Temporal-Spatial Distribution Characteristics of PM2.5 and Noise in the Under-Viaducts Space

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Abstract
As large cities grow in size and density, they come under increasing pressure for space and regeneration. Many under-viaducts spaces (UVSs) are being converted into open-air sports fields, but such spaces can cause air and noise problems for people playing sports. There is a lack of research on the pollution of the UVS. To fill this gap, this study selected a case area of an UVS in central Shanghai that has already been renovated into a sports field, and investigated the spatial and temporal distribution patterns of air and noise pollution and the factors influencing them. Based on site monitoring and data analysis, this study found that: 1) Air pollution in the UVS is significantly higher than the background levels, the higher the background levels, the greater the difference between the concentrations in the UVS and the surrounding area. 2) The noise intensity in the UVS is also higher than the background value with a more constant variation. 3) Air pollution is highly correlated with the built environment and traffic flow, while noise is more closely related to traffic flow and less so to the built environment, both of which have a negative correlation with temperature. This study provided valuable empirical evidence on the exposure to air and noise pollution in the sports space under viaduct in the micro-environment, which can help planners to adequately consider pollution reduction in the planning and management of urban renewal.

Key Words: Under-Viaducts Space, Noise, $PM_{2.5}$, Spatio-temporal distribution, Urban renewal, Shanghai

1.Introduction

With the rapid development of urbanization, there is an increasingly prominent conflict between limited land and high population density in major metropolitan areas. Elevated highways and viaducts have become essential solutions to traffic problems in many cities. The viaduct itself has public attributes [1], and the under-viaduct space (UVS) is regarded by scholars as a potential public space or site for activities [2]. In this study, the UVS was defined as the space covered by the orthographic projection under the viaduct and the surrounding neighbourhood space significantly affected by the viaduct. Effective utilization of the UVS is highly significant for urban renewal, but due to the relatively closed nature of the main space, the UVS has become an area where particulate matter pollution caused by traffic increases [3], resulting in its poor environmental quality. Noise pollution is also a major issue in the UVS [4], and the horizontal and vertical sound fields in the road space of the viaduct are greatly altered compared to ordinary roads, causing more severe noise pollution on both sides of the road [5]. Consequently, the impact of viaducts on the urban environment and the use of space around viaducts are receiving more and more attention in high-density cities.

1.1 $PM_{2.5}$ in the UVS

Air pollution caused by traffic is a major health hazard for urban dwellers worldwide [6]. Particulate matter with a diameter less than or equal to 2.5 microns ($PM_{2.5}$) is an essential criterion for determining air pollution [7]. Most $PM_{2.5}$ emissions in cities originate from transportation, especially diesel trucks and buses [8]. In Toronto, motor vehicle-related emissions account for about 40% of $PM_{2.5}$ [9]. Abu-Allaban et al. [10] found that the percentage contribution of motor vehicles to $PM_{2.5}$ at seven U.S. sites ranged from 20% to 76%. In London, the mean incremental traffic contribution to $PM_{2.5}$ near motorways can be as high as 50% [11]. $PM_{2.5}$ can also cause many adverse health effects [12]. Lelieveld et al. [13] found that outdoor air pollution, mainly $PM_{2.5}$, causes 3.3 million premature deaths each year. At the same time, short-term or long-term exposure to high $PM_{2.5}$ concentrations can elevate the risk of heart disease, while potentially triggering respiratory diseases, asthma and other diseases, and may also induce cancers such as lung cancer and increase the risk of mental disorders such as major depression [14,15,16,17].

The combination of surface roads and viaducts pollution can result in 1.6 to 4.5 times the amount of pollution compared to road surfaces alone [18]. Urban roads in the UVS have become priority areas for particulate pollution [19]. $PM_{2.5}$ concentration distribution of viaducts is attracting increasing attention, but there are still relatively few relevant studies. Most existing studies have focused urban roads, such as highways, roadsides, intersections and arterials (Table 1). The urban road spaces have high similarity with the UVS, so the experimental methods and results of the studies can be used as references. Around the 2000s, studies on the $PM_{2.5}$ concentrations of major roads became more frequent, and found that the closer to the road, the higher the $PM_{2.5}$ concentration and higher than the background concentration [20,21]. In addition, some studies found that there is an attenuation effect of $PM_{2.5}$ concentration in the 200 meters range of highway [22,23]. Similar results were verified at intersections, where $PM_{2.5}$ concentrations at the downwind curb of the intersection were significantly higher than background values and were significantly higher during peak traffic hours [24,25]. Many studies have also focused on influencing factors, with traffic conditions such as traffic volume, meteorological conditions such as wind speed, local topography and surroundings, barriers or noise walls all affecting the distribution of $PM_{2.5}$ in road space [26,27].

Most studies on viaducts concentrate on the street canyons [28,29], and there are fewer studies on the horizontal distribution of $PM_{2.5}$ in the UVS. It is discovered that viaducts increase $PM_{2.5}$ concentrations in street canyons, particularly on the ground. Li et al. [30] utilized a mobile monitoring method to measure the space beneath three viaducts with different types of barriers in Xi'an, China and found that $PM_{2.5}$ concentrations have a single-peak decay trend in locations with noise barriers and combined barriers, meaning they initially increase then decrease to background levels within 300 meters. In Wuhan, China, Yin et al. [19] monitored 14 UVSs and 9 potential environmental parameters such as temperature to study spatial and seasonal differences in particulate matter like $PM_{2.5}$. They also found that $PM_{2.5}$ concentrations were related to the surrounding environment and that $PM_{2.5}$ concentrations in the UVS were higher compared to surrounding roads in winter, and vice versa in summer. The study contributes to understanding the factors influencing $PM_{2.5}$ concentrations in the UVS, but lacks spatial analysis at the microscopic scale. In summary, the realistic distribution pattern of $PM_{2.5}$ in the planar dimension and the influence mechanism of parameters are not clear, and further spatial and temporal studies are needed to guide the assessment and judgment of spatial reuse.

Table 1. Summary of research findings on $PM_{2.5}$ concentrations in road space.

Research Object		Monitoring Methods	Results	Sources
Road	Highway	Mobile monitoring	•Within 200m, $PM_{2.5}$ concentrations usually increase as the highway approaches. • $PM_{2.5}$ increases with the onset of peak hours and is strongly influenced by temperature changes in colder months.	Patton et al., 2014 [22]
Road	Highway	Mobile monitoring	•Before sunrise and peak traffic volume, downwind concentrations are highest within 100-250m of the highway. • After sunrise, pollutant levels drop sharply and the gradient becomes less pronounced.	Durant et al., 2010 [31]
Road	Highway	Fixed monitoring	The reduction in urban traffic helps to reduce the concentration of particulate matter pollution.	Azhari et al., 2021 [32]
Road	Highway	Fixed monitoring	Particulate concentrations decay exponentially with increasing distance within 100-150m from the road and return to background levels within a few hundred meters from the road.	Zhu et al., 2009 [23]
Road	Highway	Fixed monitoring	Wind speed, prevailing wind direction, daily cycle of the atmospheric boundary layer and traffic density are the main influencing factors.	Charron & Harrison, 2005 [33]
Road	On-road & Roadside	Fixed monitoring	Higher $PM_{2.5}$ concentrations were observed in Madrid during the cold season.	Kassomenos et al., 2014 [34]
Road	On-road & Roadside	Mobile and fixed-site monitoring	•$PM_{2.5}$ concentrations on the road are highly correlated with nearby roadside $PM_{2.5}$ concentrations in winter and summer. • Seasonal effects need to be considered, and short-term exceedances of particulate matter concentrations may occur in early spring.	Cheng et al., 2010 [35]; Lozhkina et al., 2016 [36]
Road	Intersection	Fixed monitoring	There was an overall decreasing trend in $PM_{2.5}$ concentrations with increasing distance from the roadside. The incremental $PM_{2.5}$ decreased by 75% between 5 m and 30 m from the road.	Mukherjee et al., 2020[37]
Road	Intersection	Mobile monitoring high-flow gravimetric personal samplers	$PM_{2.5}$ concentrations are higher in the morning, decrease at noon, and rise in the early afternoon and are even higher in the evening. This phenomenon is related to the traffic activity in the surrounding area.	Kaur et al., 2005 [24]
Road	Intersection	Fixed monitoring	• Roadside concentrations were higher than those simultaneously monitored at urban sites away from the road. • Average pollutant concentrations at downwind roadside stations are higher than at background stations. • $PM_{2.5}$ concentrations during peak traffic hours are higher than during off-peak hours.	Wang et al., 2018 [25]; Kinney et al., 2011 [38]
Road	Arterial	Fixed monitoring near-road continuous air monitoring station (CAMS)	•$PM_{2.5}$ concentrations are usually elevated close to roads. • Traffic-related $PM_{2.5}$ concentrations are usually highest at night, followed by the morning peak, evening peak and midday respectively.	Askariyeh et al., 2020 [39]
Road	Arterial	Fixed monitoring near-road continuous air monitoring station (CAMS)	$PM_{2.5}$ quality is more related to regional sources and meteorological conditions, with a limited role of traffic volume.	Kendrick et al., 2015 [40]
Road	Street canyon	Mobile monitoring	Street canyons have a significant impact on the accumulation of $PM_{2.5}$ concentrations on Hong Kong's roads.	Rakowska et al., 2014 [41]
Road	Street canyon	Fixed monitoring three heights (0.20 m, 1.0 m and 2.60 m)	The concentration decreases exponentially with increasing canyon height.	Kumar et al., 2008 [42]

Viaduct	Street canyon	Fixed monitoring	Particle mass concentrations in street canyons are negatively correlated with height, and particle mass concentrations in street canyons are negatively correlated with temperature.	Feng et al., 2015 [28]
			Viaducts increase $PM_{2.5}$ concentrations in street canyons and significantly affect airflow fields.	Zhi et al., 2020 [29]
	UVS	Mobile monitoring	$PM_{2.5}$ concentrations decay exponentially near the viaduct without any obstacle.	Li et al., 2021 [30]
		Mobile and fixed-site monitoring	•$PM_{2.5}$ concentrations in the UVS are lower in summer than in the adjacent road environment, but higher in winter. Meteorological factors, green structure, viaduct structure and surrounding built environment have a significant impact on $PM_{2.5}$ concentrations.	Yin et al., 2021 [19]

1.2 Traffic noise in the UVS

Road traffic noise is one of the main sources of noise pollution in urban areas and has become a global problem [43]. Traffic noise has harmful effects on health [44,45], including anxiety [46,47], sleep disturbance [48], and reduced cognitive performance in school-aged children [49] and an impact on cardiovascular diseases [50]. Traffic-related noise is one of the major environmental impacts of roads [51]. Therefore, the proper assessment of the noise impacts in urban traffic areas is crucial for the rational use of urban space and the preservation of human health.

