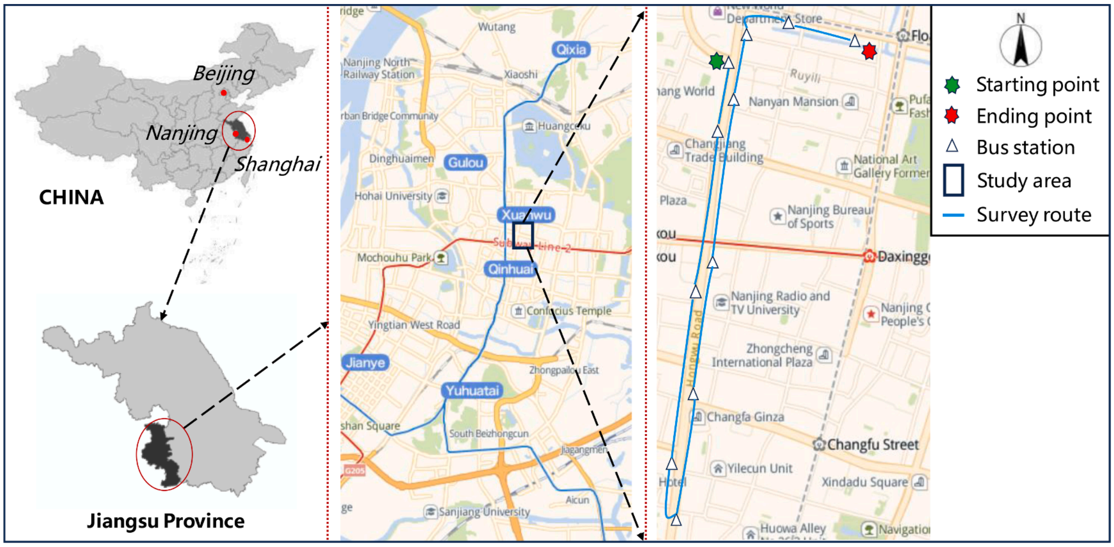

Fig. 2. Schematic of survey area (Hongwu Road and Hongwu North Road) in Nanjing.

research and videography were conducted to record the data from 11 bus stations. The survey was carried out from January to May in 2024 including 5 working days and 4 rest days.

The survey followed a route from the starting point to the ending point, stopping at each bus station. Observations were made regarding the number and demographics (i.e., children, adults, and the elderly) of passengers waiting at 11 bus stations, as well as the average waiting time for different bus routes at each station. Additionally, traffic flow was observed and photographed from the overpass on Hongwu Road. A portable high-precision air environment detector (measured as $\mu g/m^3$) was used to monitor the particle exposure level over a short period of waiting time at each bus station. The measurement time per station was 6 mins, within the range of surveyed waiting time, as described below. The monitoring data of particles can be also used for simulation validation.

Based on a 9-day survey, there were a total of 703 people waiting at 11 bus stations, with children, adults, and the elderly accounting for 17 %, 30 % and 53 % on working days, and 23 %, 31 %, and 46 % on rest days, respectively. The data showed that the main group of passengers taking buses were the elderly. The waiting time at each station was between 4 and 11 mins, and the average waiting time was around 9 mins. The detailed descriptions are shown in the supplementary material.

2.2. *Numerical simulation settings*

2.2.1. *Configuration of geometric model*

Geometric model mainly included the computational domain, bus station, green hedges, and road surfaces. In this study, it is assumed that green hedges are strategically placed around the station to reduce the exposure of particles. Green hedge heights were set as 0.5 m, 1.0 m, and 1.5 m, respectively. In this study, the maximum height was defined as 1.5 m to ensure that standing adults can be able to see coming traffic. The computational domain was larger than the bus station, in order to simulate the airflow in an open environment. The bus station was simplified and composed of two small stations. The configuration of model and its detailed dimensions are shown in Fig. 3 and Table 2.

According Chinese National Health Industry Standard (WS/T612–2018, 2018), the average height of a 7-year-old child is about 120 cm, with a breathing height of about 1.0 m. For individuals aged 18–44, the average heights for men and women in China are 169.7 cm and 158 cm, respectively, resulting in a breathing height of about 1.5 m. In Fig. 4, h1 and h2 were the breathing heights of children and adults (including the elderly), respectively.

2.2.2. *Governing equations for simulation*

Computational fluid dynamics (CFD) was used in the steady-state simulation of airflow, pollutant concentrations (such as $PM_{2.5}$), etc.

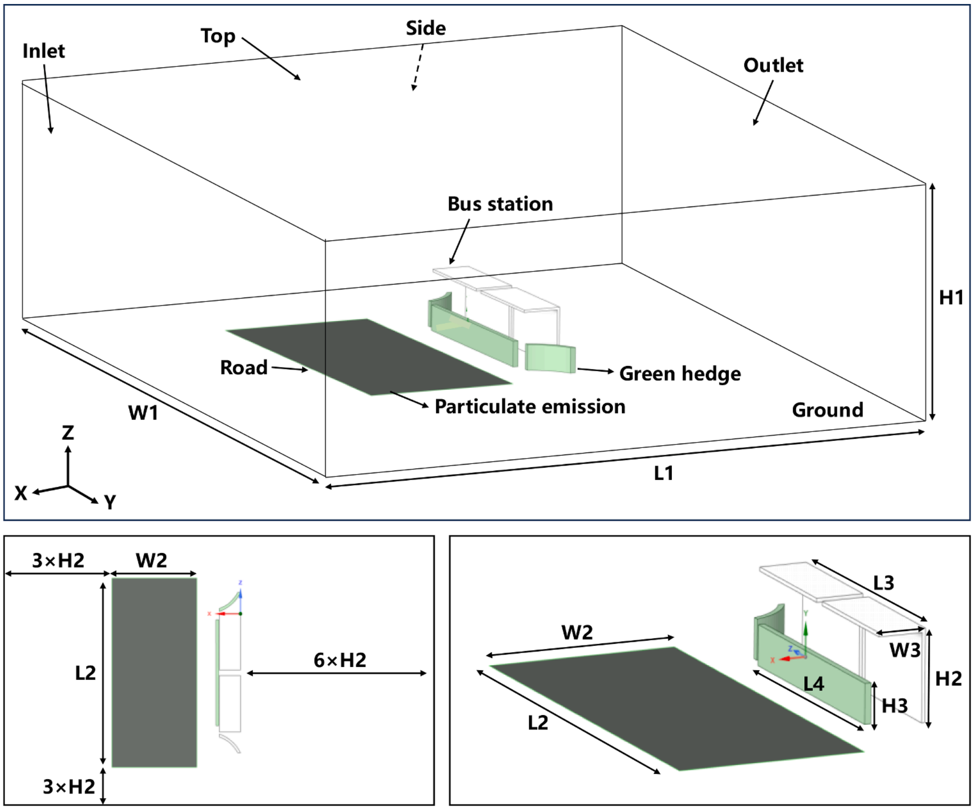

Fig. 3. Schematic diagram of geometric model.

