Individual Particulate Matter Exposure for Urban Commuters in Four Transportation Modes in Beijing, China

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Abstract

Urban traffic growth has intensified air pollution, raising public concern over health impacts. Commuting during rush hours leads to localized high concentrations of vehicle emissions, exposing commuters to greater health risks than non-commuters. This study investigates $PM_{2.5}$ exposure among commuters in Beijing's Haidian District by monitoring typical routes using taxis, buses, bicycles, and electric bicycles. Portable instruments collected high-resolution roadside $PM_{2.5}$ data, which were analyzed to determine spatial-temporal distribution patterns and the influence of background concentrations and meteorological factors. Exposure dose models quantified inhaled pollutant doses under different transportation modes, and health risks were assessed. Predictive methods for commuting pollution exposure were proposed, and simulation scenarios evaluated health risks across varying commuting distances and $PM_{2.5}$ levels, leading to optimization suggestions. Key findings reveal that cyclists experienced the highest $PM_{2.5}$ exposure concentrations ($104\,\mu g\,m^{-3}$) compared to taxi users ($86\,\mu g\,m^{-3}$). Cyclists also had the highest exposure dose ($13\,\mu g\,kg^{-1}$), with men generally receiving higher doses than women. Among commuters, individuals aged 50–54 were most affected by $PM_{2.5}$ exposure; one year of cycling commuting could result in a cumulative reduction of 217 years in overall life expectancy and a 0.2% increase in all-cause mortality. The study provides a quantitative evaluation of exposure doses and health effects associated with commuting modes, offering practical recommendations to improve commuter health and inform pollution control strategies for commuters, traffic managers, and urban planners.

Keywords: Commuting; Mode of transportation; $PM_{2.5}$ exposure concentration; Health evaluation

1. Introduction

The rapid development of urban transportation and the dense growth of city populations have led to increasingly severe environmental pollution from road traffic emissions. This issue is particularly acute in major metropolitan areas like Beijing and Shanghai, where high economic activity and concentrated populations exacerbate the conflict between traffic pollution and urban living conditions. Traffic emissions have become a significant source of air pollution; for instance, a 2020 report indicates that mobile sources like motor vehicles contribute up to 45% of Beijing's $PM_{2.5}$ levels. National policies and public concern for health are intensifying. The 19th National Congress report calls for addressing prominent environmental issues through comprehensive governance and source prevention, continuing efforts in air pollution control, and

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winning the "blue sky defense battle." Policy documents such as the Outline for Building China's Strength in Transportation, the National Comprehensive Three-dimensional Transportation Network Planning Outline, and the Green Travel Action Plan (2019–2022) emphasize effective prevention of road traffic air pollution and encourage green travel. Additionally, the central government has proposed plans for achieving carbon peaking and carbon neutrality, including the development of low-carbon transportation.

Numerous studies have shown strong associations between traffic emission pollution and various diseases. Pollutants emitted from traffic sources, such as particulate matter and polycyclic aromatic hydrocarbons, adversely affect human health. Long-term exposure to high levels of traffic emissions increases the risk of lung cancer and cardiovascular diseases. Among these pollutants, $PM_{2.5}$ — fine particulate matter with a diameter less than $25\ \mu m$ is particularly concerning due to its ability to remain suspended in the atmosphere and adsorb harmful substances and pathogens. High inhalation levels of $PM_{2.5}$ can severely damage human health and contribute to severe weather conditions like smog. Urban road environments are major areas of mobile pollution source emissions, exposing commuters to pollutant concentrations much higher than those in other areas. Regular and prolonged commuting, especially over long distances, can account for more than 30% of an individual's total daily inhaled pollutant dose (Dons et al., 2012). With policies encouraging green and low-carbon travel, zero-emission modes like cycling and electric vehicles are regaining popularity, diversifying commuting options. Different transportation modes result in varying degrees of pollutant exposure and inhaled doses, leading to different health impacts. Failure to assess and target the health impacts of urban road traffic pollution on populations could lead to deteriorating air quality and elevated health risks for residents exposed to severe traffic pollution. Therefore, it is imperative to study the $PM_{2.5}$ exposure characteristics and inhaled doses among commuters and to evaluate health impacts across different demographic groups.

Currently, the mechanisms by which urban road traffic emissions affect public health are not fully understood. There is a lack of coupling between dynamic spatiotemporal distributions of traffic pollutant concentrations and population activity patterns, making it difficult to determine the impact on populations of different sizes, age structures, and behaviors. Moreover, without evaluating exposure doses specific to local commuting populations, it is challenging to accurately reflect the differential health damages caused by traffic pollution among various groups, hindering efforts to ensure environmental equity.

This study investigates the $PM_{2.5}$ exposure characteristics of urban commuters and conducts differentiated health impact assessments based on age and gender. By examining variations in $PM_{2.5}$ exposure concentrations across different transportation modes and road types, we analyze individual particulate exposure characteristics in terms of time, space, and mode. Accurately reflecting commuters' true pollution exposure levels can provide practical strategies and recommendations for commuters and traffic managers to improve health outcomes during travel.