At present, there have been numerous studies on the spatial and temporal analysis of traffic noise and its influencing factors in urban traffic spaces (Table 2). These studies indicate that noise levels in spaces along the main roads entering and passing through the city are relatively high and that the traffic noise increases during peak hours [52,53]. Some studies have found a positive correlation between urban density and traffic noise through software simulations [54] and between urban road network density and traffic noise [55]. At the same time, there is a strong inverse relationship between the area of green space on both sides of the traffic space and traffic noise [56]. In terms of space design, the height and shape of building facades on both sides of the street are closely related to the noise levels of the traffic space [57] and other aspects. These factors have varying effects on urban road traffic noise.

The results of existing studies are summarized in Table 2. However, relatively few studies have been conducted on the noise of the UVS and its associated temporal and spatial distribution patterns. Additionally, there is a scarcity of research on the effects of human activities under traffic noise exposure.

Table 2. Summary of research findings on noise concentrations in road space.

Research Object		Monitoring Methods	Results	Sources
Road	highway	-	For outdoor environment, sound barrier, low-noise pavement and soundproof window are the most common solutions to reduce the noise generated by main noise sources	WHO, 2018 [58]
Road	On-road & Roadside	Fixed monitoring	The address noise level along the main roads entering and passing through the city is the highest As the density increases, the street noise will also increase	Thacher et al., 2020 [52]
Road	On-road & Roadside	Mobile and fixed-site monitoring	There is an inverse relationship between greening area and noise pollution	Lopez et al., 2018 [56]
Road	On-road & Roadside	Mobile and fixed-site monitoring	Increased traffic noise pollution during peak hours The noise pollution in the space near the road is large	Shakya et al., 2019 [53]
Road	Arterial & Roadside	Mobile and fixed-site monitoring	The more urban activities, the more noise the street	Mohareb & Maassarani, 2019 [59]
Road	Arterial	Software simulation	There is a positive correlation between road network density and traffic noise	Wang et al., 2011 [55]
Road	Arterial	Software simulation	The higher the urban density, the more important the noise insulation measures	Bouzir & Kang, 2017 [54]
Road	Street canyon	Fixed monitoring	Street canyon architectural design has a significant impact on street space noise	Sanchez et al., 2016 [57]

1.3 Monitor and analysing method review

Fixed monitoring and mobile detection are two types of effective methods for measuring air and noise pollution in urban environments. These methods have been tested by numerous scholars and have been proven to be successful. However, fixed measurements has limitations, such as the cost of equipment and maintenance for fixed-site air quality monitoring stations (AQMS) [60], which can make it challenging to accurately reflect pollutant distribution over short distances [61]. Mobile monitoring technology can help to overcome these limitations and provide a spatial map of population exposure in the micro-environment with higher spatiotemporal resolution [62]. Additionally, it is also an effective way to obtain noise data [63]. The specific methods include platforms such as instrumented cars and vans [60,64], public transportation such as trains and trams [62,65], bicycles [63], and backpack walking measurements [66,67,68]. In this study, backpack walking measurements were used to directly assess personal exposure to pollutants and noise in the traffic micro-environment.

The main methods of analyzing pollutants and noise include spatial analysis, temporal analysis, and correlation analysis of influencing factors. Spatial analysis is mainly divided into two categories: the differences in pollutant and noise distribution in different road spaces [35,66,69], and the continuous distribution characteristics of pollutants and noise in larger spaces, such as cities and districts [63,70], with insufficient attention given to small-scale horizontal space. Temporal analysis focuses on the differences in pollutant concentrations and noise levels during different seasons such as winter and summer [36], working and non-working days [41], and different time periods of the day [22,24,31]. The correlation analysis of impact factors includes meteorological factors such as temperature and humidity, road factors such as traffic volume, and built environment factors such as distance from the main road and height to width ratio [19].

In conclusion, there is a lack of research on the small-scale UVS, and most studies do not consider the combination of particulate and noise pollution in the same space. Many current studies focus on statistical analysis, with limited exploration of the spatial layout and potential for built-up space reuse.

To address these gaps, the research goals of this paper are as follows: 1) expand the scope of the study, and analyze the spatial and temporal distribution characteristics of particulate matter and noise under the viaduct and within a block or so (about 250m) of the surrounding space; 2) enrich the research objectives, and investigate the factors affecting particulate matter and noise in the UVS and further propose planning countermeasures for spatial reuse.

2.Data and methodology

2.1Study Area

The study area is the UVS of Tianmu Middle Road (31°14'32.7"N, 121°27'45.2"E), which is located on the south side of the intersection of Hengtong Road and Gonghexin Road in Jing'an District, Shanghai, China. As an international metropolis with a high population density and elevated roads throughout the city, Shanghai is representative in its exploration of the quality of the urban spatial environment. The city has carried out a lot of practices and explorations in the use of the UVS and has issued relevant policies and standards to guide the development and utilization. The study area is currently designed as a basketball court, with a large number of people exposed to the environment of the viaduct. Therefore, the area is of great practical importance in evaluating the fine particulate matter and noise environment under the viaduct.

The study area is located in the most prosperous centre of Shanghai, on the north side of the intersection of the North-South viaduct and the Suzhou Creek (Fig.1). The north side is close to the intersection of arterial roads, the south side is only separated from the Suzhou Creek by a branch road, and the east and west sides of the base are urban roads. The viaduct has 12 lanes and heavy traffic, while ground level has 2 lanes on either side of the space underneath the viaduct. The sports field is located under the main bridge of the North-South viaduct and consists of four basketball courts, which are sheltered on east and west sides are sheltered by the overhanging eaves of the viaduct deck. On the east side of the site there is a ramp departure point, and the degree of screening is less than on the west side. During weekday peak hours (7:00-9:00 and 17:00-19:00), slow and congested traffic is common, while road traffic is relatively smooth at other times. In summary, the study area was selected for analysis of the particulate and noise environment assessment of the UVS due to its good regional location, site shape, traffic characteristics, and pollutant sources.

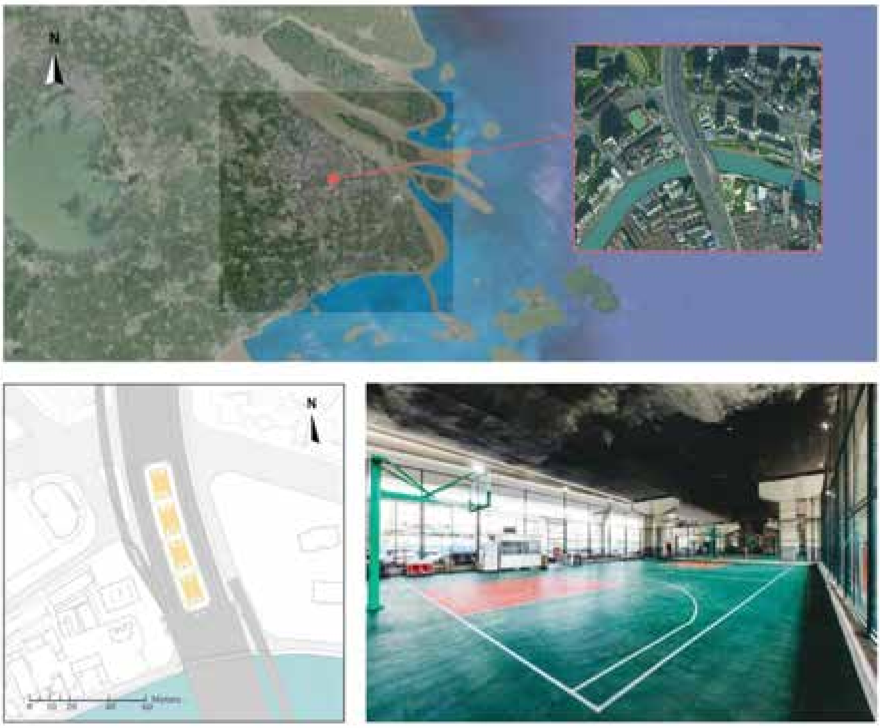

Fig.1 Sketch map and the general plan of the study area.

2.2**Data preparation**

2.2.1 Mobile site measurements

The mobile monitoring route covered the UVS and the surrounding space within 250 meters on both sides of it. The starting point of the route was a reference point used to measure background levels, which had no influence of pollution sources such as factories and parking lots within 50 meters of its surroundings, and no more than 3,000 vehicles pass through it per day (Hoek et al., 2002)[71]. Meanwhile, 32 measurement points were set up along on the route in sequence, and peripatetic measurements were performed at each point using handheld instruments. The clocks of all real-time instruments were checked for synchronization prior to the measurement. Points 3, 4 and 15-26 were located in the projected space of the viaduct, specifically indicated as the UVS-P. The remaining 18 points were peripheral spaces not covered by the viaduct and were set up to investigate the attenuation effects of pollutants and noise, specifically designated as the UVS-NP. There was a continuous wall interface on the east side of the viaduct, with green space in front of the interface (Fig. 2). The selection of this monitoring route was based on the following needs:

1) Since the site had different built environments in the north-south and east-west directions, the monitoring points were set up homogeneously in the UVS and in the road space around the viaduct respectively, to measure the distribution characteristics.

2) The viaduct had differences in the morphology of its eastern and western branches, so double rows of monitoring points were set up in the UVS to objectively reflect the numerical situation of pollutants, noise distribution and the various influencing factors. It was confirmed in advance that there were no industrial sources near the entire study area.

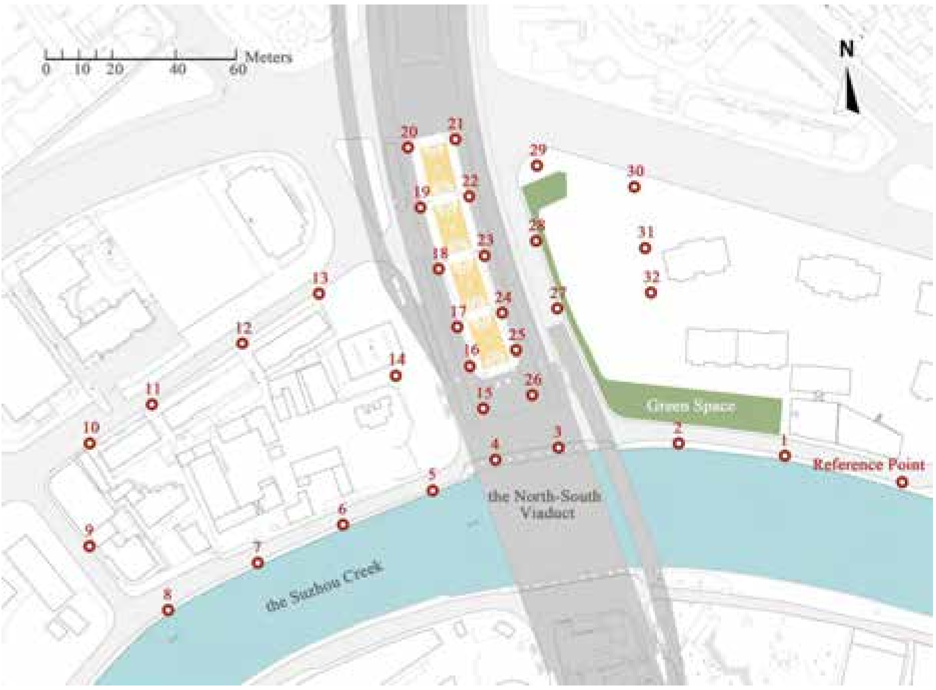

Fig.2 The locations of all the monitoring points set up on the route are numbered from small to large according to the sequence from the beginning to the end.