Table 2
Dimensions used in the geometric model.

Geometry	Symbols in Fig. 3	Length (m)
Computational domain	L1	30.6
	W1	24.8
	H1	9.0
Road	W2	6.0
	L2	14.4
Bus station	H2	2.2
	L3	8.4
	W3	1.5
Green hedge	H3	0.5, 1.0, 1.5
	L4	7.6
Distance	D1	1.6

The *Re*-Normalization Group (RNG) k-ε model was used in simulating turbulent flow (Xi et al., 2023). ANSYS Fluent 2022R1 was employed to perform the simulation. The governing equations for mass and momentum conservation were expressed as:

$$\frac{\partial(\rho\overline{u}_i)}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial}{\partial x_i}\left(\rho\overline{u}_i\overline{u}_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left((\mu+\mu_t)\frac{\partial\overline{u}_i}{\partial x_j}\right) + S_i \tag{2}$$

where, ρ is the density of the fluid; $\overline{u}_i$ or $\overline{u}_j$ is the flow velocity in three directions (i or $j = 1, 2, 3$ for x, y, z); P is the pressure; μ and μ_t is viscosity and turbulent viscosity, respectively; and S_i is the generation rate of source. The equations of RNG k-ε model are shown below.

$$\frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho\varepsilon + S_k \tag{3}$$

$$\frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial k}{\partial x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{4}$$

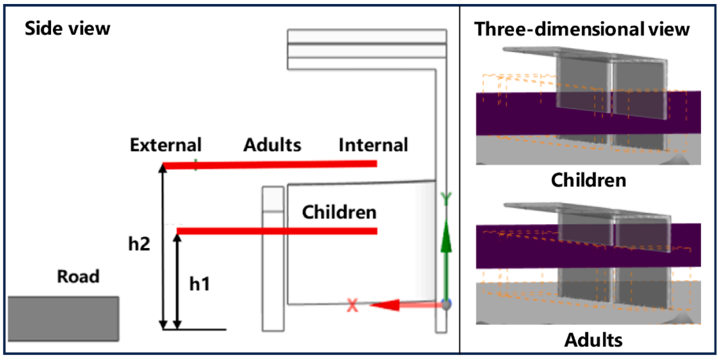

Fig. 4. Views of different breathing heights for children and adults (including the elderly).

where, k is turbulent kinetic energy; ε is dissipation rate of turbulent kinetic energy; σ_k and σ_ε are the inverse turbulent Prandt numbers of k and ε, respectively; G_k represents the turbulent kinetic energy generated by the velocity gradient; G_b represents the turbulent kinetic energy generated by the buoyancy force; $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are empirical constants; and S_k and S_ε are the source terms of k and ε, respectively.

The Lagrangian particle tracking method was used to track particle trajectories by solving the momentum equation (Ren et al., 2019). The particle trajectory was determined by the particle force balance equation, shown as follows.

$$\frac{d\overline{u}_p}{dt} = F_D\left(\overline{u}_a - \overline{u}_p\right) + \frac{g(\rho_p - \rho)}{\rho_p} + \overline{F}_a \tag{5}$$

where, $F_D\left(\overline{u}_a - \overline{u}_p\right)$ is the drag force per unit particle mass; F_D is defined using the spherical drag law; $\overline{u}_a$ is the fluid phase velocity; $\overline{u}_p$ is the particle velocity; ρ_p is the particle density; and $\overline{F}_a$ is the additional forces.

The COUPLED algorithm was applied to solve pressure and velocity fields. The momentum, turbulent kinetic energy, and turbulent dissipation rate were discretized by second-order upwind. The convergence of governing equations was assumed when the residuals were less than 10^{-6}.

2.2.3. Boundary conditions

According to Fig. 3, the top and two sides of the computational domain were set as symmetry, since the symmetric shear stress at the symmetric boundary was zero (Richards & Norris, 2015), which can minimize the impact of the top and side walls on particle concentration. The boundary conditions of the velocity-inlet and the pressure outlet were used for inlet and outlet, respectively. The inlet wind speed (U_z) was distributed according to the atmospheric boundary layer wind profile. The functional relationship between the wind speed and the longitudinal height was defined as below.

$$U_z = U_a\left(\frac{z}{10}\right)^{\alpha} \tag{6}$$

where, U_a is the average wind speed at a height of 10 m from the ground; z is the height from the ground; and α is the surface roughness coefficient, equal to 0.2 (Yang et al., 2023). According to meteorological bureau data, the average wind speed U_a in Nanjing was 2 m/s (cma.gov.cn). Three wind directions (0°, 30°, and 60°) were considered at the inlet, because these wind directions can be almost representative of common wind conditions according to previous studies (Guo et al., 2023; Meng et al., 2022). Due to the friction between vehicle tires and ground or braking, particles produced by exhaust emissions may settle on the road surface and then resuspend. This study assumed that the entire road surface was the source of $PM_{2.5}$, blowing towards the bus stop by different wind directions. The influence of temperature factor is not considered in this study, which is further discussed in Section 4.5. The overview of boundary conditions is shown in Table 3.

$PM_{2.5}$ source release rate was calculated based on traffic flow using the COPERT model, i.e., the number of vehicles per minute (Abbass et al., 2020; Meng et al., 2021). Videos of passing vehicles during peak traffic periods were recorded on the Hongwu Road Overpass to obtain the traffic volume. The average number per minutes for different types of traffic vehicles were determined as Car (38.3 vehicles/minutes) and Bus (1.6 vehicles/minute). Based on The COPERT model, the particle mass flow of the road was set as 1.01×10^{-4} kg/s.

Table 3
Overview of boundary conditions.