2. Literature review

Traffic pollution has become one of the important sources of air pollution in many cities, and the emission of particulate matter, polycyclic aromatic hydrocarbons and other pollutants from traffic sources can cause negative effects on human health (Bu et al., 2021) long-term exposure to high emissions of traffic pollutants will lead to increased health risks such as lung cancer and cardiovascular diseases (Adams et al., 2001). What's more $PM_{2.5}$ has a tiny diameter and a large unit surface area, which can easily mix with toxic substances such as heavy metals. It has the characteristics of long existence and long transmission distance in the air, which has more serious effects on human health and air quality (Mu et al., 2022). Many studies have shown that different commuting areas, especially those with dense urban traffic, are more seriously polluted by $PM_{2.5}$; when collecting data on particulate matter emissions in Xi'an in 2018, Zhang (2020) found that the contribution of road-mobile sources to PM10 was 23.49%, while the contribution to $PM_{2.5}$ had a proportion of 30.40%. With the number of motor vehicles in Beijing reaching 6.57 million in recent years, An Xinxin et al. studied the characteristics and source analysis of $PM_{2.5}$ components in Beijing urban areas, and the results of source analysis based on PMF showed that the contribution of motor vehicle source emissions was 17% (An et al., 2022). Shang et al. (2019) studied the characteristics of population exposure to particulate matter in urban and suburban areas of Beijing and found that $PM_{2.5}$ exposure was significantly higher in urban centers than in suburban areas and determined that the source of $PM_{2.5}$ exposure pollution was mainly from road traffic sources through source analysis. Kousa et al. (2002) chose six European urban areas for $PM_{2.5}$ exposure evaluation in the environment, focusing on exploring the association among individual exposure concentrations, microenvironmental concentrations and monitoring concentration site concentrations, and constructing the association among ambient concentrations inside and outside environmental monitoring sites to residential buildings and individual exposure concentrations during holidays. Cheng et al. (2021) studied the exposure levels of pollutants in communities next to major roads in the northern part of Beijing city in winter, indicating that the highest average pollutant concentrations were found in roadside parks and the lowest in hospitals, with the largest contribution of pollutant sources being tailpipe emissions from cars on the roads. There is a necessity to study the effect of tailpipe emissions on individual exposure in dense urban traffic areas. Individual pollutant exposure is also strongly related to the route, mode and time of traffic, mainly due to the different traffic routes and the different traffic modes causing different traffic pollution microenvironments. Luengo-Oroz and Reis (2019) studied the exposure of bicyclists to ultra-fine powder (UFP) on different commuter routes in Edinburgh. Their results proved that buses and bicycle routes should be avoided and that bus and truck routes have relatively high UFP exposure concentrations. Zhong et al. (2021) compared PM10 exposure concentrations observed at bus stops with simultaneous ambient air monitoring stations in Guangzhou and concluded that the exposure concentrations of particulate matter near bus stops were significantly higher than in the surrounding environment. Lv (2016) showed that the highest $PM_{2.5}$ exposure was observed in bicycle commuters ($27.2 \pm 24.5\,\mu g$), followed by walking ($23.8 \pm 18.1\,\mu g$), with relatively low $PM_{2.5}$ exposure in buses and subways. Maji et al. (2021) compared road $PM_{2.5}$ exposure in 11 transport microenvironments in Delhi, where $PM_{2.5}$ exposure in the open rickshaw and sightseeing bicycle was about 30% higher than in windowed air-conditioned vehicles and subway and when bicycling the $PM_{2.5}$ inhalation concentration per km was nine times higher in air-conditioned vehicles. Commuting time also has a large effect on exposure levels. Commuting time and transport congestion also affect individual exposure. Research on the spatial and temporal distribution characteristics of particulate matter concentrations in different commuting patterns is of great value in reducing the health burden of commuting populations exposed to the particulate matter microenvironment for long periods of time. Pollutant concentrations in the transport microenvironment are related to various factors, such as urban meteorological conditions and ambient background concentration levels. Za luska and G ladyszewska-Fiedoruk (2020) studied that indoor $PM_{2.5}$ concentrations positively correlated with outdoor ambient air particle concentrations and temperature and relative humidity. Wang et al. (2017) studied that $PM_{2.5}$ concentration patterns were higher in winter than in summer in most Chinese cities. Zheng (2021) investigated the background concentrations in Xi'an city in the winter and summer seasons, respectively, and measured that PM10 and $PM_{2.5}$ concentrations were significantly higher in winter than in summer, with PM10 at $145.3\,\mu g\,m^{-3}$ and $PM_{2.5}$ at $109.3\,\mu g\,m^{-3}$ in winter. In comparison, PM10 concentration decreased to $58.3\,\mu g\,m^{-3}$, and $PM_{2.5}$ decreased to $26.8\,\mu g\,m^{-3}$