2.2.2 Data collection

According to previous studies [19,62,70], it is recommended to conduct environmental monitoring for more than 10 days, including both working and non-working days, to ensure the accuracy of the results. Therefore, our experiment was conducted over a 12-day period in winter (February 25th to March 8th, 2022), encompassing both working and non-working days, with 4 different time segments (8:00, 11:00, 15:00 and 18:00) per day. To prevent fatigue of the backpack walking monitoring experimenters from affecting the results, each experiment was kept to a total duration of less than 30 minutes [72] and each measurement point was monitored for 20 seconds

[73]. The portable sensors used to monitor environmental elements such as $PM_{2.5}$ concentrations, noise, and meteorological parameters, were deployed at a height of approximately 1.5 meters above the ground to ensure accurate correspondence with human activities [71].

Taking into account the specifics of the environment under the viaduct, the experiment data collected in this study included geographical data, pollution and noise data ($PM_{2.5}$ concentrations, equivalent sound level), and information about the factors that influence pollution and noise (temperature and humidity, distance from the viaduct, distance from the river, and traffic volume above and below the viaduct). Table 3 shows the various instruments used for data collection. The $PM_{2.5}$ concentrations data was collected using the PM: SidePak Aerosol Monitor AM520 air particulate experiment instrument, which is designed to provide accurate mass concentrations of particulate matter at 1-second intervals. To ensure the validity of the data, the $PM_{2.5}$ monitor was factory calibrated and further verified based on the configured standard method at an outdoor site in Shanghai prior to the study. The noise data was collected using the AWA6228 multi-function sound level meter instrument. Location and distance data were collected using Unistrong handheld GPS instrument and got GPS data. This study analyzed the relationship between $PM_{2.5}$ concentrations, equivalent sound level (Leq) and each of the influencing elements separately, and evaluated the suitability of exercising at the site with all the data.

Table 3. Summary of instruments and influencing parameters

Type	Parameter	Description	Instrument and model	Sampling resolution
Geographic information	GPS positioning data	Location of each data point (m)	Unistrong handheld GPS instrument	1s
Pollutant data	$PM_{2.5}$ concentration	The 20-s average data at the sample sites (μg/m³)	PM: SidePak Aerosol Monitor AM520 Air particle test instrument	1s
	Equivalent sound level (Leq)	The 20-s average data at the sample sites, representing the intensity of the noise (dB)	AWA6228 multi-function sound level meter instrument	1s
Influence factor	Traffic volume	Traffic volume data of the overall environment (up and down the viaduct) (vel/h)	Mobile phone recording 5 minutes of video	-
	Distance from the viaduct	Distance from the centerline of the viaduct (Fixed values, pre-measured) (m)	Unistrong Handheld GPS instrument	1s
	Distance from the river	Distance from river bank (Fixed values, pre-measured) (m)	Unistrong Handheld GPS instrument	1s
	Temperature	Average value of temperature (	HOBO Temperature and humidity recorder	1s
	Humidity	Average value of humidity (%ph)		

2.3 Data preprocessing and analysis method

2.3.1 Data preprocessing

The study retained high $PM_{2.5}$ concentrations (several hundred μg/m³ or higher) and Leq data (90 dB or higher) to represent real measurements in time and space [62,74]. During pre-processing, data affected by unusual weather conditions, such as strong winds and heavy rain, and the first 2 minutes of on-site monitoring data were removed to reduce errors. The corresponding average measurements of $PM_{2.5}$ concentrations, Leq, temperature and humidity were then calculated for each monitoring site by taking the arithmetic mean of the 20-second samples. Traffic volume data was obtained by averaging the measured data over a five-minute period at the beginning and end of each measurement, to obtain the two-way hourly motor vehicle throughput. The GPS data was imported into the GIS software for subsequent analysis. The final sample consisted of 1188 geographical coordinates, 1188 $PM_{2.5}$ concentration data, 1188 noise data, 1188 temperature and humidity data, 36 traffic volume data and 66 distance data from the viaduct or the river.

2.3.2 Analysis method

After obtaining the monitoring data, this study conducted descriptive analysis, spatial analysis, temporal analysis, and correlation analysis with influencing factors for $PM_{2.5}$ concentrations and noise intensity respectively. First, a significance test was performed using SPSS Statistic 25.0 software to determine the overall distribution of pollutants and noise, and to assess the presence or absence of attenuation in the surrounding area. The Kriging interpolation technique was used to map the spatial distribution of pollutants and noise and to examine individual exposure within the site [75,76,77], which can be expressed as:

$$\mathbf{Z}^*(s_0) = \sum_{i=1}^{n} \lambda_i \mathbf{Z}(s_i)$$

where Z^* (s_0) denotes the observation at point i; Δ_i is the unknown weight of the observation at point i, s_0 is the point to be estimated, and n is the total number of observations. The temporal analysis focused on the characteristics of $PM_{2.5}$ concentrations and noise intensity during working versus non-working days, as well as peak versus non-peak hours. Finally, a backward multiple stepwise regression model was used to quantify the relative contribution of influencing elements to the changes in $PM_{2.5}$ concentrations and noise intensity in winter. The prediction model can be expressed as:

$$Y = a + b_1X_1 + b2X_2 + b_3X_3 + \dots + b_nX_n \; (n \leq 5)$$

where Y denotes $PM_{2.5}$ concentration or Leq; a is a constant; $b_1, b_2, \dots b_n$ denote the coefficients of the independent variables; $X_1, X_2, \dots X_n$ are impact factor parameters. In the specific comparative and correlations analysis of $PM_{2.5}$ concentrations, the relative exposure concentration (REC) was used to reduce the confounding effect of ambient concentration differences [74,78,79]. A positive concentration difference indicates that the $PM_{2.5}$ concentration in the UVS exceeds the background concentration and vice versa. The REC is defined as:

$$REC = Cexposure - Cbackground$$

where $C_{exposure}$ is the actual concentration measured at the monitoring site and represents the exposure of the active population in the UVS, and $C_{background}$ is the background concentration monitored at the background site.

3.Results

3.1Results of $PM_{2.5}$ concentrations in the UVS

3.1.1Statistical analysis of $PM_{2.5}$ concentrations in UVS

Figure 3(a) shows the objective fact that the sample data for $PM_{2.5}$ concentrations in the UVS are higher than the background values at an overall level. The background $PM_{2.5}$ concentrations are the measured values at the starting point of the route, with a mean value of 86.2 μg/m³. The UVS-P $PM_{2.5}$ concentrations are directly influenced by the viaduct, with a mean value of 107.0 μg/m³. While the UVS-NP $PM_{2.5}$ concentrations represent the monitored values at peripheral points not covered by the viaduct projection, with a mean value of 99.9 μg/m³. The mean UVS-P $PM_{2.5}$ concentration is the highest, approximately 7.1% higher than the mean UVS-NP $PM_{2.5}$ concentration and 24.1% higher than the mean background $PM_{2.5}$ concentration.

The sample data for particulate matter concentrations in the UVS varied significantly, with a maximum daily mean of 167.1 μg/m³ corresponding to a background concentration of 131.0 μg/m³, and a minimum daily mean of 52.2 μg/m³ corresponding to a background concentration of 46.3 μg/m³. This study found that the background concentration had a “magnifying effect” on the $PM_{2.5}$ concentration in the UVS, with the higher the background concentration value, the greater the difference between the UVS and the background value. The differences between the daily data in Figure 3(b) are also similar, reflecting a consistent distributional trend, except for 26 February and 28 February, when the variance of the data is relatively large.

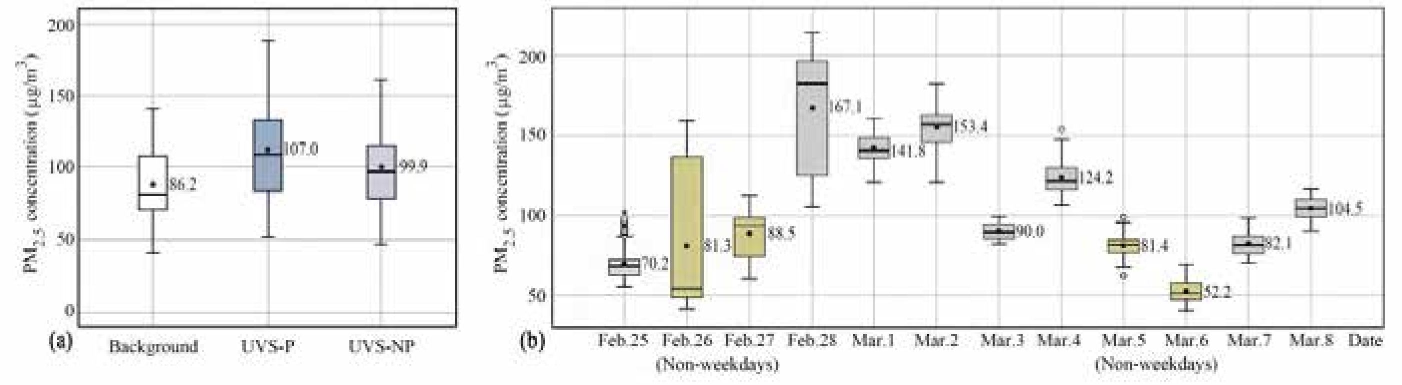

Fig.3 (a) Box plots of all $PM_{2.5}$ concentration data for background points, viaduct projection coverage, and non-viaduct projection surrounding space; (b) Box plots of $PM_{2.5}$ concentrations for each day of UVS. The dots in each box represent the mean (marked by numbers) and the solid line represents the median. Each box extends from the lower quartile to the upper quartile. Whiskers (error bars) below and above the boxes represent maximum and minimum values, and other circles represent outliers.