Boundary	Magnitude	Type
Inlet	$U_a = 2$ m/s, wind direction = 0°, 30°, 60°	Velocity-inlet
Outlet	0 Pa	Pressure-outlet
Top	/	Symmetry
Side	/	Symmetry
Ground	/	Non-slip wall
Bus station	/	Non-slip wall
Green hedge	Height = 0.5 m, 1.0 m, 1.5 m	Non-slip wall

Moreover, the grid independence among coarse, medium, and fine mesh grids was analyzed as shown in supplementary material. The average difference of wind speed between coarse and medium grids was 1.96 %, and the average difference of wind speed between medium and fine grids was 2.18 %. Thus, medium mesh size was selected in this study. The reliability of numerical simulation was confirmed through comparison with the actual measurement data, as shown in supplementary Fig. C1. The measured particle concentrations at the bus stations and simulated results were within the range of 60–80 μg/m^3, indicating that the simulation model in this study was acceptable.

2.3. Health risk assessment model

The exposure risk to particulate matter was evaluated using the health risk assessment model (USEPA, 1989). Particle concentration (C, mg/m^3) and inhalation rate (IR, m^3/h) can be converted into average daily exposure dose (ADD, mg/kg per day), as follows.

$$\text{ADD} = \frac{\text{C} \times \text{IR} \times \text{ED} \times \text{EF} \times \text{ET}}{\text{BW} \times \text{AD}} \tag{7}$$

where, ED is the exposure duration (year); ET is the exposure time (hours/day); EF is the exposure frequency (days/year); BW is the human body weight (kg); and AD is the averaging days. After determining the ADD, health risk (HI) can be obtained as:

$$\text{HI} = \frac{\text{ADD}}{\text{RfD}} \tag{8}$$

where, HI refers to the health risks associated with inhaling various pollutants during specific activities; and RfD is the reference dose (mg/kg per day) for non-carcinogenic substances. The doses less than RfD are considered to have no adverse effects on health (USEPA, 1989). For example, when $PM_{2.5}$ concentration is less than 10 μg/m^3, it poses no harm to the body. If the concentration of $PM_{2.5}$ is consistently higher than 10 μg/m^3, it will increase the risk of mortality. For every increase of 10 μg/m^3 in concentration of particles, the overall mortality risk will increase by 4 %, and the mortality risk from cardio-pulmonary diseases and lung cancer will increase by 6 % and by 8 %, respectively (Pope et al., 2002). The daily minimum intake was set to be 10 μg/m^3. The body weights for adult and children were defined as 75 kg and 25 kg, respectively. According to the guidelines of USEPA, a health risk value of less than 10^{-6} was considered acceptable and safe, and a value between 10^{-6} and 10^{-4} indicated potential health risks, and a value greater than 10^{-4} represented serious health risks (USEPA 1989).

3. Results

In this section, the simulation results of $PM_{2.5}$ concentration were firstly analyzed under different heights of green hedges (0.5, 1.0, and 1.5 m) and different wind directions (0°, 30°, and 60°). Then, the quantitative analysis of $PM_{2.5}$ concentration was performed to compare the efficiency of green hedges with different heights on reducing the exposure level of roadside particles. Based on the particle concentrations, health risks for children and adults were calculated before and after using green hedges.

3.1. Simulation of $PM_{2.5}$ concentration under different green hedge heights

3.1.1. $PM_{2.5}$ concentrations at X-Y plane

Fig. 5 shows the concentrations of $PM_{2.5}$ at different breathing heights for children and adults under different wind directions without

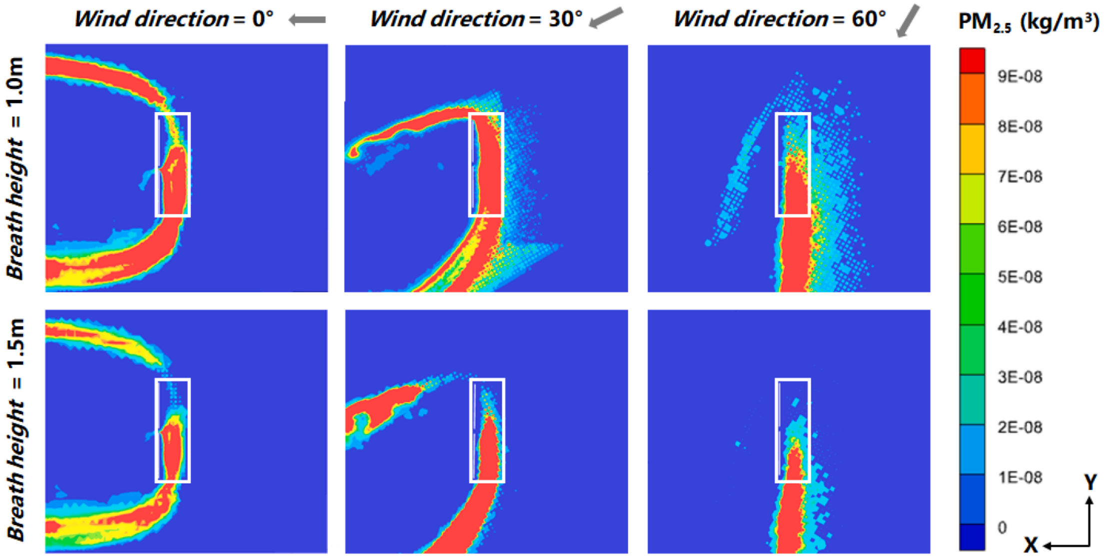

Fig. 5. $PM_{2.5}$ concentrations of X-Y plane at breathing heights of 1.0 m and 1.5 m under different wind directions (0°, 30°, and 60°) without green hedges (note: the white box is the range of activities for children and adults at the bus station).

green hedges. The white box is the range of activities for children and adults at the bus station. It is evident that at the bus station without green hedges, both children and adults respectively at the breathing heights of 1.0 m and 1.5 m were exposed to high concentration of $PM_{2.5}$. It was especially concerning for children, because $PM_{2.5}$ concentration at the height of 1.0 m was lower than that of 1.5 m. The exposure to $PM_{2.5}$ was the most severe when the wind direction was at 0°, making wider dispersion of pollutant across the bus station, compared to the wind directions of 30° and 60°. This is possibly due to the bus station's blocking effect on airflow particularly at the wind direction of 0°, making it difficult for particles to spread away from the station.

Fig. 6 shows the concentrations of $PM_{2.5}$ at different breathing heights for children and adults under different green hedge heights and wind directions. For a 0.5 m height of green hedges in Fig. 6a), it had a minimal blocking effect on $PM_{2.5}$. Although there was a slight reduction in exposure level compared to that without green hedge, most of the activity area for children and adults still experienced the high concentrations. $PM_{2.5}$ concentration at different breathing heights significantly decreased when green hedge heights were 1.0 m and 1.5 m, as shown in Fig. 6b) and c). The concentrations at a few locations may be high due to low-pressure area causing particle accumulation. Besides, a small amount of $PM_{2.5}$ entering the bus station through the gaps of green hedges would escape from the bus station, leading to particles accumulation at the gap.