in summer. The city of Xi'an has typical northern climatic characteristics, with considerable differences in temperature and humidity as well as average wind speed and dominant wind direction in winter and summer, which result in varying concentrations of particulate matter in the atmospheric environment (Lv, 2020). Whereas wind speed is the main influencing factor in meteorological conditions that can determine the rate of dispersion and deposition of particulate matter after emission, wind direction and road facility conditions together influence the process of pollutant dispersion or accumulation on the road. At present, a clear inverse relationship between wind speed and particulate matter concentration has been demonstrated in many studies: Kumar et al. (2018) showed that pollutant concentrations will increase significantly with weaker wind speed. Buonanno et al. (2011) found a strong negative correlation between wind speed and particulate concentration and further explored to obtain that the fine particulate concentration decreases more significantly with stronger wind speed than with larger particulate matter. Boarnet et al. (2011) found that under weaker ventilation, fine particulate matter around the road would be more likely to accumulate and increase pollutant concentrations. Kaur et al. (2007) confirmed that different wind directions and the layout of surrounding buildings and streets might lead to wind recirculation on the road, resulting in lower pollutant concentrations on the windward side of the road than on the leeward side.

The commuting population in large cities has a regular and continuous transport pattern and may face more severe health risks from long-term exposure to traffic emission pollution environment. Beijing, as one of the cities with a huge traffic volume, it is very meaningful to study the pollutant concentrations and exposure levels of commuters under different traffic modes and summarize the individual particulate matter exposure characteristics under each situation so as to suggest feasible and effective ways to improve the commuters' commuting health.

3. Data and Acquisition Methods

3.1. Routes of Sampling

To investigate the $PM_{2.5}$ exposure of people with different ways of commuting, the commercial core area, residential area and university urban area in the Haidian District of Beijing with large commuting volume were selected as the experimental area as shown in Figure 1, with a large motor vehicle and non-motor vehicle traffic, and some roads are heavily congested, and there are no non-traffic source emissions from heavy industries around. Residents usually choose four commuting modes: cab, bus, bicycle and electric motorcycle. A typical commuting route is illustrated in Figure 1. Starting from point A at the east gate of Beijing Jiaotong University to the digital building in the Zhongguancun area, the route goes through three sections of Beijing Jiaotong University East Road (L1), South College Road (L2) and Zhongguancun South Street (L3) to point B of the digital building, and then returns to point A in the opposite direction of the sampled road. The one-way route length is about 3.64km, and the time duration of a single trip is about 10-30 minutes, which is related to the mode of transportation and the congestion of road conditions. The route contains streets with different road conditions, which can better reflect the $PM_{2.5}$ exposure of different commuting modes. The characteristics of different road sections are described as follows, and detailed information is shown in Table 1.

Beijing Jiaotong University East Road (L1) is a two-way two-lane road with no separation of motor and non-motor, north-south direction; the section starts from the east gate of Beijing Jiaotong University to the intersection of Jiaotong University East Road and College South Road, the traffic congestion at this intersection is more serious, the intersection ratio is $0.51 \sim 0.79$, the average intersection delay time is $37.11\,\mathrm{s}$, the traffic composition is mainly small cars, bicycles, etc.