3.1.2 Spatial-temporal map

At the overall spatial distribution level, estimates of $PM_{2.5}$ concentrations at unmonitored sites were calculated by interpolation using GIS software. Figure 4 presents the 12-day map of mean $PM_{2.5}$ concentrations, which vary considerably between spatial sites, with differences in concentrations between monitoring sites as high as 15.4 μg/m^3, accounting for up to 15% of the mean concentration of all sites. There is a discernible trend of significant attenuation from the viaduct to the east and west over a distance of approximately 210 meters along the road. The areas of high mean $PM_{2.5}$ concentrations occur to the north of the UVS-P, particularly at the intersection with the main road on the north side, with all values above 107 μg/m^3. This indicates higher levels of pollutant exposure and more severe pollution in these areas. There were two areas of low $PM_{2.5}$ concentrations: one is in the green space between the viaduct and the buildings to the east, where a continuous wall of about 2m height between the building and the green space sharply reduces the pollutant concentration to about 99 μg/m^3. The other area of low concentration is the space along the river, with a clear reduction seen, particularly in the section covered by the viaduct, where the mean $PM_{2.5}$ concentration drops to 98 μg/m^3, a much lower value than in the north. This shows that urban water bodies can reduce $PM_{2.5}$ concentrations in nearby areas.

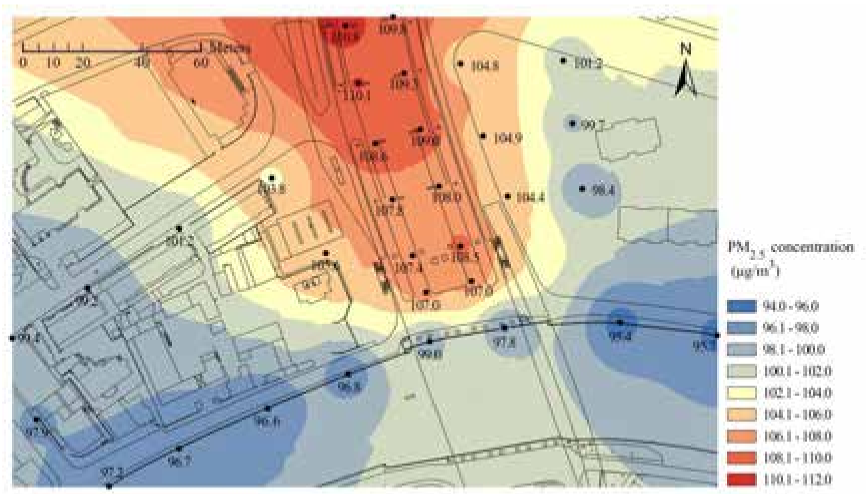

Fig.4 Map of mean $PM_{2.5}$ concentrations in the study area, black dots are actual sample locations, numbers are mean $PM_{2.5}$ concentrations at actual monitored location.

At the overall temporal level, Figure 5 shows that $PM_{2.5}$ concentrations are generally lower on non-working days than on working days. Overall, $PM_{2.5}$ concentrations at different times of the day also shows regular variations. The peak traffic periods tends to have the highest $PM_{2.5}$ concentrations of the day, especially in the evening peak period, while $PM_{2.5}$ concentrations are relatively low in the morning peak and off-peak periods. Sometimes the morning peak values are even lower than the midday off-peak values, presumably due to the difference in traffic volumes and the deposition of $PM_{2.5}$. This phenomenon is more pronounced on working days or when background $PM_{2.5}$ concentration is high.

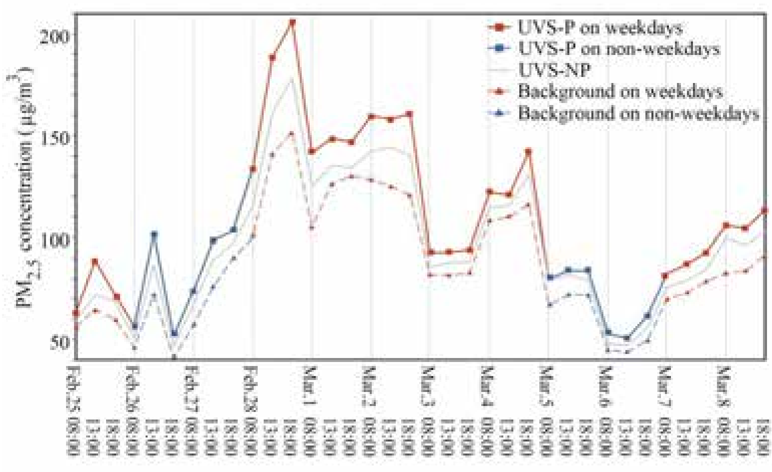

Fig 5. Mean value of $PM_{2.5}$ by time period.

On this basis, two typical days (27 February and 4 March) with similar meteorological backgrounds and traffic volumes are selected for detailed analysis of REC distribution characteristics for each time period between working and non-working days. Figure 6(a) shows that the overall REC values for the three periods on the typical non-working day are small. Figure 6(b) indicates that on a typical weekday the difference in REC between the two peaks and the midday period is greater. The trend of increasing REC towards viaducts and major roads and decreasing REC towards water bodies can be clearly seen in the morning and evening peaks. Two further findings are that 1) the distribution of $PM_{2.5}$ concentrations during a single period on a typical non-working day is more homogeneous and REC is smaller compared to the typical working day; 2) the range of high $PM_{2.5}$ concentrations on the typical working day has a wider impact, almost significantly affecting the area within 240m of the viaduct.

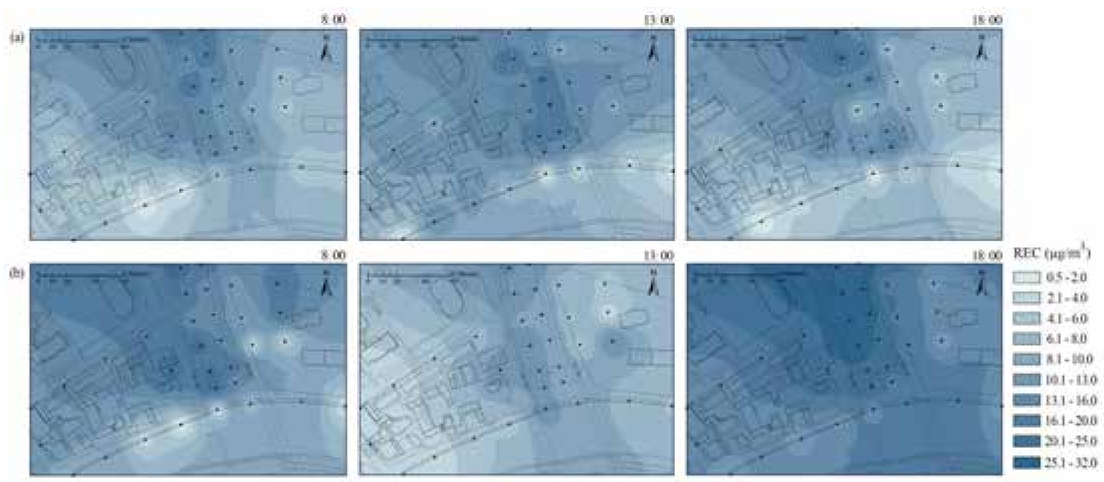

Fig.6 Spatial distribution of REC, black dots are measuring points. (a) includes values for three measurement periods on 27 February, representing non-working days. (b) includes values for three measurement periods on 4 March, representing working days.

3.1.3 Results of influencing factors

A multiple linear regression model (backward method) was used to investigate the effect of different influencing parameters on the distribution of REC in the UVS during winter. All the influencing variables listed in Table 4 have relatively small p-values (<0.05), indicating a statistically significant relationship between the predictor variables and the corresponding $PM_{2.5}$ concentrations. The standardization coefficient (beta coefficient) shows the relative contribution of different parameters to the change in REC. Furthermore, the adjusted R-squared of 0.573 indicates that the model has good explanatory power for the data.

REC is sensitive to changes in traffic, the built environment, and meteorological factors such as temperature and humidity. Among there, traffic volume has the greatest influence on REC, followed by temperature, with beta coefficients of 1.213 and -0.298 respectively. Distance to the viaduct and distance to the water body have no correlation with REC, but the ratio of the two is significantly correlated with REC. This suggests that sports venues should be located as close as possible to water and away from viaducts, and that people should choose times of high temperature, low humidity and low traffic volume to exercise.

Table 4. Regression analysis of the influencing parameters.

Variables	p-value	Beta ^{b}	
$PM_{2.5}$_TV	0.000	1.213	
$PM_{2.5}$_DD	0.000	0.225	**adjusted R^2**
$PM_{2.5}$_TP	0.013	-0.298	
$PM_{2.5}$_HM	0.041	0.121	0.573

Note: Beta ^{b} is standardized coefficient; $PM_{2.5}$_TV = traffic volume; $PM_{2.5}$_DD = the ratio of distance to viaduct and distance to river; $PM_{2.5}$_TP = temperature; $PM_{2.5}$_HM is humidity.

3.2 Results of traffic noise in the UVS

3.2.1 Statistical analysis of traffic noise in the UVS

Figure 7(a) shows that the measured equivalent sound level (Leq) of both the UVS-P and the UVS-NP is significantly higher than the background value. The background Leq has a mean value of 58.9 dB. The mean Leq of the UVS-P is 69.4 dB, which is 17.8% higher than the background level, while the mean Leq of the UVS-NP is also high at 63.2 dB, which is 7.3% higher than the background level, indicating that both are influenced by the viaduct.

Within a single day, there is a large difference in Leq, which can vary by about 10 dB (Figure 7(b)). This suggests that the noise intensity in the study area changes significantly throughout the day. Furthermore, while Leq is slightly higher on working days than on non-working days, the distribution trend is consistent, with median and mean values mostly varying in the range of 60-70 dB, and exceeding 70 dB in a few cases. Since the noise mainly comes from traffic and the activity behavior of the UVS, and the noise intensity from this type of source does not vary much from day to day, the Leq over the 12-day period varies less between single days, but varies considerably within a single day.

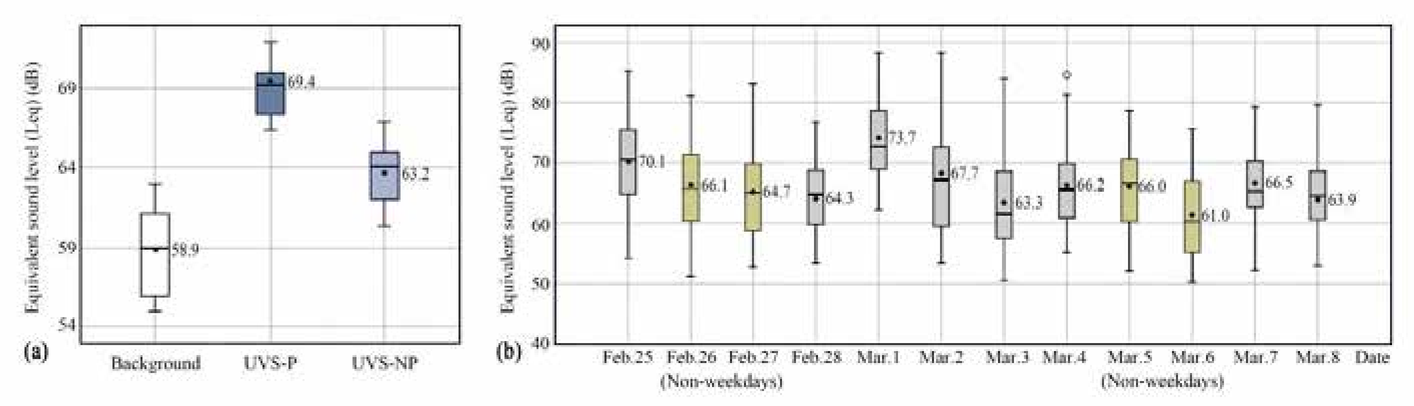

Fig.7 (a) Box plots of all Leq data for background points, viaduct projection coverage, and non-viaduct projection surrounding space; (b) Box plots of Leq for each day of the UVS. The dots in each box represent the mean (marked by numbers) and the solid line represents the median. Each box extends from the lower quartile to the upper quartile. Whiskers (error bars) below and above the boxes represent maximum and minimum values, and other circles represent outliers.