3.1.2. $PM_{2.5}$ concentrations at Y-Z plane

Fig. 7 shows the impact of green hedge of different heights on $PM_{2.5}$ concentration at the bus station, under three wind directions. When the wind direction was 0° shown in Fig. 7a), without using green hedges, particles tended to accumulate in bus station, making waiting passengers exposure to high $PM_{2.5}$ concentration. At the green hedge height of 0.5 m, a stratification phenomenon can be observed for particle concentration. However, a large amount of $PM_{2.5}$ still accumulated in the bus station, indicating that the blocking effect of green hedges on particles was not favorable enough. When the hedge heights were 1.0 m and 1.5 m, the green hedge effectively blocked and settled the roadside particles, significantly reducing the internal $PM_{2.5}$ exposure level.

According to Fig. 7b) and c), when the wind directions were 30° and 60°, $PM_{2.5}$ would accumulate at the station with the height of green hedge less than 0.5 m, resulting in children and adult's exposure to a high concentration. With the hedge heights of 1.0 m and 1.5 m, particulate pollutants gathered near the ground inside the bus station. At a height of 1.0 m, some particles still entered the station, but the concentration remained relatively low. At a 1.5 m height of green hedge, $PM_{2.5}$ concentration around 0.5 m above the ground was higher due to a low-pressure area causing particles to accumulate near the ground, but not spreading to the areas at breathing heights of 1.0 m and 1.5 m.

Overall, in the presence of green hedges, $PM_{2.5}$ could be effectively blocked and settled, then effectively reducing the concentration of particles in the activity area of children and adults at the bus station. The effective height of green hedge was suggested as 1.0 m-1.5 m, while a height of 0.5 m was less effective.

3.2. Variation of $PM_{2.5}$ concentrations under different green hedge heights

Fig. 8 and Fig. 9 display the $PM_{2.5}$ concentration variations at the breathing heights of children (1.0 m) and adults (1.5 m), respectively, under different green hedge heights and wind directions. It can be seen that with the height of green hedge less than 0.5 m, there was a high concentration of $PM_{2.5}$ both inside and outside the bus station. However, the concentration decreased when it was closer to the interior of bus station. This is possibly due to the formation of a high-pressure area caused by wind speed inside the bus station, preventing the particle accumulation.

From Fig. 8, at the children's breathing height, there were abrupt drops in particle concentration, when the green hedge heights were 0.5 m, 1.0 m, and 1.5 m. As the particle passed through the green hedge from external to internal of stations, the concentration was decreased to around 30–40 $\mu g/m^3$. However, with a 1.5 m height of green hedge and wind directions at 30° and 60°, high $PM_{2.5}$ concentrations still existed inside the bus station, potentially due to that particles entered through the gaps of green hedges and then accumulated in the low-pressure area closed to the hedge.

In Fig. 9, at the adults' breathing height, high $PM_{2.5}$ concentrations were observed outside the green hedge, slightly increasing as it approached the hedge. The obstruction effect of green hedge on wind led to a temporary particulate accumulation. However, after particles passing through the green hedge, $PM_{2.5}$ concentration decreased as they were settled. Despite the green hedge of 1.0 m height being lower than the breathing height of 1.5 m, it could still effectively block the particles.