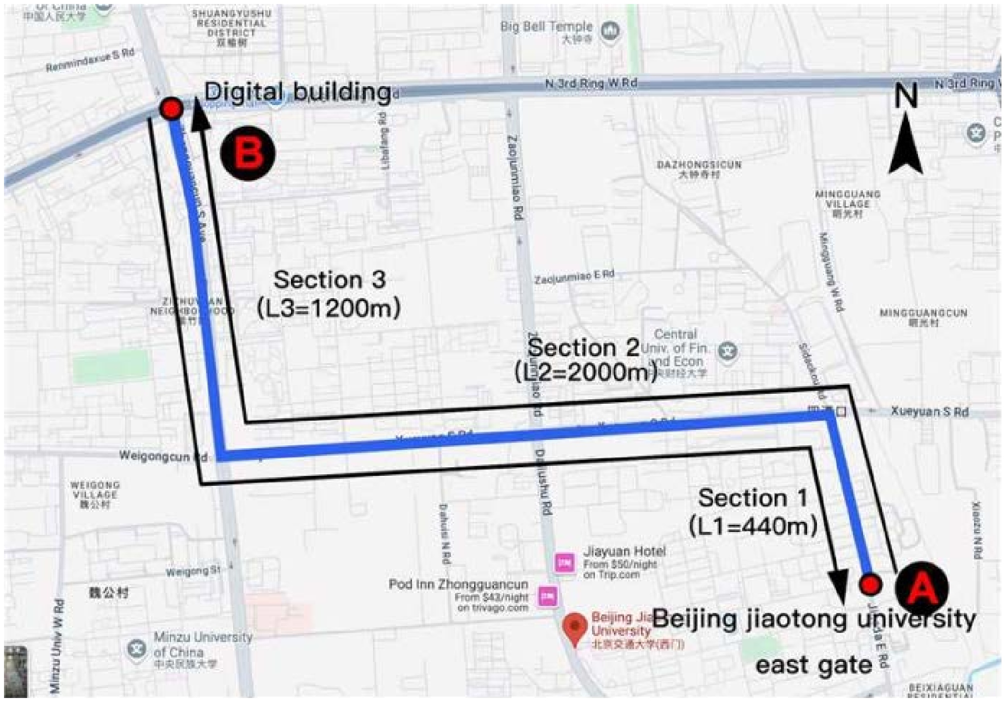


Figure 1: Study Area and Selected Routes

(a) L1 (b) L2 (c) L3

Figure 2: Realistic Image of Different Road Sections

Table 1: Road Section Information

The selected section of road		Road Grade	Length/km	Number of Lanes	Bus Stops	Number of Intersections	Surrounding Environment
Name of the Road	Serial Number						
Beijing Jiaotong University East Road	L1	Branch Road	0.44	2	2	2	High-density residential areas and stores
College South Road	L2	Collector Road	2	4	4	4	High-density residential area with a mix of stores and restaurants
Zhongguancun South Street	L3	Arterial Road	1.2	8	2	2	Mid-density shopping area and office building with good afforest facilities

South College Road (L2) is a two-way four-lane four-width road in the east-west direction, which includes the intersection of Daliushu Road, Zaojunmiao Road and South College Road. The intersection parking ratio during the morning and evening peak periods is 0.51 times, and the average delay is 30.26 s. There are more residential buildings around, and its traffic composition is mainly small cars and bicycles, etc.

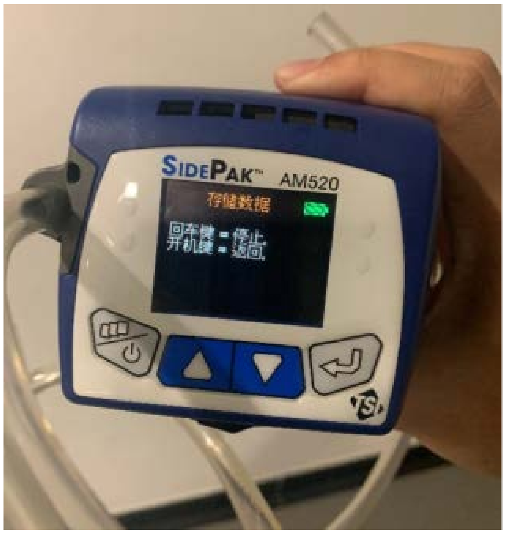
Zhongguancun South Street (L3) is a two-way eight-lane four-lane road separated by machine and non-machine, running from north to south, which has the most serious congestion in the morning and evening peaks, the highest intersection parking ratio of 0.73 to 0.8 times, and the highest intersection delay time of 32.29 to 52.63 seconds, passing through more commercial activity areas, with traffic composed mainly of small cars and buses, etc. The relevant information for the different road sections of the selected routes is presented in Table 1.

3.2. Sampling Schedule

The experimental data were collected for one consecutive week from June 12 to June 18, 2022, with three times daily sampling, which was conducted during the morning and evening peak periods (7:30–9:30, 17:00–19:00) and non-peak period (11:30-14:00) to compare the changes of individual $PM_{2.5}$ exposure concentrations at different times, and the monitoring period included weekends and workdays (Monday to Friday).

3.3. Sampling Devices

The $PM_{2.5}$ concentration in this experiment was collected and monitored by SidePak^{TM}AM520 individual exposure dust measuring instrument from TSI, USA. The instrument uses the light scattering operating principle to monitor the mass concentration of $0.1 \sim 10\,\mu m$ particles. It has a long tube that can be carried around and placed at the mouth and nose, thus monitoring the real-time $PM_{2.5}$ concentration in the human breathing zone with a 1s interval. Geographic location information is collected by the Explorer V-900 plug-in multifunctional navigation recorder, which simultaneously records the latitude and longitude information of the $PM_{2.5}$ concentration collection point. During the monitoring period, trained sampling personnel, wearing both instruments, record $PM_{2.5}$ real-time concentrations and GPS data for each transportation mode simultaneously. During the simultaneous period, the urban air quality pollution data were collected from the regional air pollution monitoring station (Wanliu station in Haidian District, 2.8 km from the study area), and meteorological data were obtained from the China Meteorological Administration. The experimental instruments utilized in this study are presented in Figures 3.



(a) SidePak™AM520 Personal Aerosol Monitor

(b) Multifunctional Navigation Recorder with SD Card

Figure 3: Experimental Instruments

3.4. *The Calculation of Exposure Dose*

The data from the measuring instrument will be imported into the computer and checked for outliers, which can be considered outliers if the difference between two adjacent monitoring data is greater than ten times. The individual average exposure concentration is the arithmetic mean of all data from different modes of commuting per day. Differences in individual inhalation particle concentrations are influenced by their own characteristics and commuting activity levels. The individual exposure dose is assessed by commuting time and exposure concentration levels, and the exposure dose is calculated by the following formula:

$$D = \int \frac{1}{60} \mathrm{IR} \times \mathrm{C} \mathrm{d} \mathrm{T} \tag{1}$$

In formula:

- D — Total Inhalation Dose to Human ($\mu\mathrm{g}$);
- IR — Breathing Volume (L/min)
- Concentration Values of $PM_{2.5}$ in the Breathing Zone ($\mu\mathrm{g}\,\mathrm{m}^{-3}$);
- T — Commuting Duration (s).