3.2.2Spatial-temporal map

At the overall spatial level, the mean noise distribution over 12 days was calculated using kriging interpolation with GIS software, and the results are shown in Figure 8. The noise levels vary widely across different spaces, with relatively high levels of Leq in the UVS-P, the north side road, and its surrounding areas, where it can reach over 70 dB. The noise levels also show a trend of gradual decay outward from high-traffic areas such as the viaduct and main road intersections. The Leq decreases sharply near the waterfront area on the south side away from the high-traffic area in the UVS-P. In addition, low Leq values appear in the waterfront area and on the west side of the viaduct, where the Leq remains at 59 to 63 dB. The noise is lower away from high-traffic areas and near the waterfront space on the south side, where the noise of the waterfront space remains around 60 dB. The existence of continuous greenery and walls on the southeast side of the viaduct allows the noise to dissipate more quickly.

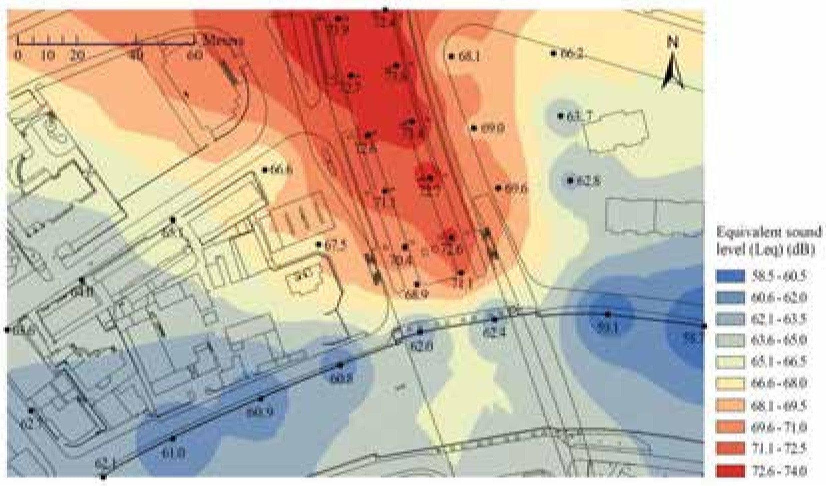

Fig.8 Map of mean Leq in the study area, black dots are actual sample locations, red numbers are mean Leq at actual monitored locations.

At the overall temporal level, the Leq of the UVS-P does not differ much between weekdays and non-weekdays, and is in a stable range of values that are about 10 dB higher than the background value for all time sections. The Leq of the UVS-NP is in the middle of the range. During the day, the Leq of the UVS-P in the morning and evening peaks is usually significantly higher than the midday value, and the difference between the former and the background values is greater than that between the latter and background values. This phenomenon is particularly evident on weekdays such as March 1st.

Overall, the Leq is higher in the morning and evening peak periods for most days, especially on weekdays. The Leq of the UVS-P basically appears as an amplification of the background value, while the Leq of the UVS-NP is in the middle.

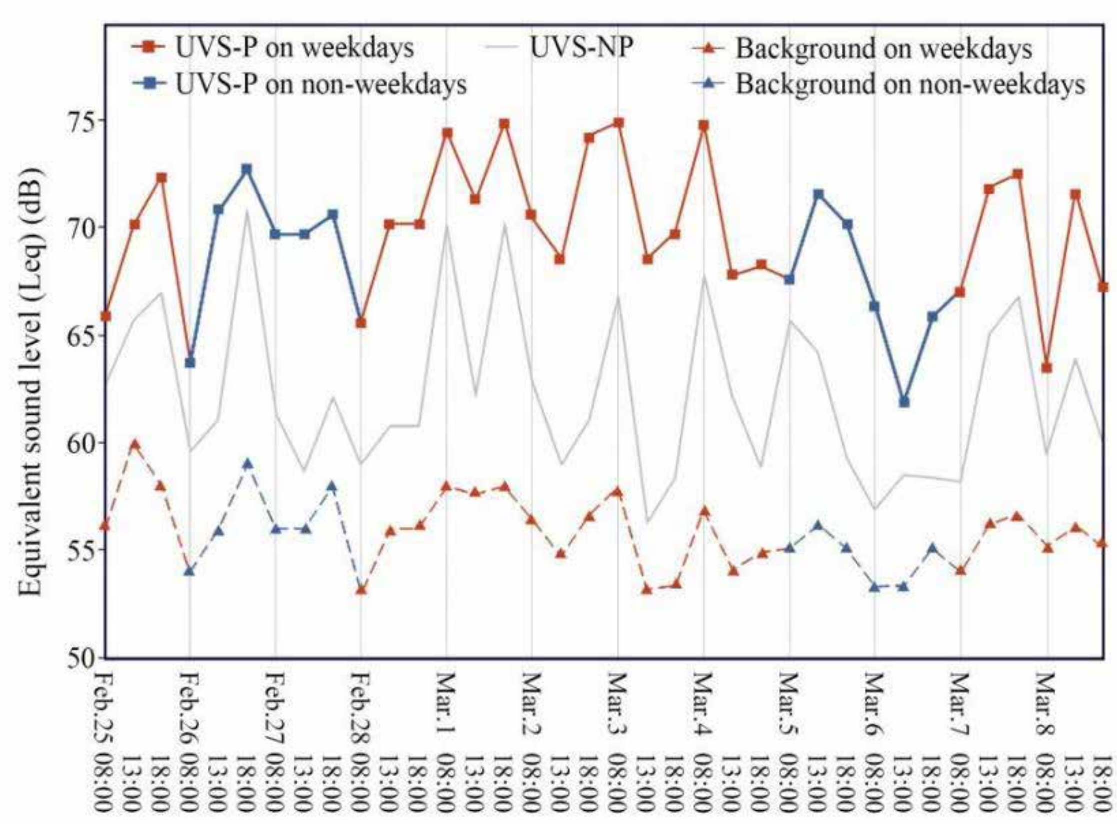

Fig 9. Mean value of Leq by time period.

Continuing with the selection of typical days above, the noise distribution characteristics of the three periods of working and non-working days are presented in Figure 10. In general, the Leq of the UVS-P is significantly higher than that of the UVS-NP and the background value in all time periods for both types of typical days, reflecting the inherent nature of noise under the viaduct. This may be due to the resonance and other characteristics of the viaduct itself, which amplify the traffic noise∆K.W. NGAI et al., 2002∆[80], and non-motorized Traffic vehicles and human activities, which also contribute to the noise pollution.

In addition, the overall difference between working and non-working days is less significant than the corresponding characteristics of $PM_{2.5}$ concentrations, with morning and evening peaks about 5-10 dB higher than normal. The Leq values at each point during the three periods of non-working days are similar, similar to the distribution characteristics of the midday period of working days. While the Leq of the UVS is still significantly higher during the working days peak period, the Leq of the UVS-P is 10-15 dB higher than the background value, indicating that the noise levels are still significantly influenced by the traffic flow. The range of noise attenuation is larger for working days (at least 50-100 meters), while the attenuation characteristics for non-working days are relatively small (between 20-100 meters). In addition, the noise attenuation effect of water bodies is not as obvious as for the $PM_{2.5}$ concentration, and it can be seen that the noise is relatively high at the monitoring sites along the river covered by the viaduct.

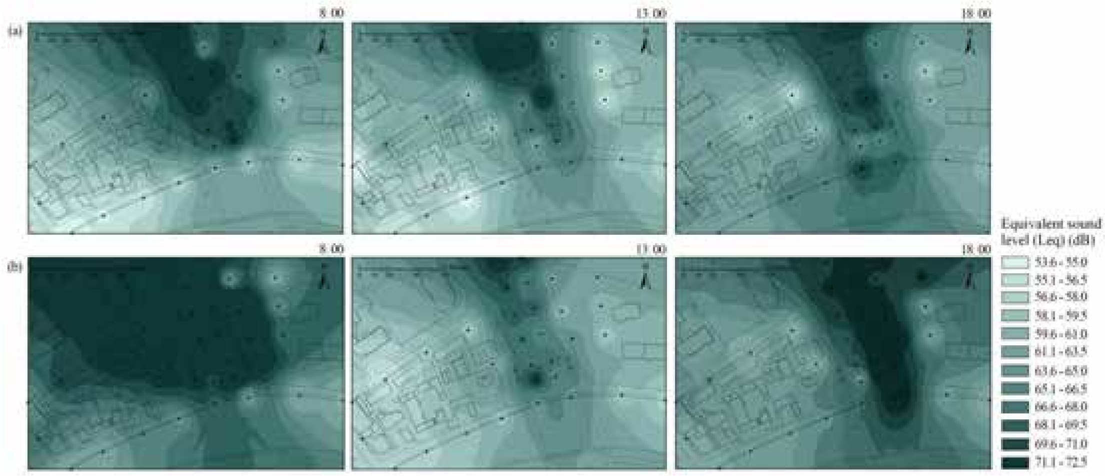

Fig.10 Spatial distribution of Leq, black dots are measuring points. (a) includes values for three measurement periods on 27 February, representing non-working days. (b) includes values for three measurement periods on 4 March, representing working days.

3.2.3 Results of influencing factors

In the case of traffic noise, the effect of different influencing parameters on the distribution of Leq in the UVS during winter was also investigated. Table 5 shows the p-values for various influencing variables, including traffic volume, humidity, and temperature. The p-values for traffic volume, humidity, and temperature are relatively small, with traffic volume having the smallest p-value. This indicates a significant relationship between these influencing factors and Leq. The adjusted R-squared value of 0.718 suggests that the model provides a good level of explanation of the data. The Leq data indicates a clear positive correlation with traffic volume, with a beta coefficient of 0.902, implying that traffic volume is the most influential factor on Leq. Additionally, it shows a negative correlation with winter temperature. This finding suggests that in order to reduce noise hazards, sports stadiums in the UVS should be located in spatial and temporal locations with low traffic flow and humidity.