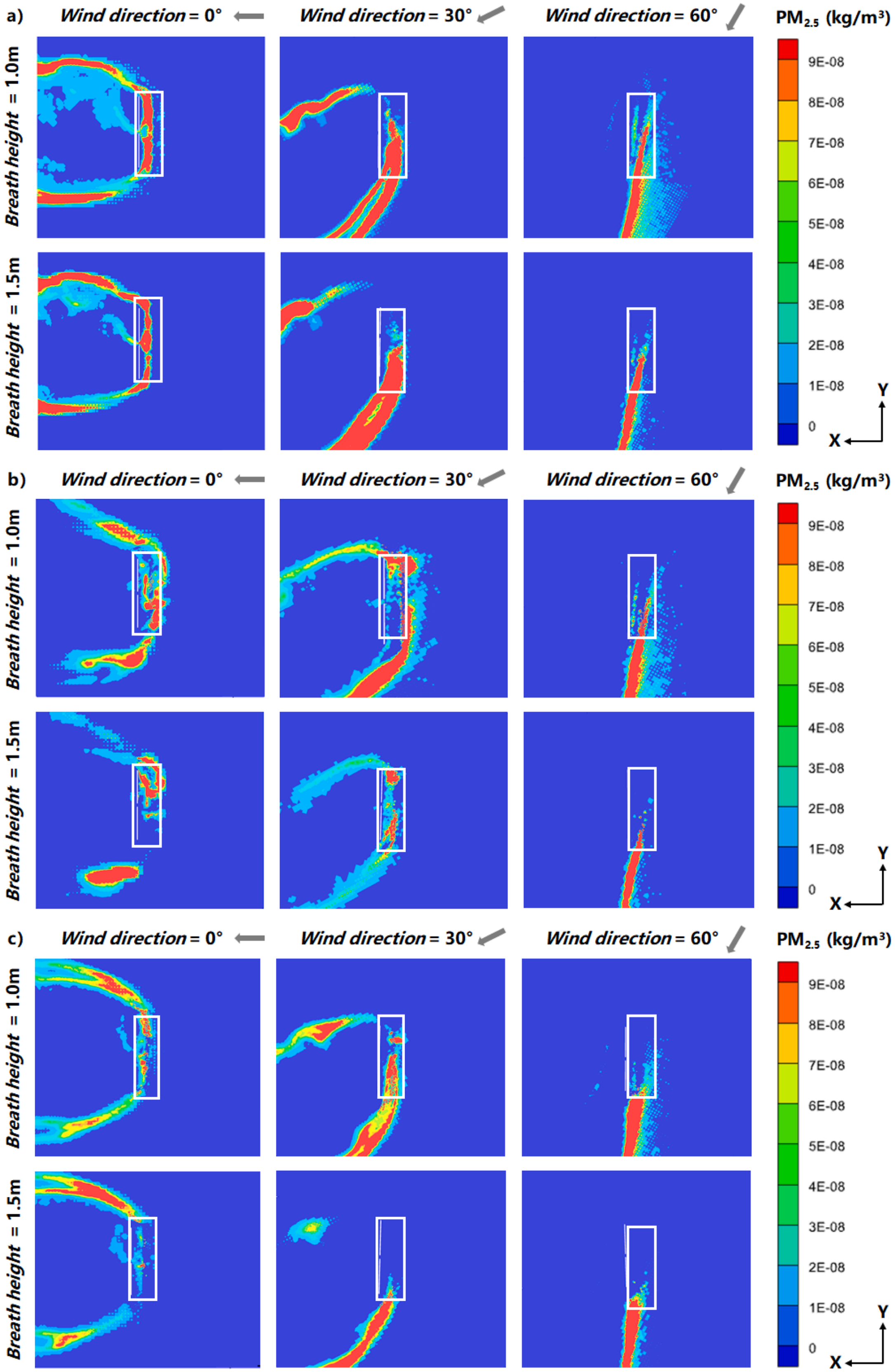

Fig. 6. PM$_{2.5}$ concentrations of X-Y plane at breathing heights of 1.0 m and 1.5 m under different wind directions (0°, 30°, and 60°) and green hedge heights: a) 0.5 m, b) 1.0 m, and c) 1.5 m (note: the white box is the range of activities for children and adults at the bus station).

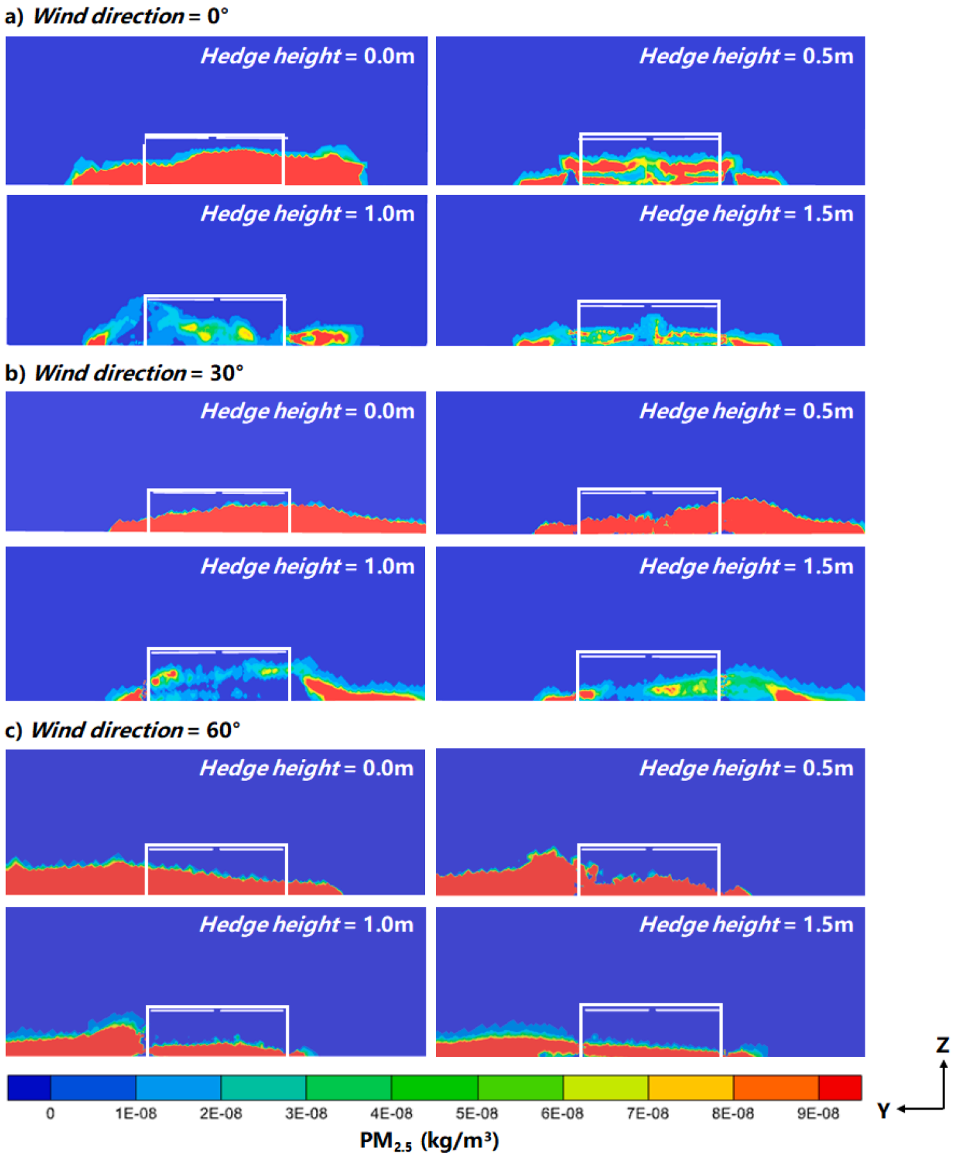

Fig. 7. $PM_{2.5}$ concentrations of Y-Z plane under different green hedge heights (0 m, 0.5 m, 1.0 m, and 1.5 m) and different wind directions: a) 0°, b) 30°, and c) 60° (note: the white box is the range of activities for children and adults at the bus station).

3.3. Health risk assessment with and without using green hedges

Table 4 displays the health risks with and without using green hedges for children and adults. The results showed that during the waiting period at bus stations without green hedges, the average daily exposure risks for adults and children were 1.82×10^{-6} and 2.33×10^{-6}, respectively, which were within the range of potential health risks. Under the protection of green hedges, the average daily exposure risks for adults and children were 0.73×10^{-6} and 0.88×10^{-6}, respectively, meeting the acceptable and safe threshold value (i.e., less than 10^{-6}). During the waiting period, if there were green hedges beside the bus stations, the exposure risks to $PM_{2.5}$ can be reduced by 60.05 % for adults and 62.33 % for children, respectively.

During waiting periods, in addition to the harmful $PM_{2.5}$, there are also nitrogen oxides and carbon monoxide (Li et al., 2016; Kumar et al., 2014) potentially affecting the health risks of passengers, which are also related to the high mortality and morbidity rate (WHO, 2016). Hence, it is crucial to limit the exposure of vulnerable demographics like children and the elderly to serious polluted environment through taking mitigation strategies such as green hedges.