4. Results and Discussion

4.1. *Individual exposure concentrations under different commuting modes*

Analyzing the average daily $PM_{2.5}$ individual exposure concentrations and ambient $PM_{2.5}$ concentrations for different transportation modes during the monitoring period, the trends of $PM_{2.5}$ individual exposure concentrations and ambient concentrations for each transport mode were basically consistent during the monitoring period. Among different transportation modes, the maximum and minimum daily average exposure concentrations were $120.56\,\mu g/m^{-3}$ for bicycles and $4.40\,\mu g/m^{-3}$ for the cab, respectively. The highest average exposure concentration of $PM_{2.5}$ during the sampling period was for the bicycle with a concentration of $(69.13 \pm 26.31)\,\mu g/m^{-3}$, and the lowest exposure concentration was for the cab $(69.13 \pm 26.31)\,\mu g/m^{-3}$. The maximum value of $PM_{2.5}$ for each transportation mode is concentrated on the sixth day, while the atmospheric ambient $PM_{2.5}$ concentration is relatively high; the minimum value is concentrated on the third day, and the ambient $PM_{2.5}$ concentration is relatively low as well. According to the "Ambient Air Quality Standard" (GB3095-2012), $PM_{2.5}$ daily average concentration of 75g/m3, the daily average exposure concentrations of all transportation modes exceeded the standard to varying degrees, with the highest and lowest being cabs and buses, with exceedance rates of 57.5% and 41.2%, respectively.

The particle inhalation concentrations of commuting routes of different modes of transportation, it can be seen that the total particle inhalation of bicycles is significantly higher than other modes of transportation, with an average exposure concentration of $(69.13 \pm 26.31)\,\mu g$, which is about six times higher than that of cabs, which have a low total inhalation, followed by buses and electric motorcycles. Particle inhalation is influenced by the traffic microenvironment, and the bicycle exposure concentration is higher than in other commuting modes, probably due to the non-motorized lane and motor vehicle exhaust emissions from motor vehicles driving in the motor vehicle lane and being in an area of high pollutant concentration during the proximity to the bus stop. In contrast, cabs have the lowest total inhalation, which may be related to the air conditioning filtration system during vehicle operating, which reduces most of the particulate matter and thus reduces the total inhalation.

Table 2: Average Daily Individual $PM_{2.5}$ Exposure Concentration and Inhalation during the Monitoring Period

Date	Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7	
	Conc.	Total Vol.	Conc.	Total Vol.	Conc.	Total Vol.	Conc.	Total Vol.	Conc.	Total Vol.	Conc.	Total Vol.	Conc.	Total Vol.
Cab	51.11	4.40	47.44	5.19	34.79	7.23	40.12	14.65	63.74	10.86	118.13	23.04	76.40	10.29
Bus	66.55	22.81	59.68	17.49	31.40	14.53	53.12	17.23	74.74	26.23	105.87	37.57	71.63	21.82
Bicycle	65.62	66.00	61.14	52.44	31.90	41.79	52.98	51.62	80.62	82.03	110.95	120.56	70.19	69.45
Electric Motorcycle	73.08	14.80	65.67	13.80	31.07	8.29	54.38	12.54	81.66	17.53	108.31	28.31	75.35	15.84
Ambient Air	16.29	-	18.00	-	14.96	-	21.54	-	24.08	-	40.17	-	34.54	-

4.2. Individual Exposure Concentrations on Different Commuting Sections of Roads

Transport routes have a more significant impact on the exposure concentration of particulate matter, and data analysis shows that each transportation mode is exposed to higher exposure concentrations than other routes when passing on the L1 route, mainly due to the impact of the motorized and non-motorized lanes of the L1 route branch roads not being separated, the slow driving speed and the higher emissions of exhaust pollutants. The secondary road of the L2 route and the main road of the L3 route had higher traffic volumes, and the overall exposure concentrations were not significantly different. In terms of the direction of traffic, the $PM_{2.5}$ exposure concentrations were higher on the way there than on the way back on each road section. The highest exposure concentration is $(150.50 \pm 15.46)\,\mu g/m^3$ for each commuting mode when going by cab transportation mode at the peak of the L1 road section. At the same time, the electric motorcycle is affected by motor vehicles and bus exhaust emissions, and the exposure concentration is higher, especially in the L1 route, and the return exposure concentration reaches $(70.87 \pm 29.62)\,\mu g/m^3$ in the peak period. The higher exposure concentration of cabs throughout indicates that in the high proportion of parking, traffic congestion, open-window exposure environment, individual particulate matter exposure concentration is instead higher, bicycle transportation exposure concentration is instead lower, mainly due to the convenience of bicycle transportation, subject to motor vehicle road congestion, parking idling motor vehicle exhaust emissions are lower.