Table 5. Regression analysis of the influencing parameters on traffic noise

Variables	p-value	Beta [b]	
Noise_TV	0.000	0.902	
Noise_DD	0.191	0.052	**adjusted R^2**
Noise_TP	0.106	-0.046	
Noise_HM	0.08	0.132	0.573

Note: Beta [b] is standardized coefficient; Noise_TV = traffic volume; Noise_DD = the ratio of distance to viaduct and distance to river; Noise_TP = temperature; Noise_HM is humidity.

4.Discussion

The $PM_{2.5}$ concentration and Leq data, as well as influencing factors in the UVS in central Shanghai, were collected based on mobile monitoring and used to analyze spatial and temporal distribution characteristics and factor correlations.

4.1 Contribution of $PM_{2.5}$ and noise distribution pattern

This study found and confirmed the spatial and temporal distribution characteristics of $PM_{2.5}$ concentrations and noise in the UVS, and also found similarities and differences between the two. Firstly, the spatial findings are as follows: 1) $PM_{2.5}$ concentrations and noise in the UVS-P are higher than the background case, consistently the highest values in the study area, and have some attenuation distance in the USP-NP. This is consistent with previous studies [19,22,31]. 2) Pollution levels along the river area are significantly lower and the water bodies contribute to the reduction of $PM_{2.5}$ concentrations as well as noise, which is in agreement with the study finding that lake wetlands can significantly reduce PM concentrations within 300 meters [81]. Furthermore, urban open spaces, green spaces and roadside continuous walls can partially offset air and noise pollution from viaducts [82,83] and effectively reduce $PM_{2.5}$ concentrations and noise attenuation distances [19,56], although the influence on $PM_{2.5}$ is much higher than that on noise, suggesting that pollution can be optimized and mitigated through appropriate design measures.

The temporal findings are as follows: 1) $PM_{2.5}$ concentrations in the UVS and its surrounding space are significantly higher on working days than on rest days, which is not reflected in the noise, a side indication that the main factors influencing the two are different: traffic flow mainly influences $PM_{2.5}$ concentrations, while both traffic flow and crowd activity influence noise [84]. 2) $PM_{2.5}$ concentrations and noise in UVS and its surrounding space are basically higher during the morning and evening peak hours than during normal times of the day. In particular, $PM_{2.5}$ concentrations are more pronounced when the background concentration itself was higher, which is consistent with existing studies [24].

This study found that the enclosed environment of the viaduct significantly increased $PM_{2.5}$ concentrations and noise intensity in the UVS, both of which were significantly and positively correlated with traffic volume. Humidity was also positively correlated with the two pollutants. While there is a negative correlation between temperature and $PM_{2.5}$ concentrations, the negative correlation between temperature and noise is weaker, supporting previous microscopic studies [85]. Additionally, $PM_{2.5}$ concentrations are more sensitive to changes in the built environment, as its formation and dispersion are often influenced by urban buildings, floor area ratio and vegetation [86], while noise intensity is not significantly correlated with the built environment.

4.2 Contribution to policy

This study innovatively focuses on the characteristics of particulate matter and noise distribution in the sports space in the UVS, which is a less studied but important topic. Building on this, the study also selects the spatial quality of the UVS as the ultimate perspective to explore the appropriateness of reusing negative spaces in high-density cities. The results of this study have relatively high application value and provide an intuitive understanding of the changes in particulate matter and noise in the UVS microenvironment. This study is expected to provide theoretical support for the future development of the UVS spatial design and urban form optimization in large cities, represented by Shanghai. According to the spatio-temporal study, the overall $PM_{2.5}$ and noise pollution in the UVS in winter is more severe than in the surrounding areas, and there is attenuation. We recommend not placing open-air sports fields under the viaduct and in the surrounding space within 240 meters to avoid health damage to sensitive people. Noise and $PM_{2.5}$ have different attenuation characteristics and are less affected by the built environment, a difference that needs to be factored into future government decisions. Considering the influence of various factors, the exercise space around the viaduct should preferably be close to the water body, and people should be guided to exercise in places with appropriately high temperature, low humidity and low traffic flow to mitigate the adverse effects of these two types of pollution.

The space for sports under existing viaducts can be transformed into an enclosed indoor space, and mitigation measures can be taken for spaces under viaducts where transformation is difficult. Firstly, they can be converted into indoor spaces by adding spatial barriers to the road or greenery. Secondly, the airflow under viaduct spaces can be maximized by using new materials such as acoustic panels and mitigation measures for the viaducts [30], as well as enhancing the microclimate design of the UVS.

4.3 Limitation

This study only selected 12 days in winter to conduct the experiment, which lacks comparability to the summer season or to a full year's worth of data, and the limited timeframe may have had an impact on the correlation analysis. Secondly, as the dispersion of airborne particulate matter is influenced by aerodynamic mechanisms, the dispersion of polluting particulate matter in the UVS is the result of a combination of meteorological factors. Although this study avoided the effects of strong winds and rain, it did not specifically consider wind environmental factors such as wind speed and direction. In the future, more factors, such as the types of moving vehicles, need to be incorporated.

This study reveals the spatial and temporal characteristics and summarizes the influencing factors of particulate matter and noise pollution in a typical UVS in a high-density city through a field experiment with high accuracy. This provides an important basis for scientifically and effectively assessing the health and comfort of the UVS.

The study has both guidance and practical significance for the design of existing or new UVS, and provides more ideas and references for the concept of urban renewal in high-density cities.

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Consent for publication
All authors consent for publication.

Ethics approval and consent to participate
Not applicable.

Availability of data and materials
All data generated or analyzed during this study are included in this manuscript.

CRediT authorship contribution statement
Chao Liu: Conceptualization, Supervision, Project administration. **Ze-Yin Chen:** Writing – original draft, Investigation, Software, Visualization, Formal analysis. **Si-Ying Li:** Writing – original draft & reviewing & editing, Investigation, Software, Formal analysis. **Zheng Liu:** Data curation.

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.

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Not applicable.

Data availability
The data that has been used is confidential.

Abbreviations
UVS under-viaducts spaces
UVS-P projected spaces of under-viaducts spaces
UVS-NP unprojected spaces of under-viaducts spaces
REC relative exposure concentration

References (elsevier-with-titles formatting style)
[1] Kaiming Xiao, Jianming Su. The Utilization of Underside Space of Viaduct from the Perspective of Urban Public Space[J]. Engineering and Construction Magazine, 2011, 25(03): 1673-5781. https://doi.org/10.3969/j.issn.1673-5781.2011.03.009.

[2] Yingying Peng, Jun Liang, Zhirui Mao. Research on the space form and intervention strategy under the bridge——Take Kunming as an example[J]. Urbanism And Architecture, 2021, 18(04):30-32: 1673-5781. https://doi.org/10.19892/j.cnki.csjz.2021.04.06.

[3] L. He, J. Hang, X. Wang, B. Lin, X. Li, G. Lan, Numerical investigations of flow and passive pollutant exposure in high-rise deep street canyons with various street aspect ratios and viaduct settings, Science of The Total Environment. 584–585 (2017) 189–206. https://doi.org/10.1016/j.scitotenv.2017.01.138.

[4] C. Hao, X. Xie, Y. Huang, Z. Huang, Study on influence of viaduct and noise barriers on the particulate matter dispersion in street canyons by CFD modeling, Atmospheric Pollution Research. 10 (2019) 1723–1735. https://doi.org/10.1016/j.apr.2019.07.003.

[5] Y. Huang, C. Lei, C.-H. Liu, P. Perez, H. Forehead, S. Kong, J.L. Zhou, A review of strategies for mitigating roadside air pollution in urban street canyons, Environmental Pollution. 280 (2021) 116971. https://doi.org/10.1016/j.envpol.2021.116971.

[6] UN-Habitat, Planning and design for sustainable urban mobility: Global report on human settlements 2013, UN-Habitat, 2013.

[7] W. Guo, Y. Tan, X. Yin, Z. Sun, Impact of $PM_{2.5}$ on Second Birth Intentions of China's Floating Population in a Low Fertility Context, IJERPH. 16 (2019) 4293. https://doi.org/10.3390/ijerph16214293.

[8] Y.C. Chan, R.W. Simpson, G.H. Mctainsh, P.D. Vowles, D.D. Cohen, G.M. Bailey, Source apportionment of $PM_{2.5}$ and PM_{10} aerosols in Brisbane (Australia) by receptor modelling, Atmospheric Environment. 33 (1999) 3251–3268. https://doi.org/10.1016/s1352-2310(99)00090-4.

[9] P.K.H. Lee, J.R. Brook, E. Dabek-Zlotorzynska, S.A. Mabury, Identification of the Major Sources Contributing to PM2.5 Observed in Toronto, Environ. Sci. Technol. 37 (2003) 4831–4840. https://doi.org/10.1021/es026473i.

[10] M. Abu-Allaban, J.A. Gillies, A.W. Gertler, R. Clayton, D. Proffitt, Motor Vehicle Contributions to Ambient PM_{10} and $PM_{2.5}$ at Selected Urban Areas in the USA, Environ Monit Assess. 132 (2006) 155–163. https://doi.org/10.1007/s10661-006-9511-3.

[11] V. Singh, R.S. Sokhi, J. Kukkonen, $PM_{2.5}$ concentrations in London for 2008–A modeling analysis of contributions from road traffic, Journal of the Air & Waste Management Association. 64 (2013) 509–518. https://doi.org/10.1080/10962247.2013.848244.

[12] M.P. Walsh, $PM_{2.5}$: global progress in controlling the motor vehicle contribution, Front. Environ. Sci. Eng. 8 (2014) 1–17. https://doi.org/10.1007/s11783-014-0634-4.

[13] J. Lelieveld, J.S. Evans, M. Fnais, D. Giannadaki, A. Pozzer, The contribution of outdoor air pollution sources to premature mortality on a global scale, Nature. 525 (2015) 367–371. https://doi.org/10.1038/nature15371.

[14] C.A. Pope III, Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution, JAMA. 287 (2002) 1132. https://doi.org/10.1001/jama.287.9.1132.

[15] D.W. Dockery, Health Effects of Particulate Air Pollution, Annals of Epidemiology. 19 (2009) 257–263. https://doi.org/10.1016/j.annepidem.2009.01.018.

[16] L. Perez, M. Medina-Ramón, N. Künzli, A. Alastuey, J. Pey, N. Pérez, R. Garcia, A. Tobias, X. Querol, J. Sunyer, Size Fractionate Particulate Matter, Vehicle Traffic, and Case-Specific Daily Mortality in Barcelona, Spain, Environ. Sci. Technol. 43 (2009) 4707–4714. https://doi.org/10.1021/es8031488.

[17] G. Hao, L. Zuo, P. Xiong, L. Chen, X. Liang, C. Jing, Associations of $PM_{2.5}$ and road traffic noise with mental health: Evidence from UK Biobank, Environmental Research. 207 (2022) 112221. https://doi.org/10.1016/j.envres.2021.112221.