4. Discussion

4.1. Particle distributions at bus stations

As shown in Fig. 6, the hedges at a height of 0.5 m did not have a significant effect on blocking particles, as also reported by the previous study (Abhijith & Kumar, 2019). Vehicle emissions, tire and road friction, as well as road dust could disperse particulate matters to the roadside, and at this point the particulate retention height was generally lower than 1.0 m. Therefore, green hedge at 1.0 m and 1.5 m height could block and settle most particulates. $PM_{2.5}$ concentration closed to the hedge was relatively high, probably because of the adsorption and sedimentation effects of green hedges on particles (Zhao et al., 2024; Lu et al., 2018). Near the inner wall of bus station, two low-concentration areas were formulated, because the airflow swiftly went through the gaps and sides of hedges and then formed two vortex areas, preventing particles from accumulating. Fig. 10 also illustrates the blocking mechanism of hedges on particulate matters from roads, which can be supported by previous work (Abhijith et al., 2017; Barwise et al., 2021). Based on Fig. 7, when the wind direction was 30°, a large amount of

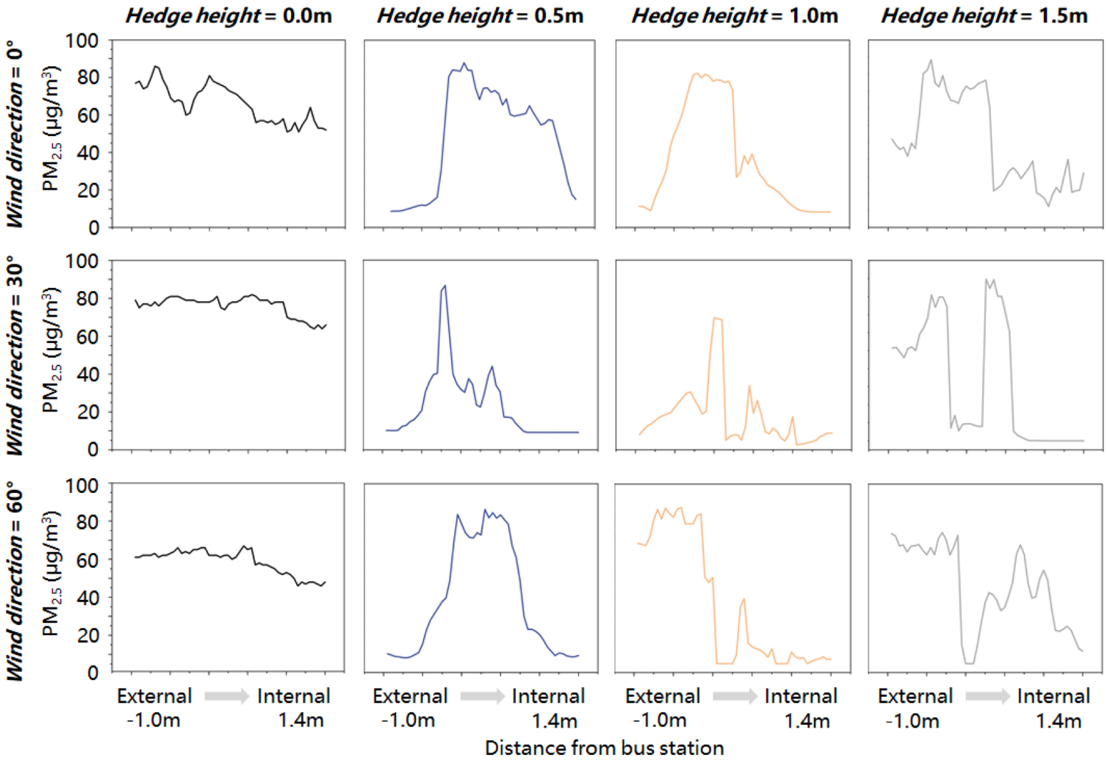

Fig. 8. Variation of $PM_{2.5}$ concentrations at the breathing height of children under different green hedge heights (0 m, 0.5 m, 1.0 m, and 1.5 m) and different wind directions (0°, 30°, and 60°).

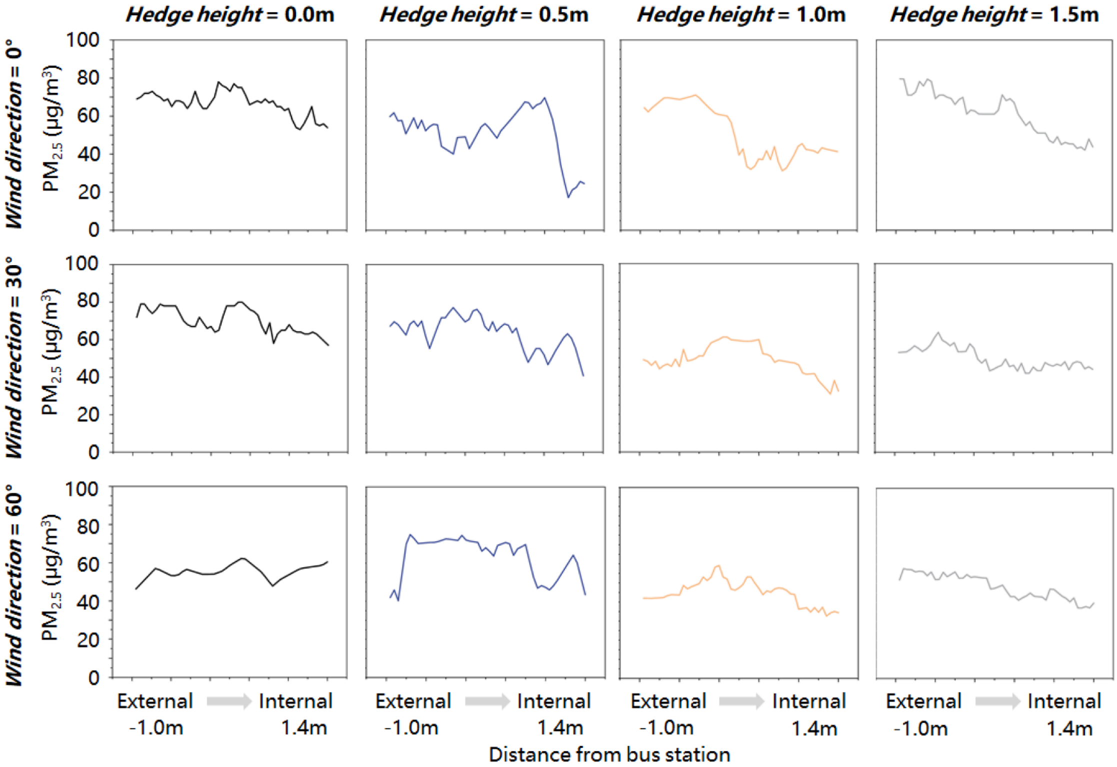

Fig. 9. Variation of $PM_{2.5}$ concentrations at the breathing height of adults under different green hedge heights (0 m, 0.5 m, 1.0 m, and 1.5 m) and different wind directions (0°, 30°, and 60°).