Table 3: Individual Exposure Concentrations by Commuting Mode on Different Roads

	Time Period	L1		L2		L3	
		Go	Back	Go	Back	Go	Back
Cab	**(Morning Peak Hours)**	150.50±15.46	81.72±13.54	119.86±13.94	84.62±7.03	102.60±7.63	95.85±8.5
Cab	**(Midday Sub-peak Hours)**	60.14±10.05	/	59.13±8.02	/	62.19±7.20	/
Bus	**(Morning Peak Hours)**	69.74±6.98	67.50±6.93	69.36±5.90	64.53±6.05	70.94±6.53	67.43±6.9
Bus	**(Midday Sub-peak Hours)**	60.77±8.16	/	58.13±6.49	/	67.89±7.0	/
Bicycle	**(Morning Peak Hours)**	68.07±5.88	70.68±7.27	67.76±6.20	70.06±6.27	69.31±14.69	70.15±6.1
Bicycle	**(Midday Sub-peak Hours)**	64.39±5.45	/	63.90±7.81	/	65.49±5.86	/
Electric Motorcycle	**(Morning Peak Hours)**	71.27±6.52	76.87±9.51	70.45±6.10	74.10±7.73	71.24±6.20	72.85±5.7
Electric Motorcycle	**(Midday Sub-peak Hours)**	67.26±12.33	/	/	62.94±6.01	65.54±5.8	/

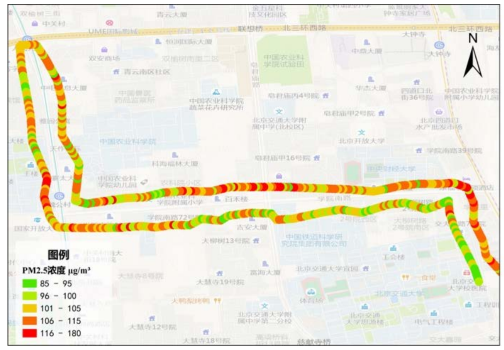
4.3. Spatial and Temporal Distribution Characteristics of Particle Exposure Concentration

The spatial distribution characteristics of $\mathrm{PM}_{2.5}$ concentrations in different road sections during non-peak and peak periods are analyzed, as shown in Figures 1 and 2. Each color in the heat map represents a certain concentration interval of $\mathrm{PM}_{2.5}$, and the darker the color represents the higher $\mathrm{PM}_{2.5}$ concentration and more serious pollution. It can be seen that the pollution hotspot areas of each commuting mode are often found near intersections and road intersections, especially at L1 sections and L2-L3 intersections.

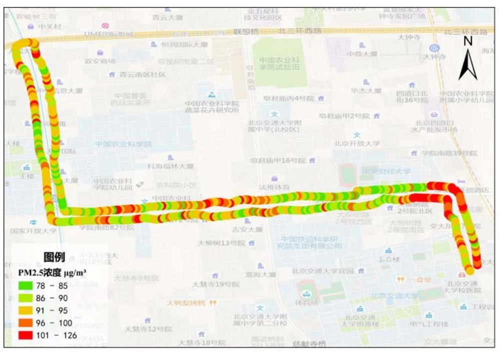
High values of $\mathrm{PM}_{2.5}$ concentrations exist during the morning and evening peak periods when bicycles and electric vehicles are moving to and from all road sections, with concentrations above $100\,\mu\mathrm{g/m^3}$, especially in the L2-L3 road sections. These roads are mainly surrounded by many restaurants and stores, residential areas and the university district, where the density of residents is high and where pedestrians often gather, and bicycles and electric bikes are important commuting tools for the residents in the area. The large number of tailpipe emissions caused by a large number of vehicles on the road and indoor cooking fumes on the roadside are the main sources of pollution that cause exposure hotspots for commuters during this time. For cabs and buses, the locations with high concentrations are mainly found in the L1 section and intersection locations, and buses have more points with high pollution values than cabs in the L2 section. The reason is that there are several bus stops in the L2 road section, the bus will stop and transfer frequently, the vehicle acceleration and idling process produces large emissions, and in a short period of time, the pollutants inside the vehicle cannot be quickly diluted by the air exchange system and the air outside the vehicle, people will be directly exposed to the exhaust gas emitted inside the vehicle, so it will produce a larger exposure concentration of commuting pollutants. There are relatively few high-value $\mathrm{PM}_{2.5}$ pollution points on the L3 road section, with a $\mathrm{PM}_{2.5}$ concentration range of 70–90 $\mu\mathrm{g/m^3}$, mainly located near the back intersection area. This road section has more spacious lanes, the vehicles run smoothly, the buildings are medium density gathering, and the afforest is relatively good so that the exhaust generated by the previous vehicle will be diluted quickly, and the exhaust will not be channeled into the vehicle through the ventilation system of a vehicle behind, thus making the exposure concentration of $\mathrm{PM}_{2.5}$ pollution relatively low in this road section when the crowd takes cabs and buses.