[18] L. He, J. Hang, X. Wang, B. Lin, X. Li, G. Lan, Numerical investigations of flow and passive pollutant exposure in high-rise deep street canyons with various street aspect ratios and viaduct settings, Science of The Total Environment. 584–585 (2017) 189–206. https://doi.org/10.1016/j.scitotenv.2017.01.138.

[19] L. Yin, T. Hang, F. Qin, X. Lin, Y. Han, Measuring and Quantifying Impacts of Environmental Parameters on Airborne Particulate Matter in Under-Viaducts Spaces in Wuhan, China, IJERPH. 18 (2021) 5197. https://doi.org/10.3390/ijerph18105197.

[20] N.A.H. Janssen, D.F.M. Van Mansom, K. Van Der Jagt, H. Harssema, G. Hoek, Mass concentration and elemental composition of airborne particulate matter at street and background locations, Atmospheric Environment. 31 (1997) 1185–1193. https://doi.org/10.1016/s1352-2310(96)00291-9.

[21] P. Tiitta, T. Raunemaa, J. Tissari, T. Yli-Tuomi, A. Leskinen, J. Kukkonen, J. Härkönen, A. Karppinen, Measurements and modelling of $PM_{2.5}$ concentrations near a major road in Kuopio, Finland, Atmospheric Environment. 36 (2002) 4057–4068. https://doi.org/10.1016/s1352-2310(02)00309-6.

[22] A.P. Patton, J. Perkins, W. Zamore, J.I. Levy, D. Brugge, J.L. Durant, Spatial and temporal differences in traffic-related air pollution in three urban neighborhoods near an interstate highway, Atmospheric Environment. 99 (2014) 309–321. https://doi.org/10.1016/j.atmosenv.2014.09.072.

[23] Y. Zhu, J. Pudota, D. Collins, D. Allen, A. Clements, A. DenBleyker, M. Fraser, Y. Jia, E. McDonald-Buller, E. Michel, Air pollutant concentrations near three Texas roadways, Part I: Ultrafine particles, Atmospheric Environment. 43 (2009) 4513–4522. https://doi.org/10.1016/j.atmosenv.2009.04.018.

[24] S. Kaur, M. Nieuwenhuijsen, R. Colvile, Personal exposure of street canyon intersection users to $PM_{2.5}$, ultrafine particle counts and carbon monoxide in Central London, UK, Atmospheric Environment. 39 (2005) 3629–3641. https://doi.org/10.1016/j.atmosenv.2005.02.046.

[25] Z. Wang, S. Zhong, H. He, Z.-R. Peng, M. Cai, Fine-scale variations in $PM_{2.5}$ and black carbon concentrations and corresponding influential factors at an urban road intersection, Building and Environment. 141 (2018) 215–225. https://doi.org/10.1016/j.buildenv.2018.04.042.

[26] Y. Zhu, W.C. Hinds, S. Kim, S. Shen, C. Sioutas, Study of ultrafine particles near a major highway with heavy-duty diesel traffic, Atmospheric Environment. 36 (2002) 4323–4335. https://doi.org/10.1016/s1352-2310(02)00354-0.

[27] R. Baldauf, E. Thoma, M. Hays, R. Shores, J. Kinsey, B. Gullett, et al., Traffic and Meteorological Impacts on Near-Road Air Quality: Summary of Methods and Trends from the Raleigh Near-Road Study, Journal of the Air & Waste Management Association. 58 (2008) 865–878. https://doi.org/10.3155/1047-3289.58.7.865.

[28] H. Feng, J. Zhao, Z. Li, Experimental study on the diffusion of respirable particulate matter in street valley under elevated roads, Proceedings of the 2015 2nd International Conference on Machinery, Materials Engineering, Chemical Engineering and Biotechnology. (2016). https://doi.org/10.2991/mmeceb-15.2016.79.

[29] Zhi, Z. Qiu, W. Wang, G. Wang, Y. Hao, Y. Liu, The influence of a viaduct on PM dispersion in a typical street: Field experiment and numerical simulations, Atmospheric Pollution Research. 11 (2020) 815–824. https://doi.org/10.1016/j.apr.2020.01.009.

[30] B. Li, Z. Qiu, J. Zheng, Impacts of noise barriers on near-viaduct air quality in a city: A case study in Xi'an, Building and Environment. 196 (2021) 107751. https://doi.org/10.1016/j.buildenv.2021.107751.

[31] J.L. Durant, C.A. Ash, E.C. Wood, S.C. Herndon, J.T. Jayne, W.B. Knighton, M.R. Canagaratna, J.B. Trull, D. Brugge, W. Zamore, C.E. Kolb, Short-term variation in near-highway air pollutant gradients on a winter morning, Atmos. Chem. Phys. 10 (2010) 8341–8352. https://doi.org/10.5194/acp-10-8341-2010.

[32] A. Azhari, N.D.A. Halim, A.A.A. Mohtar, K. Aiyub, M.T. Latif, M. Ketzel, Evaluation and Prediction of PM_{10} and $PM_{2.5}$ from Road Source Emissions in Kuala Lumpur City Centre, Sustainability. 13 (2021) 5402. https://doi.org/10.3390/su13105402.

[33] A. Charron, R.M. Harrison, Fine ($PM_{2.5}$) and Coarse ($PM_{2.5-10}$) Particulate Matter on A Heavily Trafficked London Highway: Sources and Processes, Environ. Sci. Technol. 39 (2005) 7768–7776. https://doi.org/10.1021/es050462i.

[34] P.A. Kassomenos, S. Vardoulakis, A. Chaloulakou, A.K. Paschalidou, G. Grivas, R. Borge, J. Lumbreras, Study of PM_{10} and $PM_{2.5}$ levels in three European cities: Analysis of intra and inter urban variations, Atmospheric Environment. 87 (2014) 153–163. https://doi.org/10.1016/j.atmosenv.2014.01.004.

[35] Y. Cheng, S.C. Lee, K.F. Ho, J.C. Chow, J.G. Watson, P.K.K. Louie, J.J. Cao, X. Hai, Chemically-speciated on-road $PM_{2.5}$ motor vehicle emission factors in Hong Kong, Science of The Total Environment. 408 (2010) 1621–1627. https://doi.org/10.1016/j.scitotenv.2009.11.061.

[36] O. Lozhkina, V. Lozhkin, N. Nevmerzhitsky, D. Tarkhov, A. Vasilyev, Motor transport related harmful $PM_{2.5}$ and PM_{10}: from onroad measurements to the modelling of air pollution by neural network approach on street and urban level, J. Phys.: Conf. Ser. 772 (2016) 012031. https://doi.org/10.1088/1742-6596/772/1/012031.

[37] A. Mukherjee, M.C. McCarthy, S.G. Brown, S. Huang, K. Landsberg, D.S. Eisinger, Influence of roadway emissions on near-road $PM_{2.5}$: Monitoring data analysis and implications, Transportation Research Part D: Transport and Environment. 86 (2020) 102442. https://doi.org/10.1016/j.trd.2020.102442.

[38] P.L. Kinney, M.G. Gichuru, N. Volavka-Close, N. Ngo, P.K. Ndiba, A. Law, A. Gachanja, S.M. Gaita, S.N. Chillrud, E. Sclar, Traffic impacts on $PM_{2.5}$ air quality in Nairobi, Kenya, Environmental Science & Policy. 14 (2011) 369–378. https://doi.org/10.1016/j.envsci.2011.02.005.

[39] M.H. Askariyeh, M. Venugopal, H. Khreis, A. Birt, J. Zietsman, Near-Road Traffic-Related Air Pollution: Resuspended $PM_{2.5}$ from Highways and Arterials, IJERPH. 17 (2020) 2851. https://doi.org/10.3390/ijerph17082851.

[40] C.M. Kendrick, P. Koonce, L.A. George, Diurnal and seasonal variations of NO, NO_2 and $PM_{2.5}$ mass as a function of traffic volumes alongside an urban arterial, Atmospheric Environment. 122 (2015) 133–141. https://doi.org/10.1016/j.atmosenv.2015.09.019.

[41] A. Rakowska, K.C. Wong, T. Townsend, K.L. Chan, D. Westerdahl, S. Ng, G. Močnik, L. Drinovec, Z. Ning, Impact of traffic volume and composition on the air quality and pedestrian exposure in urban street canyon, Atmospheric Environment. 98 (2014) 260–270. https://doi.org/10.1016/j.atmosenv.2014.08.073.

[42] P. Kumar, P. Fennell, R. Britter, Measurements of particles in the 5–1000 nm range close to road level in an urban street canyon, Science of The Total Environment. 390 (2008) 437–447. https://doi.org/10.1016/j.scitotenv.2007.10.013.

[43] I. Ivković, O. Čokorilo, S. Kaplanović, The estimation of GHG emission costs in road and air transport sector: case study of Serbia, Transport. 33 (2016) 260–267. https://doi.org/10.3846/16484142.2016.1169557.

[44] J. Dratva, E. Zemp, D.F. Dietrich, P.-O. Bridevaux, T. Rochat, C. Schindler, M.W. Gerbase, Impact of road traffic noise annoyance on health-related quality of life: results from a population-based study, Qual Life Res. 19 (2010) 37–46. https://doi.org/10.1007/s11136-009-9571-2.

[45] World Health Organization. Regional Office for Europe, Night noise guidelines for Europe, World Health Organization, Regional Office for Europe, 2009. https://apps.who.int/iris/handle/10665/326486.

[46] W. Babisch, G. Pershagen, J. Selander, D. Houthuijs, O. Breugelmans, E. Cadum, F. Vigna-Taglianti, K. Katsouyanni, A.S. Haralabidis, K. Dimakopoulou, P. Sourtzi, S. Floud, A.L. Hansell, Noise annoyance — A modifier of the association between noise level and cardiovascular health?, Science of The Total Environment. 452–453 (2013) 50–57. https://doi.org/10.1016/j.scitotenv.2013.02.034.

[47] C. Clark, R. Crombie, J. Head, I. van Kamp, E. van Kempen, S.A. Stansfeld, Does Traffic-related Air Pollution Explain Associations of Aircraft and Road Traffic Noise Exposure on Children's Health and Cognition? A Secondary Analysis of the United Kingdom Sample From the RANCH Project, American Journal of Epidemiology. 176 (2012) 327–337. https://doi.org/10.1093/aje/kws012.

[48] World Health Organization, Regional Office for Europe, Burden of disease from environmental noise: quantification of healthy life years lost in Europe. World Health Organization, Regional Office for Europe, 2011. https://apps.who.int/iris/handle/10665/326424

[49] C. Clark, J. Head, S.A. Stansfeld, Longitudinal effects of aircraft noise exposure on children's health and cognition: A six-year follow-up of the UK RANCH cohort, Journal of Environmental Psychology. 35 (2013) 1–9. https://doi.org/10.1016/j.jenvp.2013.03.002.