$PM_{2.5}$ gathered on the right side of the bus station. At the wind direction of 60°, $PM_{2.5}$ tended to accumulate on the left side of the bus station, because different wind directions caused varying wind pressures inside the station, resulting in different particle distributions.

Table 4
Health risks (average daily exposure risks to $PM_{2.5}$) for adults and children.

Health risk (10^{-6})	Without green hedges	With green hedges
Adult	1.82	0.73
Children	2.33	0.88

4.2. *Optimization of green hedge heights*

An in-depth analysis was further conducted to determine the optimal height for green hedges, favorable to largely mitigate particle exposures. It is essential that this strategy does not obstruct the sightlines of waiting passengers and bus drivers. Although taller green hedges can be more effective on obstructing $PM_{2.5}$, they also obstruct the views of passengers, potentially causing inconvenience or safety issues. Thus, in this study, the maximum height of green hedges was set as 1.5 m. The goal is to achieve an optimal obstruction of both particles and views.

In this study, three hedge heights were considered. It was found that a 0.5 m high hedge had a minimal effect on particle interception. However, at 1.0 m and 1.5 m heights, the interception effect on $PM_{2.5}$ improved significantly. Based on these findings, it is recommended that green hedge height be between 1.0 m and 1.5 m, with the final design tailored to the specific needs of each bus station. Additionally, the survey revealed that children accounted for 17.6 % of passengers at bus stations, with adults (including the elderly) being the primary ones. Besides, children taking the bus are often accompanied by adults. Therefore, the hedge heights can be slightly higher than the average children's height, as long as it does not obstruct adults' sightlines.

4.3. *Potential effectiveness of green hedges*

4.3.1. *Protection of passenger safety*

In the process of survey, it was found that the elderly waited for buses on the road rather than at the station, as displayed in Fig. 11. This not only affects traffic safety but also increases the risk of passenger waiting for buses (Zhang et al., 2023). After installing green hedges surrounding the platform edge, the movement area of waiting passengers on the station platform will not be reduced. At the same time, green hedges can act as the guardrail to effectively prevent passengers waiting bus from standing on the road. Through placing warning signs near the platform, it can also serve as a deterrent for passengers waiting on roads, and encourage them to wait bus by staying at the station.

4.3.2. *Optimization of entrance and exit*

The actual streets and buildings within the city are complex and ever-changing. Due to the layout of buildings and wind directions, different wind conditions can be generated in street canyons (Liu et al., 2024; Xi et al., 2024). Fig. 12 displays the effect of wind directions on airflow surrounding the bus station. When the wind direction was 90°, buildings obstructed the incoming wind, resulting in a relatively low wind speed. Considering that particulate matters were mainly emitted by traffic flow, the entrance and exit can be better positioned on the side opposite to the traffic flow. When the wind direction was 0° and 45°, a canyon wind was formed, causing the particles to suspend and spread along the wind direction. Hence, the entrance and exit can be placed in the front of the bus station to minimize the particles entering the bus station from the sides.

4.4. *Additional mitigation strategies at bus stations*

Green hedges are effective at blocking $PM_{2.5}$ under normal weather conditions but are less effective during severe smog conditions. Therefore, it is recommended that people waiting for buses, especially children and the elderly, wear masks (Sande et al., 2008). As shown in Fig. 13, to reduce exposure, it is advisable for passengers to stand on the inner side of the station when waiting for the bus. Besides optimizing the bus station's design, the surrounding facilities like green belts can also be optimized. When waiting at the bus station, particles from tire,

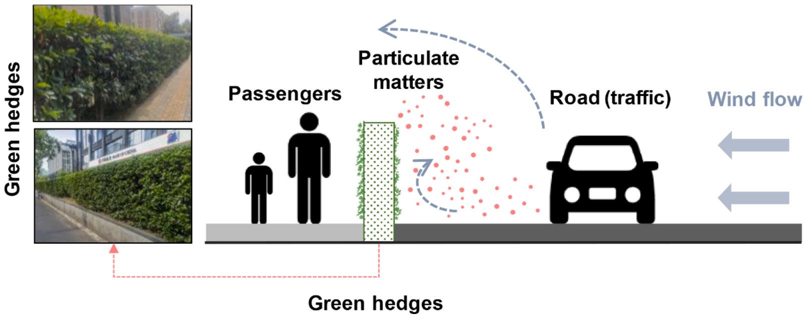

Fig. 10. Actual photo of green hedges to block particulate matters from roads and diagram of its blocking mechanism (Abhijith et al., 2017; Barwise et al., 2021).

Fig. 11. Effectiveness of green hedges on protecting passenger safety.

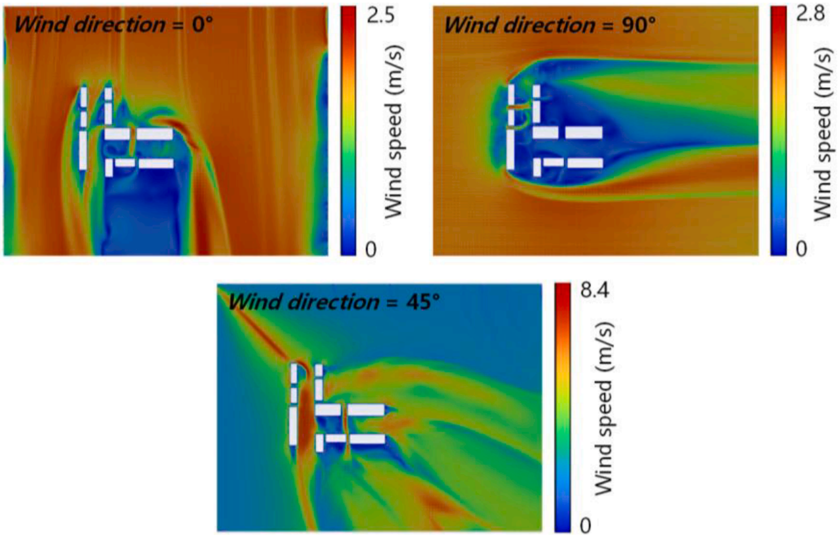

Fig. 12. Wind flow fields under different wind directions of 0°, 90°, and 45°.