The $\mathrm{PM}_{2.5}$ exposure concentrations of all commuting modes during the midday sub-peak period were significantly reduced, especially the $\mathrm{PM}_{2.5}$ pollution concentrations of bicycle and electric vehicle commuting were significantly reduced for each road section. However, the $\mathrm{PM}_{2.5}$ pollution from buses and cabs is still relatively high, and in the L2 section, due to more bus stops and frequent stops, passengers taking buses are still exposed to a densely distributed area of high $PM_{2.5}$ pollution values, with concentrations ranging from 36–75 $\mu g/m^3$. The L3 road section has wide and smooth traffic, with $PM_{2.5}$ concentrations ranging from 15–30 $\mu g/m^3$ for each commuting mode.

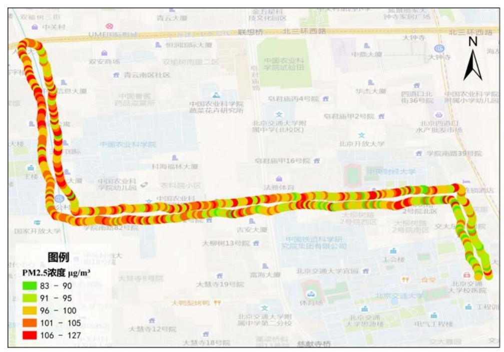
(a) Cabs



(b) Electric Bikes



(c) Buses



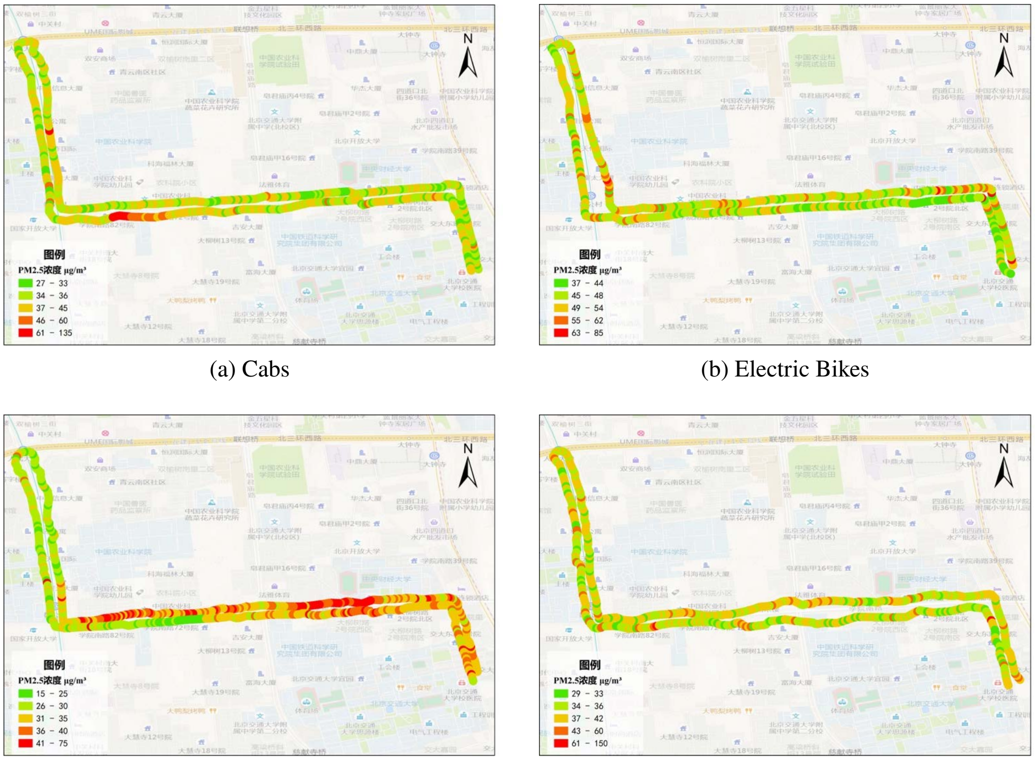
(d) Bicycles

Figure 4: $PM_{2.5}$ Heat Map for Non-peak Period

4.4. The Meteorological Conditions Influence on Individual $PM_{2.5}$ Exposure Concentrations

The correlations between meteorological factors such as temperature, humidity, wind speed and rainfall and individual $PM_{2.5}$ exposure concentrations for different transportation modes were analyzed, and whether there was a significant relationship between them through correlation analysis. From Table 3.3, it can be seen that there is a significant positive correlation between temperature and ambient air particulate matter concentration for different transportation modes. At the same time, wind speed and humidity have a weak negative correlation for different transportation modes. Wind speed has a small effect on individual particulate matter exposure concentration in this study because the wind speed is static and light during the sampling period. Regarding different transportation modes, cabs are more influenced by temperature and humidity conditions, while ambient air pollution concentrations more influence motorcycles and bicycles.