[50] A.L. Hansell, M. Blangiardo, L. Fortunato, S. Floud, K. de Hoogh, D. Fecht, R.E. Ghosh, H.E. Laszlo, C. Pearson, L. Beale, S. Beevers, J. Gulliver, N. Best, S. Richardson, P. Elliott, Aircraft noise and cardiovascular disease near Heathrow airport in London: small area study, BMJ. 347 (2013) f5432–f5432. https://doi.org/10.1136/bmj.f5432.

[51] P. Pamanikabud, P. Vivitjinda, Noise prediction for highways in Thailand, Transportation Research Part D: Transport and Environment. 7 (2002) 441–449. https://doi.org/10.1016/s1361-9209(02)00012-3.

[52] J.D. Thacher, A.H. Poulsen, O. Raaschou-Nielsen, A. Jensen, K. Hillig, N. Roswall, U. Hvidtfeldt, S.S. Jensen, G. Levin, V.H. Valencia, M. Sørensen, High-resolution assessment of road traffic noise exposure in Denmark, Environmental Research. 182 (2020) 109051. https://doi.org/10.1016/j.envres.2019.109051.

[53] K.M. Shakya, P. Kremer, K. Henderson, M. McMahon, R.E. Peltier, S. Bromberg, J. Stewart, Mobile monitoring of air and noise pollution in Philadelphia neighborhoods during summer 2017, Environmental Pollution. 255 (2019) 113195. https://doi.org/10.1016/j.envpol.2019.113195.

[54] T.A.K. Bouzir, N. Zemmouri, Effect of urban morphology on road noise distribution, Energy Procedia. 119 (2017) 376–385. https://doi.org/10.1016/j.egypro.2017.07.121.

[55] B. Wang, J. Kang, Effects of urban morphology on the traffic noise distribution through noise mapping: A comparative study between UK and China, Applied Acoustics. 72 (2011) 556–568. https://doi.org/10.1016/j.apacoust.2011.01.011.

[56] G.A.P. Lopez, L.C.L. de Souza, Urban green spaces and the influence on vehicular traffic noise control, Ambient. Constr. 18 (2018) 161–175. https://doi.org/10.1590/s1678-86212018000400299.

[57] G.M. Echevarria Sanchez, T. Van Renterghem, P. Thomas, D. Botteldooren, The effect of street canyon design on traffic noise exposure along roads, Building and Environment. 97 (2016) 96–110. https://doi.org/10.1016/j.buildenv.2015.11.033.

[58] World Health Organization, Regional Office for Europe, Environmental noise guidelines for the European Region, World Health Organization, Regional Office for Europe, 2018. https://apps.who.int/iris/handle/10665/279952

[59] N. Mohareb, S. Maassarani, Assessment of street-level noise in three different urban settings in Tripoli, Urban Climate. 29 (2019) 100481. https://doi.org/10.1016/j.uclim.2019.100481.

[60] J.S. Apte, K.P. Messier, S. Gani, M. Brauer, T.W. Kirchstetter, M.M. Lunden, et al., High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data, Environ. Sci. Technol. 51 (2017) 6999–7008. https://doi.org/10.1021/acs.est.7b00891.

[61] J.L. Santiago, F. Martín, A. Martilli, A computational fluid dynamic modelling approach to assess the representativeness of urban monitoring stations, Science of The Total Environment. 454–455 (2013) 61–72. https://doi.org/10.1016/j.scitotenv.2013.02.068.

[62] Z. Li, J.C.H. Fung, A.K.H. Lau, High spatiotemporal characterization of on-road $PM_{2.5}$ concentrations in high-density urban areas using mobile monitoring, Building and Environment. 143 (2018) 196–205. https://doi.org/10.1016/j.buildenv.2018.07.014.

[63] A. Can, L. Dekoninck, D. Botteldooren, Measurement network for urban noise assessment: Comparison of mobile measurements and spatial interpolation approaches, Applied Acoustics. 83 (2014) 32–39. https://doi.org/10.1016/j.apacoust.2014.03.012.

[64] Y. Shi, K.K.-L. Lau, E. Ng, Developing Street-Level $PM_{2.5}$ and PM_{10} Land Use Regression Models in High-Density Hong Kong with Urban Morphological Factors, Environ. Sci. Technol. 50 (2016) 8178–8187. https://doi.org/10.1021/acs.est.6b01807.

[65] Y. Shi, X. Xie, J.C.-H. Fung, E. Ng, Identifying critical building morphological design factors of street-level air pollution dispersion in high-density built environment using mobile monitoring, Building and Environment. 128 (2018) 248–259. https://doi.org/10.1016/j.buildenv.2017.11.043.

[66] K.M. Shakya, P. Kremer, K. Henderson, M. McMahon, R.E. Peltier, S. Bromberg, J. Stewart, Mobile monitoring of air and noise pollution in Philadelphia neighborhoods during summer 2017, Environmental Pollution. 255 (2019) 113195. https://doi.org/10.1016/j.envpol.2019.113195.

[67] J. Gillespie, N. Masey, M.R. Heal, S. Hamilton, I.J. Beverland, Estimation of spatial patterns of urban air pollution over a 4-week period from repeated 5-min measurements, Atmospheric Environment. 150 (2017) 295–302. https://doi.org/10.1016/j.atmosenv.2016.11.035.

[68] L.M. Zwack, C.J. Paciorek, J.D. Spengler, J.I. Levy, Characterizing local traffic contributions to particulate air pollution in street canyons using mobile monitoring techniques, Atmospheric Environment. 45 (2011) 2507–2514. https://doi.org/10.1016/j.atmosenv.2011.02.035.

[69] C.H. Yu, Z. Fan, P.J. Lioy, A. Baptista, M. Greenberg, R.J. Laumbach, A novel mobile monitoring approach to characterize spatial and temporal variation in traffic-related air pollutants in an urban community, Atmospheric Environment. 141 (2016) 161–173. https://doi.org/10.1016/j.atmosenv.2016.06.044.

[70] Y. Gao, Z. Wang, C. Liu, Z.-R. Peng, Assessing neighborhood air pollution exposure and its relationship with the urban form, Building and Environment. 155 (2019) 15–24. https://doi.org/10.1016/j.buildenv.2018.12.044.

[71] G. Hoek, K. Meliefste, J. Cyrys, M. Lewné, T. Bellander, M. Brauer, P. Fischer, U. Gehring, J. Heinrich, P. van Vliet, B. Brunekreef, Spatial variability of fine particle concentrations in three European areas, Atmospheric Environment. 36 (2002) 4077–4088. https://doi.org/10.1016/s1352-2310(02)00297-2.

[72] J. Yong Jeon, J. Young Hong, P. Jik Lee, Soundwalk approach to identify urban soundscapes individually, The Journal of the Acoustical Society of America. 134 (2013) 803–812. https://doi.org/10.1121/1.4807801.

[73] X.-H. Zhu, K.-F. Lu, Z.-R. Peng, H.-D. He, S.-Q. Xu, Spatiotemporal variations of carbon dioxide (CO_2) at Urban neighborhood scale: Characterization of distribution patterns and contributions of emission sources, Sustainable Cities and Society. 78 (2022) 103646. https://doi.org/10.1016/j.scs.2021.103646.

[74] S. Hankey, J.D. Marshall, Land Use Regression Models of On-Road Particulate Air Pollution (Particle Number, Black Carbon, $PM_{2.5}$, Particle Size) Using Mobile Monitoring, Environ. Sci. Technol. 49 (2015) 9194–9202. https://doi.org/10.1021/acs.est.5b01209.

[75] Krige D G. 1951. A statistical approach to some basic mine valuation problems on the Witwatersrand[J]. Journal of the Southern African Institute of Mining and Metallurgy, 52(6): 119-139. https://hdl.handle.net/10520/AJA0038223X_4792

[76] Z. Liu, M. Xie, K. Tian, P. Gao, GIS-based analysis of population exposure to $PM_{2.5}$ air pollution—A case study of Beijing, Journal of Environmental Sciences. 59 (2017) 48–53. https://doi.org/10.1016/j.jes.2017.02.013.

[77] W. Wang, C. Wu, Z. Mu, Y. Gu, Y. Zheng, L. Ren, Y. Hu, A. Liang, L. Peng, L. Zhang, J. Li, Effect of ambient air pollution exposure on renal dysfunction among hospitalized patients in Shanghai, China, Public Health. 181 (2020) 196–201. https://doi.org/10.1016/j.puhe.2020.01.001.

[78] M. Van Poppel, J. Peters, N. Bleux, Methodology for setup and data processing of mobile air quality measurements to assess the spatial variability of concentrations in urban environments, Environmental Pollution. 183 (2013) 224–233. https://doi.org/10.1016/j.envpol.2013.02.020.

[79] H. Hu, Q. Chen, Q. Qian, X. Zhou, Y. Chen, Y. Cai, Field investigation for ambient wind speed and direction effects exposure of cyclists to $PM_{2.5}$ and PM_{10} in urban street environments, Building and Environment. 223 (2022) 109483. https://doi.org/10.1016/j.buildenv.2022.109483.

[80] K.W. NGAI, C.F. NG, STRUCTURE-BORNE NOISE AND VIBRATION OF CONCRETE BOX STRUCTURE AND RAIL VIADUCT, Journal of Sound and Vibration. 255 (2002) 281–297. https://doi.org/10.1006/jsvi.2001.4155.

[81] L. Zhao, T. Li, A. Przybysz, Y. Guan, P. Ji, B. Ren, C. Zhu, Effect of urban lake wetlands and neighboring urban greenery on air PM_{10} and $PM_{2.5}$ mitigation, Building and Environment. 206 (2021) 108291. https://doi.org/10.1016/j.buildenv.2021.108291.

[82] J. Chen, L. Zhu, P. Fan, L. Tian, R. Lafortezza, Do green spaces affect the spatiotemporal changes of PM2.5 in Nanjing?, Ecol Process. 5 (2016). https://doi.org/10.1186/s13717-016-0052-6.

[83] A. Lee, H. Jordan, J. Horsley, Value of urban green spaces in promoting healthy living and wellbeing: prospects for planning, RMHP. (2015) 131. https://doi.org/10.2147/rmhp.s61654.

[84] L.H. Schaudinischky, A. Schwartz, The sports ground as a noise source, Applied Acoustics. 5 (1972) 119–131. https://doi.org/10.1016/0003-682x(72)90016-3.

[85] M.-A. Kioumourtzoglou, J. Schwartz, P. James, F. Dominici, A. Zanobetti, $PM_{2.5}$ and mortality in 207 US cities: Modification by Temperature and City Characteristics, Epidemiology. 27 (2015) 221. https://doi.org/10.1097/ede.0000000000000422.

[86] X. Deng, F. Gao, S. Liao, S. Li, Unraveling the association between the built environment and air pollution from a geospatial perspective, Journal of Cleaner Production. 386 (2023) 135768. https://doi.org/10.1016/j.jclepro.2022.135768.