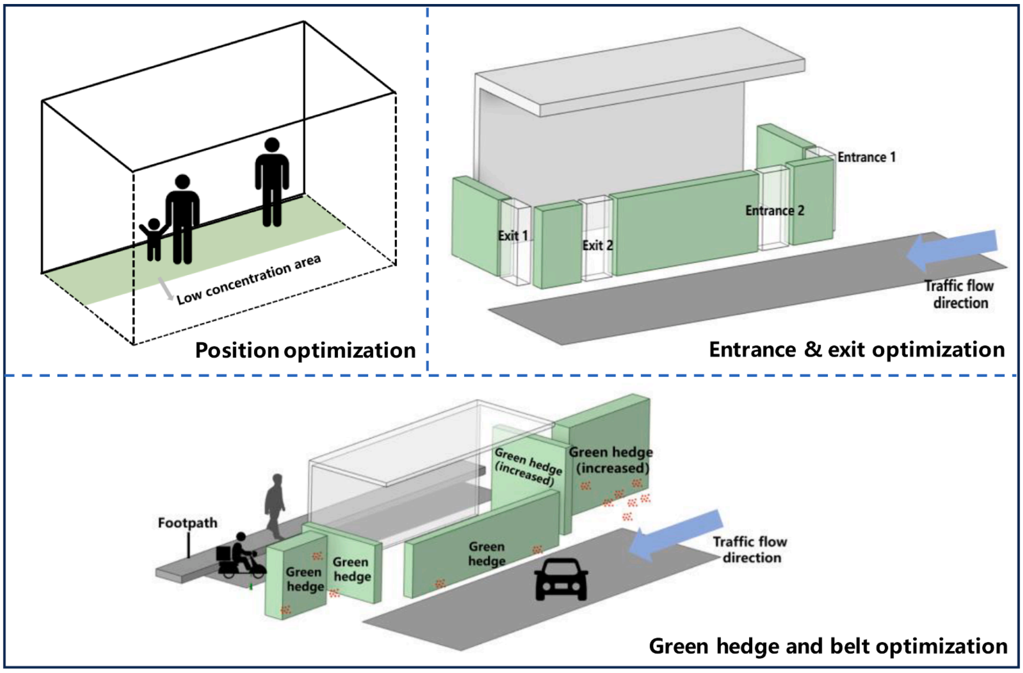

Fig. 13. Additional mitigation strategies at bus stations.

asphalt wear and ground dust resuspension are carried to the station by vehicle-generated airflow. Increasing the height of the green hedge and belt on the side facing incoming vehicles can block the spread of particulates and prevent them from reaching non-motorized lanes and sidewalks.

Strategic mitigation and policies that enhance the quality of life for city dwellers are crucial in urban planning. One key strategy is the creation of walkable cities, which prioritize residents' well-being by emphasizing pedestrian traffic, people-oriented urban spaces, and integrating housing with public transportation. This approach ensures safety, enhances social interaction, and promotes sustainability by reducing the reliance on private vehicles. Additionally, walkable cities require regulations and infrastructures to minimize road traffic risks to pedestrians and cyclists. This can be achieved through implementing strict traffic rules, creating designated lanes for cyclists, and ensuring well-lit & well-maintained pedestrian path. Government investment in environmentally friendly and sustainable public transportation is also critical. By investing in clean and efficient modes of public transport, governments can further reduce reliance on private vehicles, contributing to the overall sustainability of the city (Pinto et al., 2020).

4.5. Limitations and future work

There are some limitations that need to be discussed. Firstly, the selected city in this study may not represent all types of cities. Future study should consider more cities (including urban center and new built areas in different cities), to enhance the universality of our findings. Secondly, this study did not consider the environmental parameters like temperature, relative humidity, and precipitation, as well as more types of prevailing winds in different seasons, which may also have impacts on diffusion and deposition of particulate matters. Road orientations were not fully investigated in this study, and future research should involve these above-mentioned background factors. Thirdly, influenced by wind flow and vehicle wake, particulate matters from tire-ground friction, car brake, and exhaust emission can settle on roads and will be resuspended. However, the particle mass flow was estimated by using traffic flow data due to the lack of detailed information. Fourthly, the limited simulation cases (based on three heights of green hedges) and limited measurement data at bus stations (also used for validation of simulation model) may increase the uncertainty of our findings.

Despite the limitations, this study can provide valuable insights for policymakers and practitioners to effectively design urban environments and reduce the exposure of passengers to particulate matters. Human-centered urban design is an important topic that warrants further exploration in future city planning (Yang et al., 2024). Future research could explore comprehensive methods to coordinate the control of thermal environment and pollution, e.g., incorporating different green infrastructures and other potential filtration options, to reduce traffic pollution exposure and improve thermal environment through refined urban design (Xi et al., 2023; Wang, 2023). Additional road pollution substances such as microplastics (Rasmussen et al., 2023) could be further investigated.

5. Conclusions

This study used the CFD simulation method to investigate the exposure of passengers to roadside particulate matters under green hedge, considering different hedge heights and wind directions. Furthermore, mitigation strategies (e.g., optimization of passenger positions, station entrance/exit, and combination of green hedges and belts) were also proposed. The main conclusions are provided as follows.

1) The high particle concentrations at bus stations without green hedges were found particularly at the breathing height of children (1.0 m). Green hedges with 1.0 m and 1.5 m height were more favorable to obstruct particles than that of 0.5 m.
2) The exposure health risks for adults and children without using green hedges were 1.82×10^{-6} and 2.33×10^{-6}, respectively, both within the potential health risk range. With the protection of green hedges, the health risks can be greatly reduced by 62 %, meeting the safety threshold.
3) The particle-blocking effect at bus stations could maintain feasibility at the height between 1.0 m and 1.5 m. Using face masks is suggested under the condition of high particle concentrations. Additional strategies of controlling passengers' locations, optimizing entrance and exit of bus station, and integration of green hedges and belts are proposed.

CRediT authorship contribution statement

Junqi Wang: Writing – review & editing, Writing – original draft, Supervision, Conceptualization, Project administration. **Zixuan Li:** Writing – original draft, Methodology, Investigation. **Prashant Kumar:** Writing – review & editing, Project administration. **Chen Ren:** Writing – review & editing, Visualization, Validation, Software, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2024.105703.

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