$PM_{2.5}$ ambient concentrations were also positively correlated with transportation mode, especially for bicycle and motorcycle commuting modes, which significantly affected $PM_{2.5}$ individual exposure concentrations. The results of Wu, DL et al. using linear model analysis showed that temperature, transportation conditions and wind speed contributed 27.3% of the exposure concentration for commuting mode, while relative humidity and wind speed were important determinants of road mode, contributing 14.1%.



(a) Cabs

(b) Electric Bikes

(c) Buses

(d) Bicycles

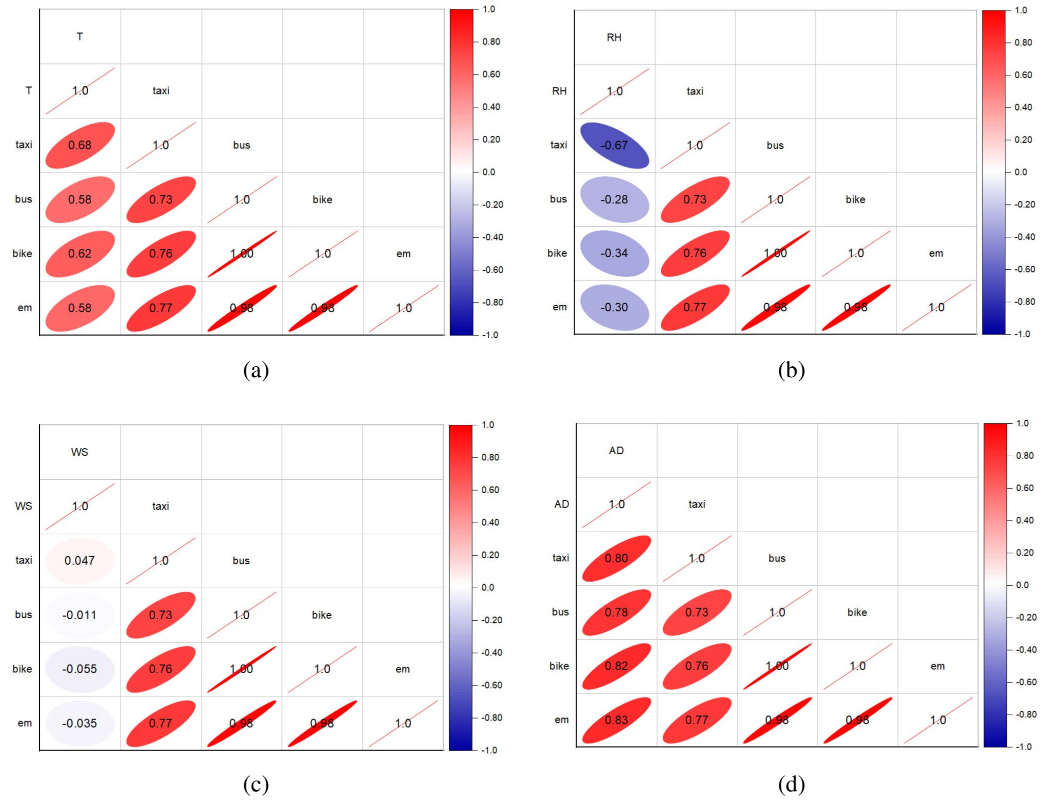
Figure 5: $PM_{2.5}$ Heat Map during Peak Period

Table 4: Relationship between Meteorological Conditions and $PM_{2.5}$ Exposure Concentration

Condition	Taxi	Bus	Bike	Emissions (em)
TEM/°C	0.68	0.58	0.62	0.58
RH%	-0.67	-0.26	-0.34	-0.30
Wind Speed	0.047	-0.011	-0.055	-0.035
Background Concentration	0.80	0.78	0.82	0.83

5. Conclusion

1. Their choice of transportation mode significantly influenced the $PM_{2.5}$ exposure of commuters. During the monitoring period, the individual exposure mass concentrations of atmospheric $PM_{2.5}$ for different modes of transportation were cab > bus > motorcycle > bicycle, while particulate matter inhalation was higher for bicycle and motorcycle, which was mainly influenced by the long exposure time and activity status of the bicycle.
2. From the perspective of commuting routes, the L1 road section is not separated between motor and non-motor. There are intersections close to residential areas. The road section has a higher exposure concentration and inhalation of each mode of passage. At the same time, the L3 express lane traffic conditions are good, motor vehicle exhaust emissions of pollutants are relatively low, exposure concentration and inhalation are small, and exposure concentration spatial and temporal distribution characteristics likewise indicate that cabs and buses in close proximity to intersections congested roads, exposure concentration are higher.



(a) (b) (c) (d)

Figure 6

3. Commuting time also affects individual exposure concentrations, morning and evening peak periods and non-peak atmospheric $PM_{2.5}$ individual exposure concentrations. Except for commuting time, background pollutant concentrations have a strong positive correlation with exposure concentrations during each commuting mode, and meteorological conditions such as temperature, humidity, and wind speed have inconsistent effects on exposure concentrations of the four commuting modes. Among them, the temperature was positively correlated with each commuting mode row, and the higher temperature was also an essential factor in pollution formation.

Authors' contribution

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